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Building Resilient communities: Techno-economic assessment of standalone off-grid PV powered net zero energy (NZE) villages

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ABSTRACT

The use of renewable energy resources for off-grid electricity production has gained more importance in recent decades for meeting the energy needs of remote areas, even with limited resources. This research aims to provide an optimized and cost-effective approach for generating electricity in rural areas. By using current methodology, a stand alone energy source of PV is designed for development of NZE village. Solar irradiance of the selected location is 6.16 kWh/m^2/day while the estimated electric load data for whole village is 64.259 kWh. Electric load and solar irradiance of the loaction is used in the Hybrid Optimization Model for Electric Renewable (HOMER) to design and analyze the techno-economic feasibility of the stand alone PV system to meet the load requirements. The study obtained the total Net Present Cost (NPC) of $0.511 M and the Cost Of Electricity (COE) is 2.26$/unit through the HOMER analysis, which is further refined by performing sensitivity analysis using parameters such as PV panel price, battery price, solar irradiance, variations in electric load and discount rates. According to the results, system is feasibile by annual electricity production of 30,078 kWh with initial capital investment of $0.434 M. This analysis compared the system performance and showed that it is economically and technically viable to meet the complete electricity needs of the village with a payback period of 7.2 years. Research can be utilized for policy making and implementation of NZE approach in remote areas by the government.

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1. Introduction

The essential component for human economic growth and social development is electricity. Even though it is one of the key inventions and has profoundly changed the lives of millions of people, but even then, around 1.1 billion people in the world are still striving for the electricity [1]. The majority of people who are currently without electricity reside in rural parts of underdeveloped countries [2]. Similarly, Pakistan has a significant population without access to electricity. In recent years, demand in electricity is increased due to the growth in economy. The country now has a 25,000 MW electricity consumption, which is expected to rise to 40, 000 MW in 2030 [3].However, there is still a 5000–7000 MW electrical deficit due to the supply remaining between 18,000 and 20, 000 MW [4]. In major cities, this substantial electricity shortfall causes load shedding for 8–10 h, while load-shedding lasts up to 18 h per day in remote areas [5]. However, situation is considerably worse in the remote areas of Sindh and Baluchistan, where load shedding sometimes last for days.

Despite of abundance in natural resources, Pakistan has shortage of electricity. According to studies, insufficient electrification in the rural areas is due to the reason of 85 % residents currently residing in remote areas [6].The distance between two villages is large in majority of the rural areas, hence, such regions are too expensive and unprofitable to connect to the grid. Second, just 50–100 W of electricity are required per residence in rural locations, which is extremely low [7].

Many researches state the viability of off-grid net zero energy approach for rural electrification due to the great characteristics of Photovoltaic i.e., modular, lighter, and easier to install [8,9]. Additionally, solar PV eliminates the fuel shipment charges with the onsite utilization of renewable resources. According to Mishra and Behera [10], the installation of solar PV system improves the lifestyle in rural areas and enhances the standard of living for households, particularly for women. Life cycle cost analysis of solar PV NZEBs was demonstrated by Sandwell et al. [11]. According to the results of the study, PV based NZEBs are great option for the local environmental protection, increase in net energy ratio, and sustainable source of rural electrification. In another study of feasibility of solar PV, Hosenuzzaman et al. [12] concluded that PV-based electricity offers significant environmental advantages over conventional energy sources. Solar photovoltaic energy has many environmental advantages with reduction on CO_2 emissions, noiseless environment and reduced health hazards. Additionally, solar PV reduces the air pollution by eliminating the need of kerosene lights. In rural Ghana, Obeng et al. [13] found that solar PV can lessen the indoor air pollution by 50 % caused due to the usage of kerosene lights. In many researches it is concluded that solar PV is the best way for the NZEB developments in remote areas [14–18]. Moreover, due to the circumstances of rural areas, it can be difficult to construct solar PV projects in Pakistan. Numerous scholars have extensively investigated the concept of net-zero energy buildings (NZEBs) through simulations and a limited number of experimental studies [19]. For example, Jin et al. utilized Ecotect to design an NZEB in Northern China, focusing on energy balance, financial viability, and environmental sustainability [20]. Their findings demonstrated that integrating a 12.25 KW capacity PV system and a solar hot-water collector allowed for almost two days' worth of electricity supply for family use. Stefanović et al. undertook a project involving PV technology and refurbishment for an NZEB in Serbia [21]. Their results underscored that the high cost of local photovoltaic panels and inverters led to a current investment return period of 8–12 years, potentially deterring significant investor interest. Examining an office NZEB in China, Zhou et al. evaluated PV efficiency and energy utilization. Their study revealed that PV electricity generation accounted for only 58.9 % of the building's energy consumption due to the challenging atmospheric conditions in Tianjin, China [22]. In the context of tropical climates, Sun et al. explored the economic implications of active and passive retrofit designs for NZEBs. They found that active solutions such as lighting retrofits and air-conditioning enhancements were more economically viable in hot-humid climates [23]. Alajmi et al. engaged EnergyPlus simulation and integrated PV panels and solar water heating to develop an NZEB in the U.S. Their outcomes indicated that 26 m^2 of integrated PV panels generated 4053 kWh/year, and incorporating solar water heaters yielded energy savings of 2045 kWh/year while reducing CO_2 emissions by 0.25 tons [24]. Asaee et al. offered insights into transforming housing stocks in cold-climate countries into NZEBs, highlighting the significance of energy retrofits and renewable energy technologies [25]. Moschetti et al. delved into a Norwegian NZEB project involving PV panels and low-carbon insulation materials. They determined that PV panels had the greatest impact on lowering operational energy, and the embodied energy and emissions of materials played a pivotal role in NZEB success [26]. In the realm of hot and humid climates, Feng et al. reviewed 34 NZEB cases and found that passive designs and technologies were often preferred [27]. Dong et al. evaluated the performance of an NZEB in a hot summer and cold winter zone, emphasizing the potential of carbon offsets through appropriate PV system adjustments to achieve life-cycle zero-emission buildings [28]. Trofimova et al. explored indoor environment quality in a Chinese NZEB under challenging climatic conditions. Their findings indicated that the mean summer indoor temperature slightly exceeded standard limits in the NZEB, reflecting the complexities of maintaining comfortable conditions [29]. However, China's severe cold climate region presents substantial challenges due to climate constraints, economic factors, resource limitations, and limited environmental awareness among farmers [30]. Achieving Net Zero Energy Ready Homes (NZERHs) in this context remains a formidable task with few existing studies. Addressing this gap, Wang et al. conducted a comprehensive evaluation of NZERHs in cold regions of China, Europe, and America. They highlighted the increasing focus on passive technologies followed by PV and renewable technologies [31]. Ni et al. examined the operational performance and PV system integration in a wooden NZERH located in China's severe cold zone. Their findings showcased the significant energy reduction achieved by a water-passing wooden structure wall and the complementary role of the PV system in NZERH operations [32]. Lastly, in northern China, a substantial proportion of heating relies on coal, leading to extensive non-renewable resource consumption and environmental pollution [33]. Addressing this challenge involves transitioning from coal-fired heating to cleaner alternatives, a critical aspect in realizing NZERHs in severe cold regions.

Houses in remote areas are usually of one-room huts and made of mud and straw, only need lighting. Therefore, installing power lines for such a low demand is an expensive practice. Also, there are minimum chances for grid connectivity in near future by the government of Pakistan. Additionally, it is very difficult to transport fuel for diesel generators, which can be an alternative option.

Lastly, investors are hesitant to invest in rural electrification because of location of the remote areas, the absence of infrastructure facilities in the different province, and the lack of rural energy data. Considering these aspects, solar energy is the ideal option for development of NZEB villages in the remote areas of Pakistan due to the abundant solar irradiance [34]. According to the evaluation by the World Bank for the solar potential in Pakistan, Baluchistan region has the highest average sunlight hours in the entire world [35]. The high temperature in Pakistan, according to Sustainability Advocacy, makes solar photovoltaic (PV) the greatest option for electrification. Additionally, Sustainability Advocacy suggested that installing solar panels on each home is a more cost-effective strategy for improving the socio-economic standing of the rural residents of Baluchistan than extending grid lines to remote locations [7]. Furthermore, according to the Asian Development Bank (ADB), off-grid electricity generation is one of the most viable option to decrease energy shortfall in the remote areas of Pakistan [36].

The NREL-developed Hybrid Optimization Model for Electric Renewables (HOMER) is a tool for cost and feasibility analysis of any project. HOMER is capable of hourly simulations and can handle simulation of all types of renewable resources. Using HOMER software, Munuswamy S. et al. [37] conducted an economic analysis for the health clinic in remote areas. According to the results, if the distance between the villages is small than on grid electricity is not a feasible solution. A PV installation feasibility report for a small village of 100 families was provided by Luiz et al. [38]. The proposed system was designed to be more affordable in comparison with diesel generator, which lowers the fuel costs. Similar to this, Lau et al. [39] used HOMER software to fullfil the residential load using PV-Diesel genertaor. Simulation was performed for a community of 40 houses with a over designed PV system. Also, Olatomiwa et al. [40] evaluated various possible energy generating methodologies for different sites in Nigeria. Based on the results, hybrid renewable combination of different resources are the most practical solution with less carbon emissions.

While the existing literature extensively examines various aspects of NZE buildings and villages, there is a noticeable scarcity of studies specifically addressing the challenges and simulation based strategies for implementing NZE concepts in regions with extreme climates and limited resources, such as Sindh, Pakistan. The literature predominantly focuses on temperate and tropical climates, with limited attention given to severe hot climate zones and resource-constrained environments. Sindh, characterized by its arid climate and challenging socio-economic conditions, presents unique obstacles to achieving NZE villages. Hence, simulation based extensive research is required to evaluate the solar power potential and to examine the economic viability of renewable energy resources to fill the research gap which lies in the limited attention given to the applicability and challenges of NZE concepts in regions with extreme climates, resource constraints, and specific socio-economic contexts, such as Sindh.Addressing these gaps through comprehensive research can provide valuable insights for policymakers, researchers, and practitioners aiming to establish NZE villages in such challenging environments.

Main objectives of the research are.

1. Evaluation of solar power potential in extreme climate of Sindh to provide insights into the feasibility of harnessing solar energy as a primary renewable resource for achieving Net Zero Energy (NZE) village.
2. Examination of simulation based economic viability of renewable energy in the context of extreme climate and limited resources of Sindh. This includes assessing the costs, discount rates and payback period
3. Development of simulation-based Strategies i.e., energy-efficient design and PV integration to achieve NZE status while considering the specific socio-economic conditions of the region.

The manuscript is divided into different sections as follow.

1. Site selection according to the solar irradiance
2. Thermal load calculation for three categories

➢ Community
➢ Household
➢ commercial

3. HOMER based simulation for the selected site for standalone PV NZE village
4. Examination of the main conclusions drawn from the simulation results
5. Conclusion and recommendations

2. Methodology

In current research, NZE approach is utilized to develop a completely energy independent village without the need of electricity from grid. By doing so, expenditure of the electricity could be minimized with the cutting costs of power lines which are required for grid station setups. Methodology for the research was.

3. Site selection

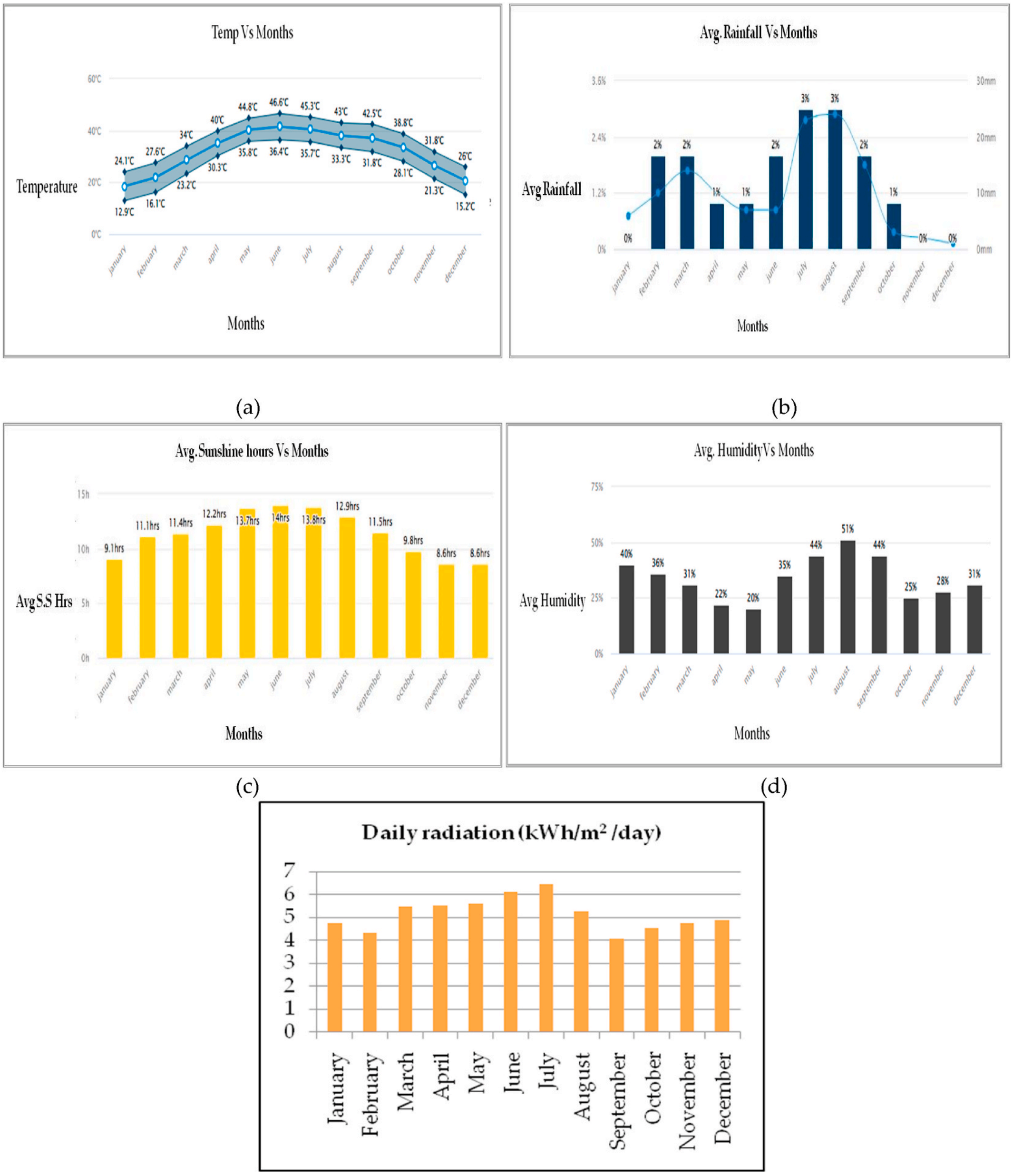
2. Electric load calculation
3. NZE model development in HOMER pro based on solar irradiance potential and costs of PV
4. Sensitivity analysis and optimization of the results
5. Feasibility estimation of the proposed approach.

4. Village design

In current research, selection of the site is one of the most critical parameter. Site is selected according to the highest irradiance potential.

4.1. Selection of study area W.R.T solar irradiance of selected site

The selected site for NZE village is a small community near Burriro Sindh. Burriro is a small village in Jacobabad district in the Sindh province of Pakistan (longitude 28.1817°N and latitude 68.7259°E). The distance of the community from district headquarter is 36 km. The total population is 800 while the primary source of earning is farming. According to the Köppen-Geiger scale, burriro has a very hot climate, which is the primary reason for the selection of site. In burriro, the annual highest temperature ranges from 38 °C in



(e)

Fig. 1. (a) Monthly average temperature profile, (b) Monthly average rainfalls, (c) Average sunshine hours, (d) Average humidity, (e) Onsite solar irradiance potential.

January to 47 °C in June. The total rainfall is 117 mm annually. However, minimum amount is recorded in December with 1 mm value and maximum amount is 24 mm in August. Fig. 1(a–e) show the outside temperature profile, monthly rainfall, humidity, daily sunshine hours and solar irradiance of the selected site.

June is the peak summer load time due to the temperature range available in Fig. 2.

4.2. Identification of zones and 3dmodelling

After the selection of site for the development of NZE village, 3D model is designed as shown in Fig. 7. In current research, Basic facilities for the selected site is a health clinic, small school, basic utility shops and a load of 8 households.

4.3. Three dimensional modeling of the village

Map of the village is designed according to the map specifications given in Table 1.

4.4. Electric load estimation

The first step in designing a NZE model is the electric load estimation of the village. This involves analyzing the energy consumption of various loads, such as lighting, appliances, cooling and heating systems, water pumps, etc. and estimating the energy demand in kilowatt-hours (kWh) per day. Hence, electric load is estimated by considering electronic components of each entity of the villagers. The proposed system is designed for the peak thermal loads in summer. Design conditions for the NZE village are given in Table 2.

5. Homerprogram

HOMER (Hybrid Optimization Model for Electric Renewables) is a software tool used for the design and optimization of off-grid and grid-connected power systems. The software was developed by the National Renewable Energy Laboratory (NREL) in the United States, and it has been widely adopted by researchers, engineers, and energy practitioners worldwide. The HOMER software is a powerful tool that allows users to model complex power systems with multiple renewable energy sources, energy storage, and backup generators. It uses advanced optimization algorithms to minimize the overall cost of the system while meeting the energy demands of the user.

The HOMER software can be used to design a wide range of power systems, from small off-grid systems for remote communities to

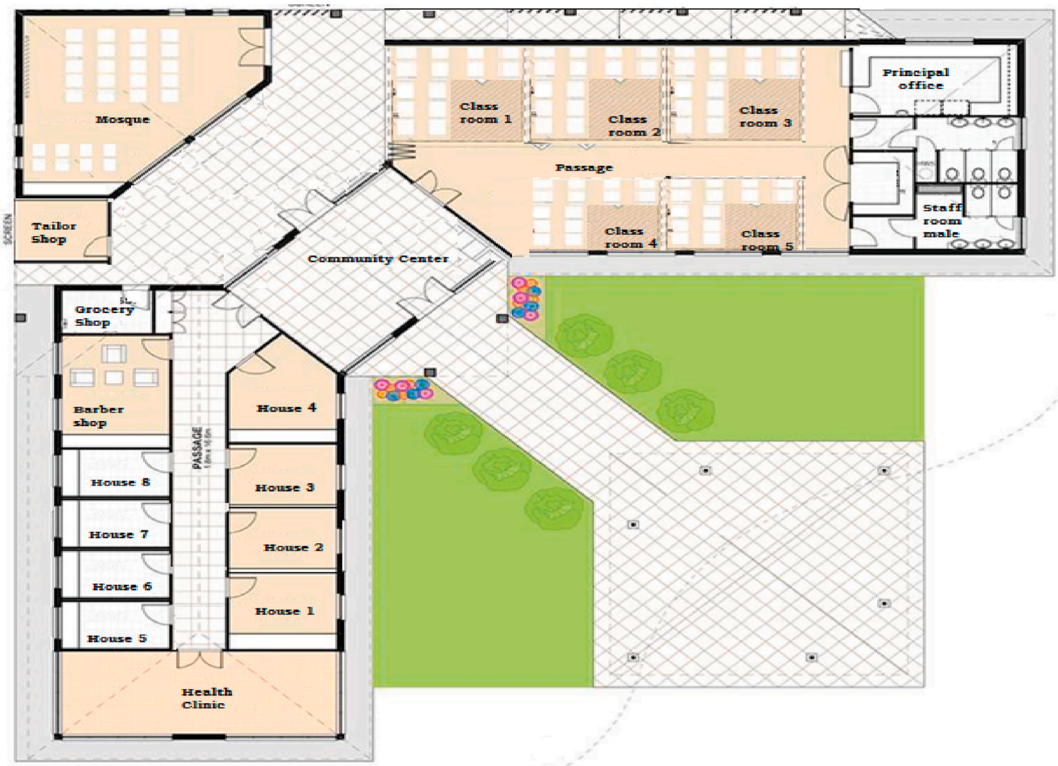


Fig. 2. Three dimensional model ofthe NZE village.

Table 1
Table summary of no of units in proposed NZE village.

Building type	Number of units
Small hospital	01
School	01
Mosque	01
Barber shop	01
Tailor shop	01
Grocery shop	01
Community center	01
Houses	08

Table 2
Electric load of the village.

		Lighting	Fan	Fridge	TV	Phone	Water pump	Iron
Household load	**No of units**	3	2	1	1	2	1	1
	Power (watts)	24	50	100	175	30	750	1000
	Utilization hours	9	14	24	5	2	1	0.2
	House hold load (01 units) (Wh)	648	1400	2400	875	120	750	200
	House hold load (08 units) (kWh)	5.184	11.2	19.2	7	0.96	6	1.6
Total load 1 (kWh)	**51.144**							

			Lighting	Fan	Total load (Wh)
Commercial and Community load	**Health centre**	No of units	5	4	3800
		Power (watts)	40	50	
		Utilization hours	7	12	
	Mosque	No of units	4	4	2800
		Power (watts)	40	50	
		Utilization hours	5	10	
	School	No of units	12	10	4940
		Power (watts)	40	50	
		Utilization hours	3	7	
	Shops (3 units)	No of units	3	3	1575
		Power (watts)	25	50	
		Utilization hours	5	8	
Total load 2 (kWh)	**13.115**				

Hence total electric load of whole village is 64.259 kWh.

large grid-connected systems for commercial and industrial applications. It can also be used to model microgrids, which are local energy systems that can operate independently of the main grid. The HOMER software is user-friendly. It includes a comprehensive database of renewable energy resources, such as solar, wind, hydro, and biomass, as well as a library of energy storage and backup generator technologies [41]. In current research, the HOMER software is a valuable tool for the design, optimization, and analysis of NZE system.

5.1. Homer pro model development of Nze village

HOMER Pro model of village is developed as per the methodology. Initially, after site selection based on weather conditions, simulation is performed for components given in section 4.2. Afterwards, all the parameters for each component of the system are selected based on simulation results and feasibility is projected. Moreover, electric load of the village and weather data were the input parameters.

5.2. Input simulation parameters

5.2.1. Solar PV panels

In HOMER Pro software, solar PV panels refer to a type of renewable energy technology which are used for the conversion of sunlight into electrical energy by using PV cells. PV panels are a key component of a standalone solar power system, which can be modeled and analyzed using HOMER Pro. For current research PV system is designed by using rated capacity, efficiency, temperature coefficient, and orientation.

5.2.2. Power converters

In HOMER Pro software, power converters refer to devices that convert the electrical output of a renewable energy system into a form that can be used by the loads in the system. In current research, converters are used to convert Direct Current (DC) produced by solar panels into Alternative Current (AC) that can be used by the loads in a system.

5.2.3. Battery bank

In HOMER Pro software, a battery bank refers to a collection of batteries that are used to store energy in a standalone power system. The battery bank used as a backup power source when renewable energy sources such as solar panels are not producing enough electricity to meet the load demands of the system. HOMER Pro allows users to model and analyze the performance of battery banks in standalone power systems.

5.3. Design of Pv system based on solar irradiance potential

Solar irradiance potential refers to the amount of solar radiation that a particular location receives. Burriro, Jacobabad, Sindh, Pakistan is located in a region that receives high levels of solar irradiance throughout the year due to its location in a desert climate. According to the Global Solar Atlas, a tool developed by the World Bank Group, the highest annual solar irradiance in Burriro, Jacobabad is around 6.16 kWh/m^2/day [42]. This means that Burriro, Jacobabad has a high potential for solar energy generation. However, solar energy output from a solar panel installation will also depend on a variety of factors, such as panel efficiency, temperature, shading, and other environmental conditions.

Based on the load analysis and solar resource assessment, HOMER Pro is used to devise a solar PV system that meets the energy demand of the village. The system design includes the size and number of solar panels, the type and size of the battery bank, the inverter, and any other balance-of-system components as shown in Fig. 3a.

Fig. 3b shows the design schematic of NZE approach for the off grid PV connected village in HOMER pro. Estimated load for the village is 64.259 kWh/day and peak load is 9.05 kW.

5.3.1. Grid information

For the development of off grid solar powered NZE village, two main parts of the system design are PV panels and Inverters. A system with the 350 W Jinko solar PV panels are selected for the desired purpose. However 10.7 kW capacity converter is used. By the simulation results, peak demand of electricity is 9.05 kW.

5.3.2. Proposed solar module design parameters

Jinko solar company is top manufacturers in the world. Hence in undergoing research, 350W PV panels of the Jinko Company are utilized for the said purpose. Panel type is selected on the basis of highest efficiency with the lowest prices which is flat plate mono crystalline. Maximum power voltage of the selected module is 33.7V with the open circuit voltage of 40.8A. However, maximum current is 10.38A. Capital cost of the proposed system is $504943 with the replacement cost of $1120 and O&M cost of $4706. Life span of the selected PV panels is 25years with operating hours of 4385/y. Table 3 describes all the design parameters.

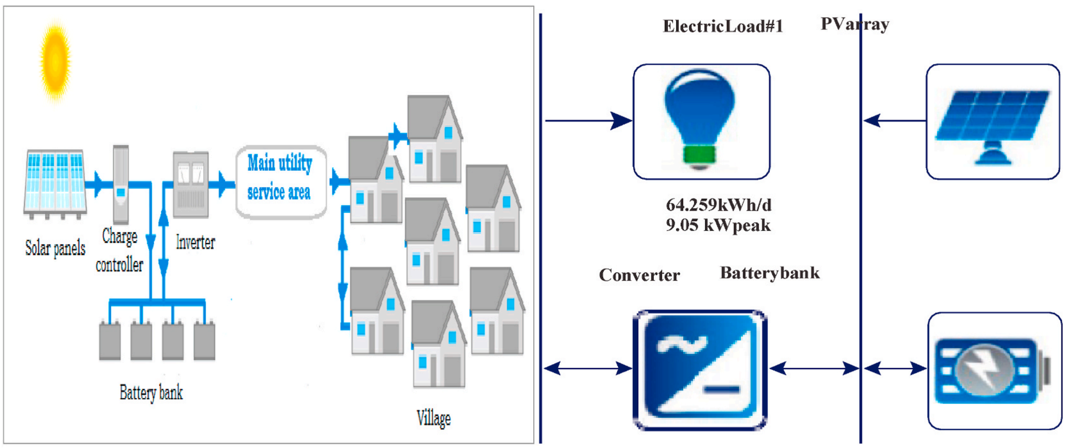
5.3.3. Photo Voltaic design

For the designing of solar PV system, PV array capacity, derating factor, incident radiations, and temperature coefficient of the PV cells is used as per Eq (1) [43].

$$P_{pv=}Y_{PV} \times f_{pv}\left(\frac{G_T}{G_{T,STC}}\right)\left[1+\alpha_P\left(T_C - T_{C,STC}\right)\right] \tag{1}$$

Where;

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions (kW),



(a) (b)

Fig. 3. (a)Average solar irradiance at the selected site per month, (b) Schematic of NZE village for HOMER Pro model.

Table 3
Design parameters of the PV system.

Design Parameters	
Manufacturer	Jinko solar
Panel type	Flat plate mono crystalline
Capital cost ($)	504943
Replacement cost ($)	1120
Operation& Maintenance cost ($/yr)	4706
De-Rating Factor (%)	85
Rated Capacity (kW)	350
Life time (yr)	25
Slope (Degree)	24.5
Maximum power voltage (V)	33.7
Maximum power current (A)	10.38
Open circuit voltage (V)	40.8
Short circuit current (A)	11.08

f_{pv} is the PV derating factor (%),

$\overline{G_T}$ is the solar radiation incident on the PV array in the current time step (kW/m^2),
$G_{T,STC}$ is the incident radiation at standard test conditions (1 kW/m^2),
α_P is the temperature coefficient of power (%/°C),
T_C is the PV cell temperature in the current time step (°C),
$T_{C,STC}$ is the PV cell temperature under standard test conditions (25 °C)
$P_{pv=}$ Output of the PV array

5.3.4. Selection of converter

There are different types of converters i.e., on grid converters, off grid converters and combinational converters. To obtain the desired result of conversion of direct current into alternative current stand alone off grid converters are selected. Selected types of converters have ability to perform dual operations of rectification and inversion of DC to AC with an efficiency of 95 %. The minimum converters capacity is 10.7 kW.

5.3.5. Maximum power point (Mpp) calculation of converter

The MPP is the operating point of the PV module or array at which it produces the maximum power output. The MPP voltage and current is calculated using Eqs. (2) and (3);

$$V_{mpp} = V_{oc} - \left(I_{sc} \ / \ I_{mp}\right) * \left(V_{oc} - V_t\right) \tag{2}$$

$$I_{mpp} = I_{mp} * \left(V_{mpp} \ / \ V_{mp}\right) \tag{3}$$

Where:
V_{oc} = Open-circuit voltage of the PV module or array.
I_{sc} = Short-circuit current of the PV module or array.
I_{mp} = Current at the maximum power point.
V_t = Thermal voltage (about 25 mV at room temperature)
V_{mpp} = voltage at maximum power point.
I_{mpp} = current at maximum power.
Estimated results of mean output are 1.30 kW with rectification of 1.51 kW. However, maximum output of converter is 8.82 kW with the rectifier output of 10.7 kW.

5.4. Evaluation Criteria for optimization

The main objective of the current study was to develop an optimized standalone off grid NZE village for a remote location Burriro, Sindh in Pakistan. To assess the impact of uncertainty, the HOMER program conducted various optimizations with input variables. The optimization process determined the most effective factors that improved the system's performance [44,45]. HOMER identified the optimal combination of modules necessary to meet specific electrical loads [46]. Using a proprietary derivative-free algorithm, HOMER estimated the most cost-effective system and presented a list of schematics based on NPC and payback period.

To achieve the best possible outcomes with the HOMER software, specific variables, including electric and solar data, were selected. In calculating the discount factor, a discount rate of 15 % was used, while the rate of inflation was 6.8 % [47,48]. The fuel cost escalation rate was determined to be 4.10 % [49], and the interest rate was 20 % [50,51]. Typically, the lifespan of solar panels is between 25 and 30 years [52].

5.4.1. Net Present Cost (NPC)

The Net Present Value (NPV) is the sum of the discounted cash flows over the system's lifespan, minus the initial investment. We can calculate this by using Eq (4) as follows:

$$NPV = -Totalsystemcost + (Annualsavings / Discountrate)x(1-(1 + Discountrate)\hat{}(-Systemlifespan)) \quad (4)$$

5.4.2. Operating cost

The HOMER program defines operating cost as any annual costs and revenues, excluding initial capital costs. Equation (5) is used to calculate the operating cost as follows:

$$C_{operating} = C_{ann,tot} - C_{ann,cap} \quad (5)$$

Here, $C_{operating}$ represents the total annualized cost of the system in USD per year, while $C_{ann,tot}$ is the total annualized capital cost in USD per year and $C_{ann,cap}$ is the total annualized capital cost ($/year)

5.4.3. Primary capital expenditure

At the start of a project, the primary capital of a project refers to the complete installed cost of that particular project.

5.5. Reults and discussion

In this section, various outcomes derived from the three primary functions of HOMER software will be discussed, namely simulation, optimization, and sensitivity analysis, which were employed to perform an economic evaluation and feasibility of the project.

5.5.1. PV power output

The mean output of the PV flat plate system is 82.4 kWh per day. Comparing the power output values in Fig. 4 ranging from 0 to 20 kW with the mean output give information about how the PV system's performance varies throughout the day. It indicates that the PV system generates varying amounts of energy during different hours, contributing to the overall daily mean output. Also, the total annual production of the PV system is 30,078 kWh per year. This is the cumulative energy generated over the entire year. By considering the power output values for each hour of the day, it is estimated that how much energy is generated during peak hours and non-peak hours. This insight contributes to understanding the distribution of energy generation across different times of the day. Additionally, the PV system operates for 4389 h per year. Comparing the power output values to the total number of operating hours will gauge the efficiency and utilization of the system. It indicates how effectively the system is capturing sunlight and converting it into electricity during its active hours. Moreover, the PV penetration is noted as 128 %, suggesting that the PV system's capacity is 28 % higher than the demand. By relating the power output values to the PV penetration rate, it is analyzed that how the system's output compares to the demand during different hours. This information is valuable for understanding potential energy surplus or deficits. Hence by examining the power output values in Fig. 4, following insights of mean output, total annual production, operating hours, and PV penetration are inferred.

- ➢ **Peak Generation Hours**: Hours of the day when the PV system generates its highest power output can be estimated. These peak hours contribute significantly to both the mean output and the total annual production of energy.
- ➢ **Variability in Energy Generation:** The variation in power output throughout the day shows the PV system's response to changing solar irradiance levels. It helps to understand how the system adapts to different sunlight conditions.
- ➢ **Energy Generation Patterns:** By analyzing the power output values over the entire day, different energy generation patterns are observed. This understanding can guide decisions related to energy storage, grid integration, and load management.

5.5.2. Analyzing the impact of PV panel cost Fluctuations on economic Indicators

It is determined that the cost of a 325-W panel in Pakistan is 72.80$. Using HOMER Pro software, incorporating PV panel details and costs, and conducting simulations, the inverter output ranges between 8.82 kW and 10.7 kW. In Table 4, by manipulating the

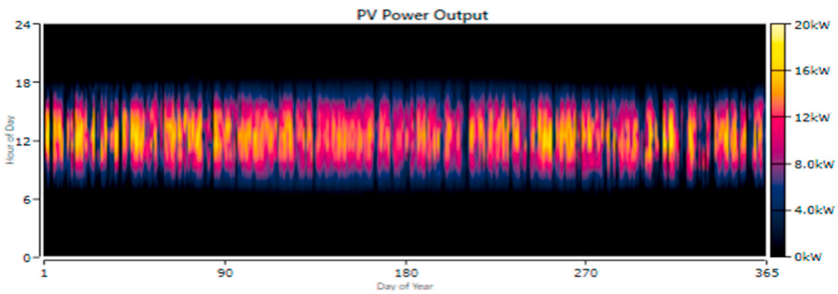


Fig. 4. PV power output of flat plate.

Table 4
Details of costs and electricity production by PV panels and converters.

Primary capital cost ($ millions)	0.434	0.434	0.434	0.434	0.434	0.434	0.434
Discount rate	15 %	7.5 %	8 %	10 %	11.5 %	13 %	15 %
Net Present Cost ($ millions)	0.511	0.537	0.533	0.529	0.522	0.519	0.511
Operating cost($/yr)	1742	2870	2716	2319	2132	1997	1742

With the discount rate of 15 %, which is currently used in Pakistan [39], Net Present Cost and operating cost is minimum. Hence, for the development of NZE village, NPC of 0.511 $million and 1742$/yr operating cost of the system is required.

discount rates from 7.5 % to 15 % depending upon current economic situations, details of operating cost and cost of electricity is given.

5.5.3. Optimization of costs associated with electricity production by PV panels and converters

The last column in Table 4 outlines the outcomes of an optimization process in HOMER Pro for the system costs and electricity production. Through careful analysis and strategic decision-making, the system's parameters were fine-tuned to achieve the most efficient and economically viable configuration.

The optimized primary capital cost remains fixed at $0.434 million, indicating that this specific investment is the most suitable for setting up the NZE village system. This suggests that after evaluating various options in Table 4, the selected configuration aligns with the initial capital required, ensuring a balanced approach between upfront investment and long-term benefits.

The discount rate chosen during optimization is 15 %, signifying the emphasis on present value in decision-making. This rate influences the weighing of future costs and benefits and has a notable impact on financial considerations. It suggests that for this specific configuration, the optimal trade-off between immediate returns and long-term financial health lies at this discount rate.

The minimized Net Present Cost (NPC) of $0.511 million showcases the outcome of the optimization process. It indicates that the selected configuration, with the given primary capital cost, discount rate, and operating costs, results in the lowest total cost over the system's anticipated lifespan.

Lastly, the optimized operating cost of $1742 underscores the successful strategic decisions that resulted in the most efficient annual expenses for running and maintaining the NZE village system. Table 4 reflects the operational strategies integrated into the optimized configuration to ensure cost-effective maintenance while maintaining optimal system performance.

Hence, the optimization process has yielded a configuration that harmonizes technical and financial considerations. The selected primary capital cost, discount rate, and operating costs collectively enable the achievement of an economically viable and sustainable NZE village system.

5.5.4. Battery specifications

The battery specifications provided for the Net Zero Energy (NZE) village in Fig. 5. The system employs a total of 123 batteries, configured with a string size of 1 and connected in parallel across 123 strings with bus voltage of 6 V. Also, with an autonomy of 36.8 h, the battery system can provide energy for more than a day without requiring a recharge. This autonomy is particularly significant in scenarios where the solar energy generation might experience intermittency due to weather conditions. The battery's nominal capacity is 123 kWh, indicating its maximum energy storage potential. However, the useable nominal capacity is 98.4 kWh, which is the portion of the nominal capacity that can be safely utilized without affecting the battery's lifespan. The expected life of the battery system is projected to be 15 years.

The specifications further delve into energy flows. The system receives 13,210 kWh of energy from the solar source annually, while 11,949 kWh is consumed for various applications. Storage depletion accounts for 63.4 kWh/year, representing energy lost due to

Fig. 5. Battery specifications of the system.

factors like self-discharge. Additionally, losses in the system amount to 1324 kWh/year, encompassing energy losses during charging and discharging cycles. The annual throughput of the battery system, totaling 12,595 kWh, showcases the comprehensive energy utilization within the system on a yearly basis. This metric considers both the energy input from the solar panels and the energy output for end-use applications.

5.5.5. Converter specifications

In Fig. 6all the parameters of converter for the transformation, control, and distribution of energy, contributing to its overall performance and efficiency are given. The inverter and rectifier units have an equal capacity of 10.7 kW, which indicates their ability to handle the conversion of energy between different forms – from direct current (DC) to alternative current (AC) in the case of the inverter, and vice versa in the case of the rectifier. The mean output power values of 1.3 kW for the inverter and 1.51 kW for the rectifier reflect their typical operational power levels. Also, the minimum output power of 0 kW for both units suggests that they have the capacity to operate at lower power levels if required, possibly reaching zero output during periods of low demand or in specific scenarios. On the other hand, the maximum output power for the inverter is 8.82 kW, while the rectifier has a maximum output power of 10.7 kW. These values indicate the upper limits of power conversion that the units can handle effectively. Similarly, the capacity factor, at 12.2 % for the inverter and 14.1 % for the rectifier, provides insights into how efficiently the converters operate over time. It signifies the ratio of actual output power to the maximum possible output power under optimal conditions. The hours of operation further illustrate the time duration during which the units are actively operating. The inverter operates for 5201 h annually, while the rectifier operates for 2664 h annually, revealing their utilization patterns.

Energy flow metrics encompass the energy input, output, and losses within the system. The energy input for the inverter is 11,352 kWh per year, which could represent the energy it receives from the renewable energy sources such as solar panels. Similarly, the rectifier receives 13,210 kWh of energy input per year. The energy output signifies the useable energy that each unit provides for the overall system. The inverter yields 11,949 kWh, while the rectifier contributes 14,678 kWh annually.Losses, at 597 kWh for the inverter and 1468 kWh for the rectifier, represent the energy that is lost due to various factors during the conversion processes. These could include inefficiencies in the conversion, heat dissipation, and other operational losses.Hence, these converter design parameters play a pivotal role in ensuring the efficient transformation of energy, enabling seamless integration of renewable sources, energy storage, and distribution mechanisms.

5.5.6. Cost of electricity (COE)

As, intensity of solar radiations is highest for the selected location with an average of 16 peak sun hours. A surface plot embossed with NPC is illustrating the cost of electricity (COE) in Fig. 7. The cost of electricity by stand alone PV is 2.62 $/unit.

5.6. Off grid Nze village feasibility analysis

After the simulation of selected off grid system. For the selection of an optimal design approach to build NZE village, a detailed cost analysis is performed. Payback period and Net present Value of the system were the two main governing factors for the prediction of feasibility of the project. However, operating costs, replacement cost and capital costs are also evaluated to check the proposed system monetary evaluation.

5.6.1. Payback period

The final aim of the research was to assess the practicality and profitability of the suggested NZE approach for whole village. As per the HOMER Pro results, the payback period for the proposed system is 7.2 years. The return on investment is 17.1 %.

Quantity	Inverter	Rectifier	Units
Capacity	10.7	10.7	kW
Mean Output	1.30	1.51	kW
Minimum Output	0	0	kW
Maximum Output	8.82	10.7	kW
Capacity Factor	12.2	14.1	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	5,201	2,664	hrs/yr
Energy Out	11,352	13,210	kWh/yr
Energy In	11,949	14,678	kWh/yr
Losses	597	1,468	kWh/yr

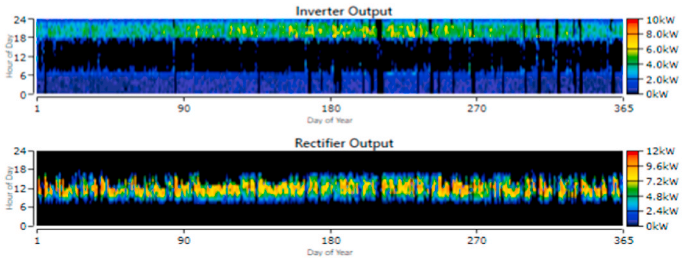


Fig. 6. Converter design parameters.

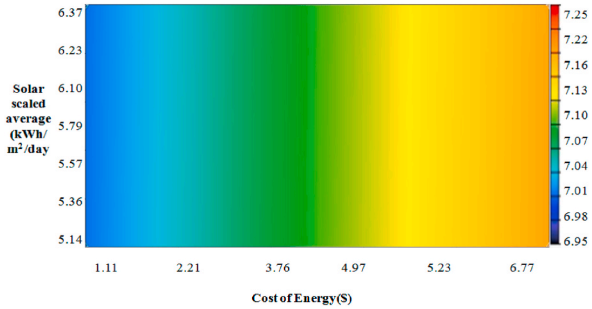


Fig. 7. Cost of electricity (COE) in Pakistan.

5.6.2. Net Present Cost (NPC)

For the success of the project, an optimized NPC value is essential. Figure illustrates the impact of varying discount rates on the Net Present Cost (NPC). Fig. 8 presents a range of discount rates from 7.5 % to 15 %, with the corresponding NPC values measured in millions of dollars. The discount rate serves as a critical financial parameter that captures the trade-off between the value of money today and its future worth. As the discount rate increases, the present value of future cash flows diminishes, reflecting a stronger emphasis on immediate gains. Upon examining the data, a consistent trend emerges: as the discount rate increases, the associated NPC values decrease. At a 7.5 % discount rate, the NPC is $0.537 million, which decreases incrementally to $0.533 million at an 8 % discount rate. This downward pattern persists with further increases in the discount rate. Notably, at the highest rate of 15 %, the NPC reaches its lowest point at $0.511 million.

5.6.3. Total system costs

Table 5 shows comprehensive breakdown of the costs associated with various components of the system. The capital cost of battery component amounts to $67,650. This represents the initial investment required to acquire and integrate the battery system into the setup. The replacement cost, at $1,057, accounts for the expense of replacing components or the entire battery unit when necessary. The O&M cost of $4094 reflects the ongoing expenses associated with maintaining and ensuring the proper functioning of the battery over time. Summing up these costs, the total cost of the battery component stands at $72,776.

Moving to the photovoltaic (PV) plate, the capital cost is notably higher at $434,095. The O&M cost, at $611, encompasses the ongoing maintenance activities to ensure the optimal performance of the PV panels. The total cost of the PV plate is $434,707.

For the converter component, the capital cost is comparatively lower at $3197. This expenditure pertains to obtaining and incorporating the converters that play a crucial role in facilitating the energy conversion processes within the system. The replacement cost, represented by $62.3, accounts for potential replacement expenses for components of the converter. There are no O&M costs listed for the converter, which indicate that this component might have lower maintenance requirements. Consequently, the total cost of the converter is $3258.

Similarly, In Fig. 9 it is clear that system costs of Flat plate have the highest share in total costs. As, life span of PV is 25 years and system is also designed for the period of 25 years, so there is no replacement cost in case of PV.

5.7. Verification of findings using an Earlier study

The design, analysis of performance, and optimization of a NZE village is validated with already conducted research name: “Techno-economic feasibility analysis of a solar biomass off grid system for the electrification of remote rural areas in Pakistan using

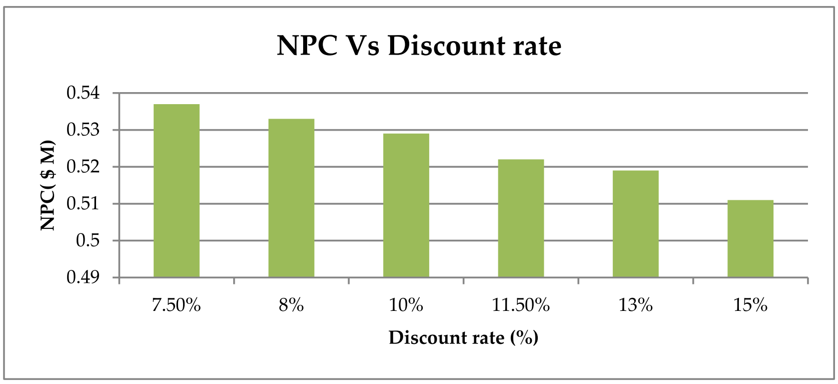


Fig. 8. Net Present Cost analysis of NZE village.

Table 5
System costs of different components of NZE village.

	Capital cost ($)	Replacement cost ($)	O&M cost ($)	Total cost of each component ($)
Battery	67650	1057	4094	72776
PV plate	434095	0	611	434707
Converter	3197	62.3	0	3258
Total system costs ($)	504943	1120	4706	510740

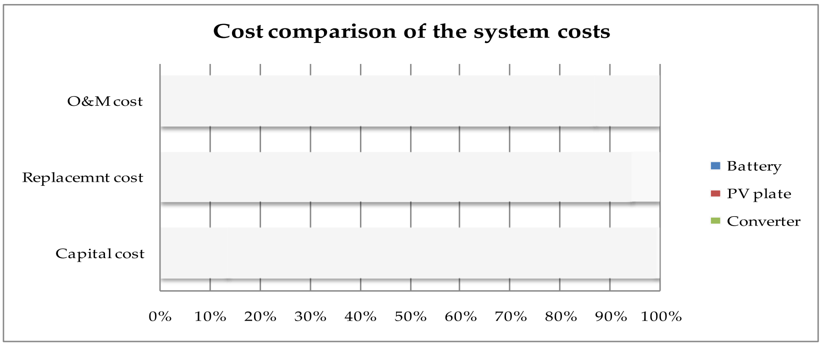


Fig. 9. Cost comparisons of different system costs.

HOMER software" [53]. Solar radiation intensity data for the chosen site and power consumption were collected over a one-year period, which was later utilized for the designing of micro-grid with combination of biomass and PV.

The optimization of the system was centered on two parameters.

1. The overall performance of the system.
2. The economic viability of the project.

Also, optimization was based on different cost outcomes for electricity production. Inflation rates, discount rates and interest were other factors for the feasibility checked by HOMER Pro software. Main objective of the research was to check the feasibility of hybrid off grid system for electrification [54].

Similarly, in the present research feasibility of standalone off grid NZE village is checked for the remote location of Burriro Sindh. In desert area of Sindh, biomass production is nearly zero. Hence, current research is development of only PV based NZE system for the electrification.

Hence, the current research has revealed several key findings, including.

1. Potential of solar radiation for electricity production
2. Operating cost of the standalone PV system
3. Initial capital cost for system installation
4. Total energy generated by PV annually
5. Payback period for system profitability
6. Net Present Cost to verify feasibility of the project

By development of PV based NZE village, the unit cost of electricity is 2.26$. System is feasible to improve the living standards of villagers. In current case, grid connection and diesel generator is not a practical solution due to the costs associated with installation of grid lines and transportation of fuel to remote areas. Selected study for the validation has payback period of 9.7 years, however, current system will be profitable after 7.2 years.

Additionally, this research is continuation of already conducted research on feasibility analysis of NZEB hospitals in Pakistan. The payback period of mentioned research was 2.53 years and in current research it is 7.2 years [55].

6. Conclusion

The current research forecasts the techno-economic feasibility of standalone off-grid PV system for development of NZE village in Burriro, Sindh Pakistan. An off grid standalone PV system is designed and analyzed in HOMER using a dynamic hybrid model, and was further optimized by sensitivity analysis using parameters such as solar irradiance, electric consumption and system sizing. Afterwards, an optimal solution was suggested based on cost analysis. The selected site for NZE village is a small community near Burriro Sindh. Peak Solar irradiance was estimated i.e., 6.25kwh/m^2/day. Moreover, flat plate PV modules were selected to achieve NZE concept.

After examination of simulation results based on economic viability, the results indicated that a combination of 18.4 kW PV modules, 123 Li-Ion storage batteries, and 10.7 kW converter was the optimized solution for the electric load of 64.26 KWh, with an initial capital investment of $0.434 M and a total Net Present Cost (NPC) of $0.511 M. The proposed system provides electricity to consumers in remote areas at a unit cost price of 2.26$, which will be actually given by the government to establish development process in remote area of Burriro. The standalone renewable system generates about 30,078 kWh/yr, with the excess electricity generation of 4072 kWh/year which enables the studied area to be self-sufficient and independent of the grid. Additionally, the system exhibits a justifiable NPC over the 25-year projection period, with an estimated payback period of 7.2 years and a 17.1 % rate of return on investment due to successful integration of PV and energy efficient design of village.

The current research recognizes about beyond financial gains. It has strategic and non-financial motivations, such as improving the quality of life for rural residents. This perspective adds a broader societal dimension to the adoption of renewable energy solutions. Prior research often remained at a theoretical level without clear pathways for localized implementation. The present study bridges this gap by presenting a practical case study in a specific rural village, providing insights into how renewable energy solutions can be effectively applied to address local energy challenges.

Current research also comes with certain limitations. These limitations highlight areas where the study has potential areas for further investigation. The current research focuses on a specific region, Sindh, Pakistan, which has unique climate and socio-economic characteristics. The findings and conclusions may not be directly applicable to other regions with different climate conditions or resource availability. Furthermore, the experimental validation of the findings, especially for NZE villages in challenging environments, could be limited. This could result in a gap between model predictions and actual performance. The study primarily focuses on technical and economic aspects, possibly neglecting other factors like policy barriers, regulatory challenges, and community engagement that play a critical role in implementing NZE villages. Also, the study not fully addresses the long-term viability and scalability of the proposed NZE village model. Over a 25-year lifecycle, external factors such as changes in technology, economic conditions, and policy shifts could impact the sustainability of the model.

7. Research implications

Following are some theoretical implications of the current research.

1. Most importantly, the research will contribute in development of NZE villages specifically in extreme climates and resource constraint locations. As, the study expand the applicability of NZE principles beyond temperate and tropical regions. This could lead to the refinement and expansion of existing theories related to energy-efficient building design in various contexts.
2. Also, the economic analysis conducted in the study has theoretical implications for the broader understanding of the cost-effectiveness of NZE initiatives. By assessing the Net Present Cost and operating costs under different scenarios, the research will contribute to discussions about the financial feasibility and long-term benefits of NZE projects to researchers and policy makers

Hence, current research on NZE villages generates theoretical implications that expand the understanding of renewable energy adoption and sustainable development. These implications can shape future discussions, research directions, and policy considerations within the field of sustainable energy and environmental studies.

Data availability statement

Data will be provided on reasonable request.

CRediT authorship contribution statement

Saba Arif: Conceptualization, Investigation, Writing – original draft. **Juntakan Taweekun:** Data curation, Supervision. **Hafiz Muhammad Ali:** Data curation, Investigation, Supervision. **Abrar Ahmed:** Formal analysis, Investigation. **Aqeel Ahmed Bhutto:** Investigation, Resources, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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