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Research article

Techno-economic and environmental analysis of renewable energy integration in irrigation systems: A comparative study of standalone and grid-connected PV/diesel generator systems in Khyber Pakhtunkhwa

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ABSTRACT

Water is an essential requirement for agricultural productivity. In the agriculture sector, electricity generated by conventional sources contributes to a substantial amount of carbon footprints for pumping water through tube wells. Over the past few decades, a transitional shift towards renewable resources has increased leading to decarbonizing the environment and is considered as a viable solution for electricity production. To assist and provide a road map for this paradigm shift, the proposed study presents a techno-economic and environmental analysis of irrigation systems by carrying comparative analysis of both standalone and grid-connected systems based on four independent sites in a developing country. PV system integrated with grid enabling both energy purchase and sale (PV + $G_{(P+S)}$), proved to be the most optimal configuration with cost of energy (COE) of $0.056/kWh, $0.059/kWh, $0.061/kWh, and $0.068/kWh while having net present cost (NPC) of $7,908, $20,186, $25,826, and $34,487 for Peshawar, Khyber Agency, Mardan, and Charsadda respectively, over a useful life span of 25 years. Furthermore, sensitivity analysis has been carried out based on uncertain variables such as Grid power purchase (GPP) and average solar radiation (GHI) to check the optimality behavior of the system. Results from environmental analysis revealed that (PV+ $G_{(P+S)}$) system has a relatively low carbon impact as compared with conventional sources. This configuration also has the ability to prevent excess water extraction by selling any excessive solar PV energy to the grid. This study provides a policy framework insight for the entities for future optimization.

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Nomenclature

COE	Cost of Energy
NPC	Net Present Cost
PV	Photovoltaic
GPP	Grid Power Purchase
GHI	Global horizontal irradiance
DG	Diesel Generator
G	Grid
B	Battery
PESCO	Peshawar Electric Supply Company
GDP	Gross Domestic Product
GHG	Greenhouse gas
KPK	Khyber Pakhtunkhwa
HOMOR	Hybrid optimization model for electric renewable
SA	Sensitivity analysis
SBP	State Bank of Pakistan
RF	Renewable Fraction
CRF	Capital Recovery Factor

1. Introduction

In today's industrialized world, energy is one of the most essential and growing human demands. Consequently, driving the global economy. Nevertheless, satisfying rising energy usage, particularly with non-renewable sources of energy such as fossil fuels, offers several issues for civilization. Currently, around 80 % of the main energy consumed globally is produced by fossil fuels, and between 2015 and 2040, it is estimated that global energy consumption will increase at a rate of around 2.3 % annually, posing a danger to an increase in atmospheric CO_2 concentration [1]. However, the globe is moving toward renewable resources to address the growing energy needs of many industries, especially the agricultural sector, where affordable, environmentally friendly power is urgently required. Achieving a careful balance between increasing agricultural output, preserving economic stability, saving water while using fewer resources, and minimizing negative environmental effects is the foundation of sustainable agriculture.

Pakistan is a developing nation that relies heavily on its agriculture sector, where agriculture plays a vital role in Gross Domestic Product (GDP) and standard of living. The agriculture sector contributes around 18.9 % to GDP and is responsible for almost 38.5 % of the workforce of the total population. The agriculture industry provides a substantial means of subsistence for almost 42 % of the rural population [2].

Irrigation is an important aspect of agriculture as it helps to increase the yielding capacity of crops with appropriate irrigation setup. The country's economic progress is directly impacted by the energy industry. In the last ten years, Pakistan's GDP has dropped from 8 % to 2 % [3]. Currently, the world's major energy needs are met by fossil fuels, which have limited storage capacity and whose constant price increases are the fundamental cause of the global economic downturn. According to this viewpoint, Pakistan's agriculture industry is severely impacted by the current power crisis [4]. The demand for water in irrigation significantly rises because of climate change and productive farming methods that alter crops and crop rotation. Population in the country is increasing rapidly so crop cultivation through different methods is needed of hour, for which we must irrigate land to extract maximum cropping capability of land. The globe is working on optimizing the use of alternative sources of energy including solar, wind, thermal, and hydro to address challenges hurting the economy and the energy industry. One of the naturally endowed nations with limitless indigenous power potential is Pakistan. Pakistan's projected solar irradiation is 2 MWh/m^2 and 3000 annual hours of sunlight, as the sun shines here during the whole economic year [5].

Based on the 2021 Global Climate Risk Index assessments, Pakistan is one of the top 5 nations that would have the most impact from climate change [6]. Climate change is a serious threat to different countries nowadays, including developed and underdeveloped countries. Global warming, and greenhouse gas (GHG) emissions are a serious threat to the agricultural economy in a country like Pakistan whose dependency is on the Agricultural economy. Change in climate results in a change in rainfall pattern, due to climate change shortage of rainfall has made to extract underground water resources to overcome the need for water for irrigation purposes, Farmers spend a lot of money to ensure a regular and patronized supply of water to their crops using diesel generator, solely buying electricity from grid which is costly too. On the other hand, Diesel generators (DG) (burning fuel) add up to carbon emissions and global warming along with increasing the cost of yielded crops. Diesel fuel-based tube wells are becoming impractical for many Pakistani farmers, Due to the insufficient supply of energy in rural locations, the farmers are not able to shift to electric tube wells, in addition, the groundwater levels have dropped due to persistent water pumping. Therefore, water must be pumped from deeper levels, which increases total energy demands. A study of the techno-economic implications of site-specific features is crucial for developing and optimizing hybrid systems for specific places with unique natural characteristics. To minimize the cost of crops yielding and reduce carbon emissions a renewable integrated (PV powered) solution has been proposed which will not only reduce the cost of energy (COE) and net present cost (NPC) but will help to reduce the costly import of fuel. Planning and implementing PV-powered irrigation systems requires meetings with stakeholders, workshops, and awareness campaigns with farmers. To improve local capability for system operation and maintenance, training sessions must be held. Such programs have substantial social benefits, such as increased environmental sustainability, less dependency on fossil fuels, and increased agricultural production. Involving communities in decision-making processes promotes resilience and ownership, but for the greatest effect, issues like funding and technical know-how need to be resolved.

1.1. Khyber Pakhtunkhwa

Khyber Pakhtunkhwa (KPK), Pakistan's northernmost province, is split in half by the country's southern portion and the country's second-largest province in terms of population which is situated in the northeastern part of the nation's geographical area at 34.00N and 71.32 E. This province's geography, which comprises both lowland and highland regions, is ideal for the advancement of renewable energy sources, such as biomass, solar, and wind. Khyber Pakhtunkhwa province's contribution to the agriculture sector is immense and contributes 8.39 % of the agriculture area Province contributes around 11 % labor force to the Economy of Pakistan [7]. The agriculture industry in Khyber Pakhtunkhwa is heavily dependent on irrigation systems, tube wells, and water pumps that are run by diesel generators and electricity, which presents substantial energy issues. Crop cultivation, irrigation, and post-harvest procedures are all directly impacted by unstable power supplies and expensive energy, which hinders agricultural output and regional economic expansion. In addition, the industry needs sustainable energy to prevent environmental damage and maintain long-term profitability in the face of growing water scarcity and the effects of climate change. Fig. 1 shows a complete map of the four districts in Khyber Pakhtunkhwa province. For Research purposes, a few irrigations sites in Peshawar, Khyber Agency, Mardan, and Charsadda have been taken into consideration. The agriculture industry is strongly dependent on natural water resources from rivers, mostly through canal irrigation systems. Natural water supplies are already drying up owing to climate change. Nowadays, switching to tube wells or pumping is a common practice for farmers. While this is beneficial in some ways, it also costs a lot of money because diesel-based pumping is very expensive and unsuitable for the environment due to CO_2 emissions.

However, because of the region's frequent power outages and electricity shortages, buying electricity from the utility grid is less economical and has negatively impacted the province's agriculture sector. The irrigation department general statistical data on tube wells in the KPK province is considered and indicates the total number of tube wells and the number of government and privately owned tube wells, which are further divided into grid, diesel, and solar-powered as represented in Fig. 2 [8]. From NASA's database in HOMER Pro software, the coordinates, temperature, climatic zones and solar radiation of these districts have been considered, respectively. The load data of all the understudied sites are collected from the government-owned distribution company (DISCO), particularly from Peshawar Electric Supply Company (PESCO). The peak and average load are obtained by simulating the load data in

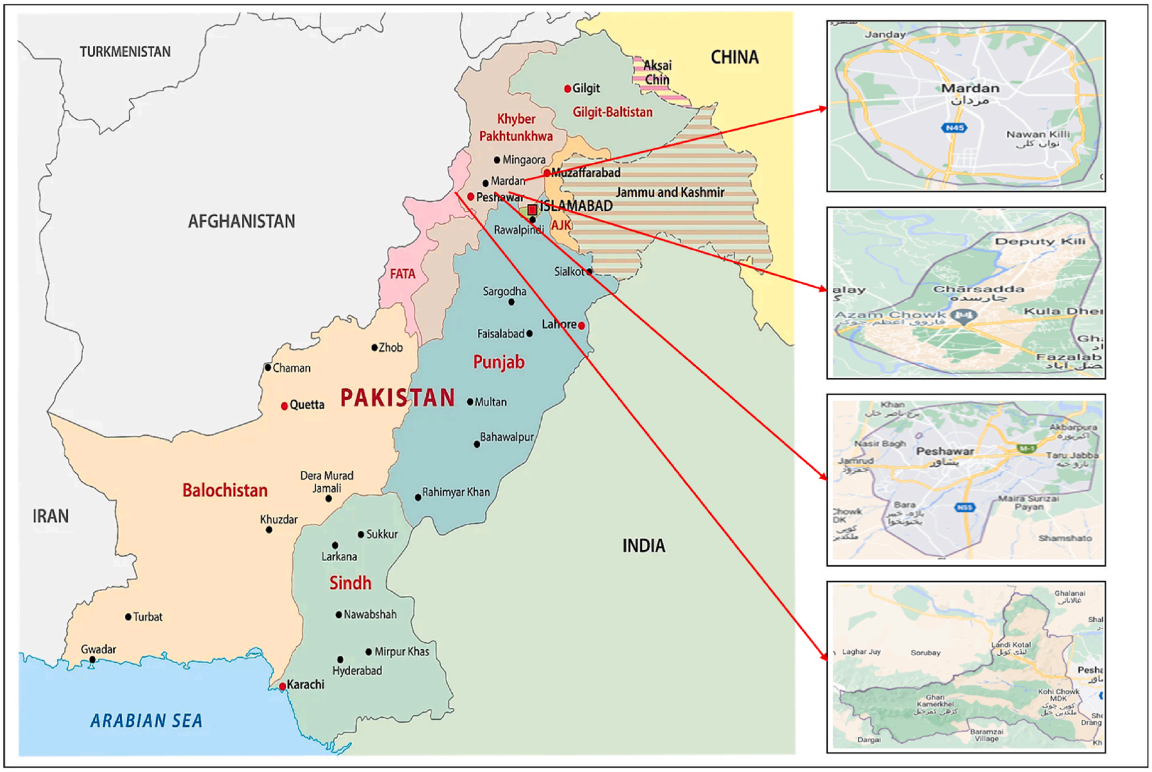

Fig. 1. Geographical representation of under-study sites.

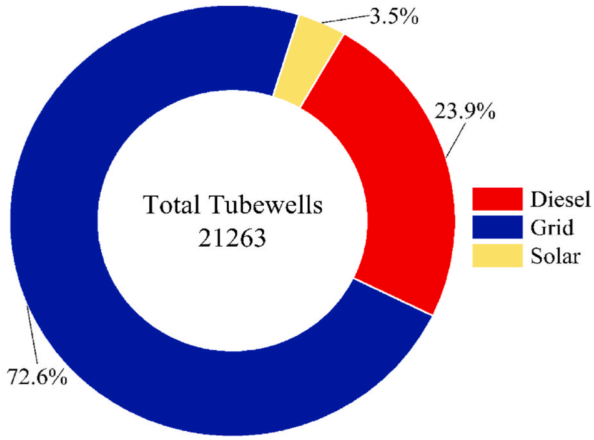

Fig. 2. Statistical data of tube wells in KPK.

HOMER Pro software and are presented in Table 1.

2. Literature review

The researchers in Ref. [9] examined the viability of installing solar-powered photovoltaic irrigation systems throughout Bangladesh's four regions in case of power outages. Author in Ref. [10] performed a techno-economic analysis of a hybrid irrigation system based on COE and NPC. The proposed study in Ref. [3] suggested an affordable and optimal design for power generation.

From a hybrid energy source for a farming operation in Central Park using Homer Pro. The proposed study in [11] stated the projected desalination, three scenarios were examined to determine how much water may be saved by replacing the current irrigation infrastructure with drip or sprinkler systems. The energy transition route was studied for all three scenarios to see how Pakistan might guarantee that the nation's desalination industry will be powered entirely by RE by 2050. Authors in Ref. [12] investigated the technical and financial viability of solar-powered irrigation for an Iranian rice crop. This research shows that the initial cost of solar-powered irrigation is nine times greater than that of a diesel-fueled system, even though the lifetime cost of a PV-based system is 65.6 % of that of a normal system. The authors in Ref. [13] discussed the potential and distribution of solar energy for irrigation before examining the key variables, such as slope and rainfall, that determine whether or not a solar water pumping system can be utilized to irrigate cassava.

The study in Ref. [14] has analyzed the viability of using PV and solar thermal technologies in irrigation systems by comparing them.

Authors in Ref. [15] determined In Gilgit and Skardu in the Gilgit Baltistan area, the technological and economic viability of solar water heating systems was assessed. By utilizing modeling in T*SOL to examine data on hot water demand and weather patterns from several sources, the possibility of a SWH system in GB has been examined. In Ref. [16] researchers have analyzed the potential for utilizing a PV water pumping system (PVWPS) to sate the need for water in the irrigation of horticultural crops. According to the results, PVWPS are not only cost-effective but also environmentally friendly and help save a significant amount of electricity. The proposed study in Ref. [17] determines the energy efficiency of the photovoltaic water pump system (PVWPS) under different radiation levels and temperatures. Using advanced algorithms, the optimal design and capacity of the system have been found to meet the water requirements of the crop of potatoes in Isfahan City. Similarly, the authors in Ref. [18] conducted a techno-economic analysis to demonstrate the standalone PV-battery (PV/BS) system competitiveness against a fossil fuel research study set in Al Minya (Egypt). The ideal PV/BS system configuration is obtained by minimizing the energy cost and net present cost.

The author in Ref. [19] has investigated 21 mini-grid efficacies in Bangladesh's off-grid areas. In addition to instruments for enhancing access to power and lowering energy poverty in off-grid areas. The researcher in Ref. [20] employed a two-stage data envelopment analysis (DEA) technique to assess the microgrids' performance in terms of installed capacity and electricity-producing capabilities. Researchers in Ref. [21] used a techno-economic study of digital agricultural technology to evaluate the environmental

Table 1
Climatic and load data of different sites.

Climatic data of sites				
	Peshawar	Mardan	Charsadda	Khyber Agency
Coordinates	34° 0.9′N, 71° 31.5′ E	34° 13.2′N, 71° 3.8′ E	34° 10.1′N, 71° 45.0′ E	34° 7.1′N, 71° 9.4′ E
Climate zone	Dry and Hot	Dry and Hot	Dry and Hot	Dry and Hot
Peak load (kW)	04.62	10.56	25.60	06.97
Average load (kWh/day)	12.76	40.62	45.95	32.21

and economic performance of ecological and traditional farming methods in the Upper Gangetic Plains of North India. In Ref. [22] the major objective of the researcher was an affordable and optimal design for power generation using a hybrid PV/Biomass energy source for a farming operation and a residential neighborhood located in the district Layyah of the Punjab province of Pakistan using Homer Pro. In Ref. [23], the author gave a high-level overview of the research into solar resource assessment using both ground-based measurements and satellite imagery. To better understand the potential for solar energy in the country, several academics have created maps. Data collected by the Pakistan Meteorological Department (PMD) on solar insolation has been measured by the World Radiation Data's long-term statistics. In Ref. [24] researcher focuses on solar energy collection, conditions in the Upper Indus Basin (UIB) area of Pakistan were studied for their potential to use (solar-powered irrigation system) SPIS in the area.

In [25] the authors analyzed a combination PV/Wind/Micro Gas turbine/Battery choice for utilizing HOMOR PRO to collect waste heat from the MGT and use it to simultaneously fulfill thermal and electric demands. The study in Ref. [26] examines how to best size hybrid systems that combine wind, solar, and geothermal energy with the addition of MGT, DG, and FC to fulfill both thermal and electric needs at the same time. The proposed research in Ref. [27] investigated the technological and economic feasibility of an off-grid hybrid energy system (HES) consisting of micro hydro, solar, biomass, biogas, diesel, and batteries for a rural Uttarakhand state in India. Using HOMER software, size optimization and sensitivity analysis of the proposed system are performed to meet the electrical requirements of the study field. The proposed study in Ref. [28] assessed the financial benefits of using a solar power irrigation system (SPIS) to grow Boro rice. They found that in terms of the benefit-to-cost ratio and gross return (DGIS), SPIS performed better than diesel-fueled irrigation systems. In Ref. [29] the author demonstrated that even a small PV-based irrigation system may result in a 25 % cost savings by using one to irrigate sugarcane plantations. Adherence to interconnection requirements is necessary for integrating PV-powered solutions with the utility grid in Khyber Pakhtunkhwa, Pakistan. These standards may include feed-in tariff programs or net metering rules to encourage renewable energy production. To regulate variations in solar power generation and preserve dependability, KPK grid stability depends on technology like voltage regulation systems and grid-interactive inverters. Installing monitoring equipment and taking part in demand response programs are prerequisites, as they assure local regulatory compliance and facilitate grid connection. Government bodies, energy companies, and agricultural stakeholders must work together to guarantee smooth integration, capacity building, and technical assistance for successfully implementing renewable energy technology. Showcasing community involvement and local engagement can help to encourage sustainable energy practices throughout the area and enable a seamless transition.

Multiple techno-economic factors, including the initial capital investment, ongoing operating and maintenance expenses, the capacity for energy production, the cost of grid connectivity, and the profiles of local energy demand are taken into account in the proposed standalone and grid-connected system. Evaluating the net present cost and energy cost over the system's lifetime involves analyzing these parameters. Optimizing these parameters to attain the lowest total cost of energy while reliably and efficiently satisfying the site-specific energy demand defines the best viable design for each site. In assessing a system's optimality, previous studies have usually concentrated on a small number of variables, including COE and NPC. Therefore, one novel aspect of the proposed study is to determine the best configuration for this system the proposed study employs and evaluates the system on multiple decision parameters on sites of various districts in Khyber Pakhtunkhwa and implementing a hybrid energy solution incorporating Tube well and Photovoltaic (PV). Another novel aspect of the A further unique feature of the suggested research is that the prior researchers primarily focused on only a few locations; However, in the present study, multiple sites have been taken into account with varied statistical data. It is worth mentioning that the previous studies only focused on the standalone or grid-connected models, while in the proposed study the novel aspect lies in the incorporation of grid-connected and standalone modes with the enabling of grid purchase and grid sale simultaneously. Keeping in view the high demand for electricity, power outages in rural areas, and high prices of fuel, the proposed study provides the most feasible configuration for tube wells irrigation setup. In addition, the present study also determines the economic parameters as well as the technical and performance parameters of the system. In a nutshell, the novelty of present studies lies in addressing the previous literature and previously discussed shortcomings. A comparative evaluation grounded in the proposed study's contribution and literature has been summarized in Table 2. The contributions of this research study are as follows.

Table 2
Summary of major research carried out and proposed study contribution.

Sr no.	Country	Method	Investigation type			Load	OGI	Analyzed technologies				Objective function		RF	SA
			Eco	Tech	Env			PV	Grid	B	DG	NPC	COE		
[9]	Bangladesh	HOMER	✓	✓	✓	Agri	Yes	✓	✓	×	×	✓	✓	✓	✓
[3]	Pakistan	HOMER	✓	✓	×	Res	Yes	✓	×	✓	✓	✓	✓	×	✓
[14]	Sudan	PTP/CDP/PVP	✓	×	×	Agri	Yes	✓	×	×	×	×	✓	×	✓
[18]	Egypt	HOMER	✓	×	✓	Agri	No	✓	×	✓	×	✓	✓	×	×
[31]	Pakistan	–	✓	×	✓	Agri	No	✓	×	✓	×	×	✓	×	×
[32]	Iran	HOMER	✓	✓	✓	Agri	Yes	✓	×	✓	×	×	✓	✓	×
[33]	Pakistan	HOMER	✓	✓	×	Res	No	✓	×	✓	✓	×	✓	×	✓
[34]	Pakistan	HOMER	✓	✓	×	Res	Yes	✓	×	×	×	×	✓	×	✓
[35]	Ramnick valley	HOMER	✓	×	×	Res	Yes	✓	×	✓	×	✓	✓	✓	✓
[36]	California	HOMER	✓	✓	✓	Agri	Yes	✓	×	✓	✓	✓	✓	×	×
PS	Pakistan	HOMER	✓	✓	✓	Agri	Yes	✓	✓	✓	✓	✓	✓	✓	✓

Note: Eco: Economical, Tech: Technical, Env: Environmental, Agri: Agricultural, Res: Residential, OGI: ON-ground inputs.

- Techno-economic optimization and comparative analyses have been carried out to find out the most practical configuration for each site.
- A comparative analysis for both standalone and grid-connected systems has been carried out based on various techno-economic parameters.
- Sensitivity analysis has been performed to determine various uncertainties that will affect ideal system behavior.
- Based on carbon footprint, environmental analysis has been done.

3. Methodology

Research work is conducted by taking the case study of KPK, the second-largest populated province of Pakistan. The proposed research highlights irrigation capability and provides a techno-economic solution for a hybrid irrigation system for selected areas. Real-time load data of selected tube wells have been taken from the irrigation department.

3.1. HOMER Pro

The software HOMER Pro (hybrid optimization model for electric renewable) version (x64 3.14.2) was used to conduct the desired research to perform techno-economic and sustainability assessments on both stand-alone and grid-connected systems. The National Renewable Energy Laboratory (NREL) developed this software. In the context of deeply convoluted configurations, adaptability, and hourly time step simulation, HOMER Pro has an advantage.

3.2. Sites selection

Statistical data of tube wells in the district of Khyber Pakhtunkhwa of Pakistan reveals that out of a total of 21,263 irrigation tube wells, 72.6% are run by energy from the public power Grid (G) and the percentage of tube wells that use DG to power their operations is 23.9 percent in grid-isolated regions. For the time being, a DG is the only means of generating electricity for the tubewells in those regions and only 3.5% among them are renewably integrated. The number of tube wells using Grid electricity and DG suggests there is adequate room to switch to renewable integrated sources. Fig. 3 represents a visual breakdown of the research's approach.

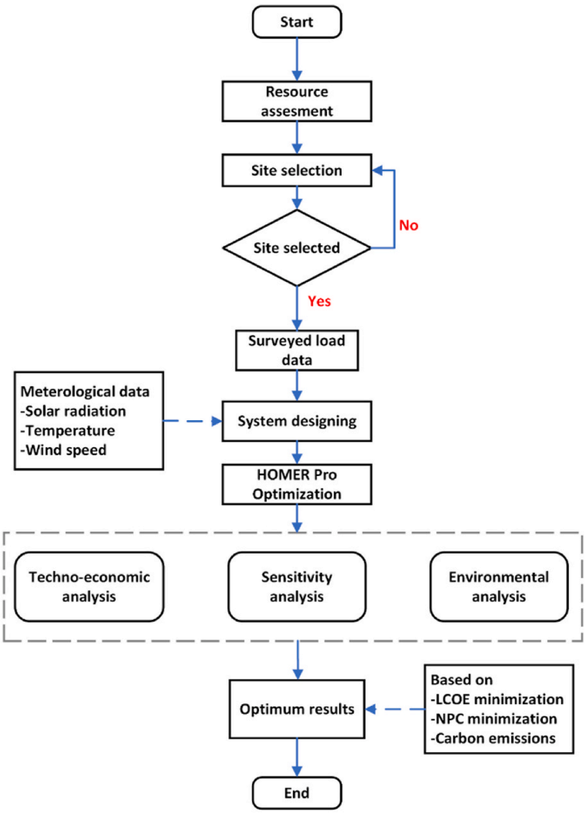

Fig. 3. Flow chart of the proposed study.

3.3. Resource assessment

In the proposed research 4 sites from each district in Khyber Pakhtunkhwa have been taken to analyze the environmental and economic viability of the tubewells with different configurations. Due to the unavailability of real-time meteorological data, average daily solar radiation, average temperature, and wind speed have been taken from the built-in historic data of the NASA database. The current inflation and discount rates of 8.50 % and 9.75 % established for the fiscal year 2021–2022, which represent a realistic viewpoint of the nation, i.e., high inflation and fluctuating policy rates of the State Bank of Pakistan (SBP), are chosen in this study [30]. Average temperature and average solar radiation are represented in Fig. 4. Based on market research and market rates, the cost of the technical and other parameters is considered.

4. Mathematical modeling

4.1. PV model

In every SPV system, the basic part is a solar cell module. It converts photons from the sun's beams into electrical energy. SPV electrical direct current (DC) power production systems are becoming more and more significant as a non-conversion energy source since they provide many advantages, such as the lack of fuel expenses, the absence of carbon emissions, the need for minimal maintenance, and the absence of noise, among others. The formula used to determine the solar PV array system's power output is illustrated in Eq. (1) [33].

$$P_{PV} = RC_{PV}DF_{PV}\left[\frac{R_{SR}}{R_{SR\ @STC}}\right]\left[1+\alpha_{tp}(T_{PV@STC})\right] \tag{1}$$

Where, P_{PV} is power produced, RC_{PV} is the PV panels' capacity in kW, DF_{PV} in % is PV's derating factor, solar radiation on the PV array is R_{SR} in kW/m^2, $R_{SR@STC}$ is the radiation at a standard testing condition in kW/m^2, The PV temperature coefficient of power, represented as α_{tp} in (%) equals Celsius. T_{PV} specifies the maximum temperature allowable for photovoltaic cells in degrees Celsius, and $T_{PV@STC}$ is the rated PV temperature. Costs associated with installing, replacing, operating, and other factors associated with PV systems are summarized in Table 3.

4.2. Battery model

Storage is always a key component in managing and maintaining a consistent voltage in renewable energy generation during times when there is a shortage in generation capacity. The least expensive per kWh storage option is regarded to be tubular flooded lead-acid batteries. The power storage's maximum battery discharge (B_D) is computed as follows [33]. The Maximum (B_D) is shown in Eq. (2) and the maximum Battery storage is illustrated in Eq. (3).

$$B_D = \frac{crN_M + cN_1{}^{-c\Delta t} + N_Tcr(1-e^{-c\Delta t})}{1-e^{-c\Delta t}+r(\ c\Delta t-1+e^{-c\Delta t})} \tag{2}$$

In a similar manner, the maximum power that the following equation is used to determine battery storage.

$$B_C = \frac{cN_I\ e^{-c\Delta t} + N_Tcr(1-\ e^{-c\Delta t})}{1-\ e^{-c\Delta t}+r(c\Delta t-1+e^{-c\Delta t})} \tag{3}$$

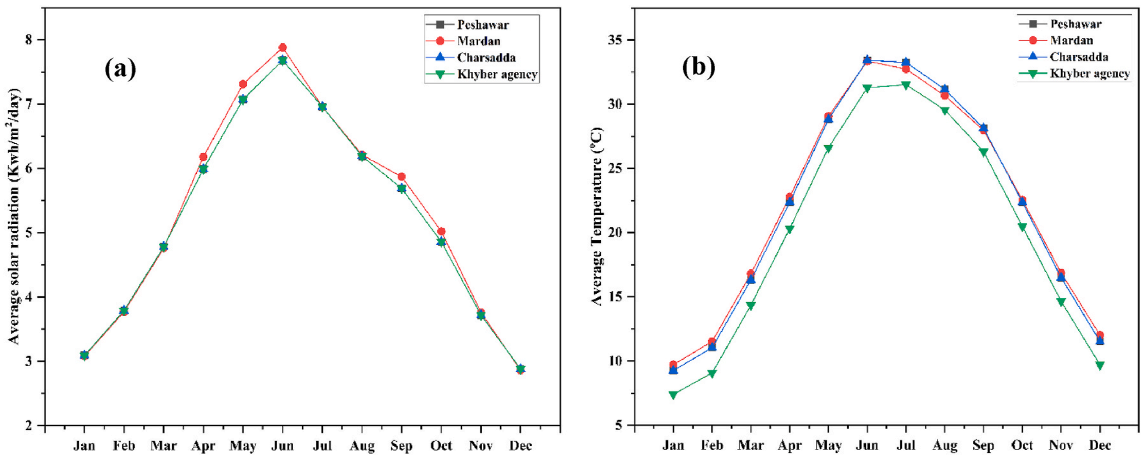

Fig. 4. Yearly Average; (a) Solar radiation (b) Temperature.

Table 3
PV system cost and technical parameters.

Capital cost	Replacement	Operation & maintenance	Time	Derating factor
($/kW)	($/kW)	($/yr)	(yr)	(%)
1000	800	10	25	80

In the above Eq. (3) Where r is the ratio of battery storage capacity, c represents the hourly constant rate of battery storage, Δt is the time step duration in hours, NM denotes the storage bank's total capacity in kWh, NI is the energy initially accessible for storage (initial) stage in kWh and NT denotes the entire amount of energy stored in the system kWh. The technical and other cost parameters of the battery are listed in Table 4.

4.3. Power converter

An electrical or electromechanical component called a power converter converts electrical energy from alternating current (AC) to direct current (DC) and vice versa. Between AC and DC, a bidirectional power converter is constantly linked. To ensure two-directional conversions, buses should be parallel to the AC generator. The ideal inverter would continue to be able to handle the highest possible monitoring of AC loads. The total wattage of AC loads should be more than the inverter's output capacity. Using Eq. (4), we can calculate the inverter electrical power rating (C_{conv}) and P_{array} donates the rated power of the solar module which is connected to the DC bus [30]. The cost and other details of the power converter are given in Table 5 [37]. Inverter output efficiency (η_{conv}) is listed in Eq. (5).

$$C_{conv}\ (\mathrm{kW}) = P_{array} \times (100 \div 85) \tag{4}$$

$$\eta_{conv}(\%) = \frac{OUTPUT_{conv}}{INPUT_{conv}} \times 100 \tag{5}$$

4.4. Diesel generator

A backup power source is the diesel generator (DG) in cases where the PV panels and battery bank's output power is insufficient to meet the load requirement. The generator fuel consumption rate (FC) is calculated using the generator power (P_{DG}) expressed in Eq. (6).

$$\mathrm{FC} = F_o.\ Y_{DG} + F_1.P_{DG} < \ P_{DGmax} \tag{6}$$

Where Y_{DG}, F_o, and F_1 are the manufacturer-provided nominal or rated power and coefficients of generator fuel consumption [38]. Similarly, the generator's efficiency is given in Eq. (7) as:

$$\eta_{Gen} = \frac{3.6\ P_{DG}}{FC\ .\ LHV_D} \tag{7}$$

In Table 6 the cost and technical details of DG are summarized. Where LHV_D is the diesel fuel's lower heating value.

4.5. Grid

Solar photovoltaic systems provide extra power during the day, which may be sold back to the grid. Similarly, without the generation of power from renewable sources, if the grid had energy available, it would be used to charge the batteries. The difference between the amount of electricity bought from the grid and the amount of electricity sold to the grid is known as net electrical energy delivered to (or by) the grid [33].

$$GEC_M = \sum_{p}^{r} \sum_{q}^{12} \begin{cases} E_{j.net\ (G).p.q}\ gec_{G.p}\ if E_{j.net\ (G).p.q} \geq 0 \\ E_{j.net(G).p.q}\ gec_{s.p}\ if E_{j.net(G).p.q} < 0 \end{cases} \tag{8}$$

In Eq. (8), $E_{j.net(G),p,q}$ is the net energy bought in kWh from the grid (G) in month q at the appropriate rate (r) of p, the grid's power price for rate p in PKR/kWh or $/kWh is represented by gecG,p. where GEC(M) represents the energy costs in kWh after a monthly net

Table 4
Cost parameter of the battery.

Capital	Replacement	O & M	Time	String size	Initial state of charge	Minimum state of charge	Throughput
($)/quantity	($)/quantity	($/yr)	(yr)	(V)	(%)	(%)	(kWh)
200	200	0	10	36	100	40	800

Table 5
Technical and cost parameters of the converter.

Capital	Replacement	Relative capacity	Useful Life	Efficiency
($/kW)	($/kW)	(%)	(yr)	(%)
150	150	100	15	95

Table 6
Technical and cost parameters of DG.

Initial Capital	Replacement	O & M	Fuel price	Useful Life
($)	($)	($/op.hr)	($)	(hr)
500	400	0.030	1	15000

generation account is made. The selling price (S) of rate p is stated in either PKR/kWh or $/kWh, just like gecS,p. The energy buy price is determined by the PESCO rate set by the National Electric Power Authority (NEPRA) [39], while the sell-back price is supplied by Zonergy Solar Development Pakistan Limited as net metering pricing. Grid power purchase and Grid sale prices are given in Table 7.

4.6. Decision parameters

4.6.1. Excess electricity

A surplus of electricity has been identified in simulations and real-life implementations. This excess electricity is available at zero marginal cost which creates serious long-term problems. This zero marginal cost electricity allows the farmer to extract a nonessential amount of water and increase its water usage. This water wastage leads to water shortages or drops in the ground or reservoir water level and puts in danger the whole ecosystem throughout its life span. The battery can store this excessive electricity, which may then be utilized for other things like supplying it to nearby households to meet their daily energy needs and can be sold to the grid. The power left over after a load has been satisfied is known as excess electricity. Excess energy (E_T) is given in Eq. (9) [9].

$$E_T = \frac{E_{excess}}{E_{Produce}} \tag{9}$$

The excess energy (kWh/yr) produced by renewable energy sources is described by E_{Excess}, whereas the total annual production of electrical energy (kWh/yr) is $E_{production}$.

4.6.2. Renewable fraction

This section of the paper indicates the renewable percentage that has been used to quantify the contribution of renewable energy to meeting energy demand. The renewable fraction (RF) is the portion of the load that is satisfied by energy derived from renewable energy technology. RF has been given by Eq. (10) [40] which implies:

$$RF = \frac{E_{Gen}}{E_{Dem}} \tag{10}$$

Given by the above equation shows E_{Gen} shows the annual amount of energy produced by renewable sources, while E_{Demand} shows the overall load demand.

4.6.3. Cost of energy

The cost of energy is a significant financial consideration when calculating the optimal size of a hybrid energy system. COE is defined as the ratio of the annualized cost of the system's components to the total energy produced to meet demand. COE has been determined in the below Eq. (11) [41]. [32].

$$COE = \frac{C_k}{E_p} \tag{11}$$

Where C_k denotes the whole annualized cost, and E_p denotes the total energy produced over the lifetime of the system.

Table 7
Cost parameters of grid (Net sale and purchase price).

Grid power purchase	Grid sale price
($/kWh)	($/kWh)
0.138	0.050

4.6.4. Net present cost

The capital recovery factor (CRF) to C_k ratio is known as Net present cost (NPC). NPC may also be described as the total of all expenses incurred over the course of a project, including replacement costs, fuel costs, original capital costs, operating costs, and maintenance costs. Eqs. 12–14 [41], were employed by HOMER software to determine the hybridized system's COE and NPC. The capital recovery factor (CRF) and yearly real interest rate (*i*%) are both expressed in Eq. (13) and Eq. (14).

$$\text{NPC} = \frac{C_k}{CRF\ (i, N)} \tag{12}$$

$$\text{CRF}\ (i, \text{N}) = \frac{i(1+N)^N}{(1+i)^N - 1} \tag{13}$$

$$i = \frac{i' - f}{1+f} \tag{14}$$

The nominal interest rate is *i*' (%), where N is counted as the life span of the project, and the yearly inflation rate is f (%).

5. Results and discussion

In this section, the results are presented and discussed. Based on cost-effectiveness, environmental factors, and evaluating the effect on the system through various uncertainties, an optimal system for each location is selected. The first section shows a techno-economic analysis based on objective parameters for different selected sites. Environmental analysis is discussed in the second section of this portion. In the third section sensitivity analysis has been discussed on uncertain variables like GPP and GHI. Fig. 5 illustrates the schematic diagram for the proposed optimal system (PV + $G_{(P+S)}$) based on the combination of the specified components, and its positive aspects are (i) Irrigated load, (ii) Feeding the irrigated load through PV system, (iii) importing the energy from the grid when PV system is unable to meet the load/outages, (iv) exporting the excess energy generated from the PV system to the grid.

5.1. Techno-economic analysis

Techno-economic optimization takes into account site-specific aspects to ensure that system components are appropriately sized without compromising dependability. Based on NPC and COE, the recommended systems are tailored for each site. Each location has an optimal system design that includes decision parameters. The optimal system configuration, component sizing, and cost parameters at the selected location depend heavily on the availability of possible different energy supplies as well as the major electrical demand in the area. Fig. 6 summarizes the energy resource contribution behavior of the most optimal configuration, i.e. PV system integrated with grid enabling both energy purchase and sale (PV + $G_{(P+S)}$), for meeting the irrigated load demand of each site. An evaluation of hybrid configurations based on their NPC, COE, and renewable fraction for under-study sites is illustrated in Table 8 and represented in Fig. 7.

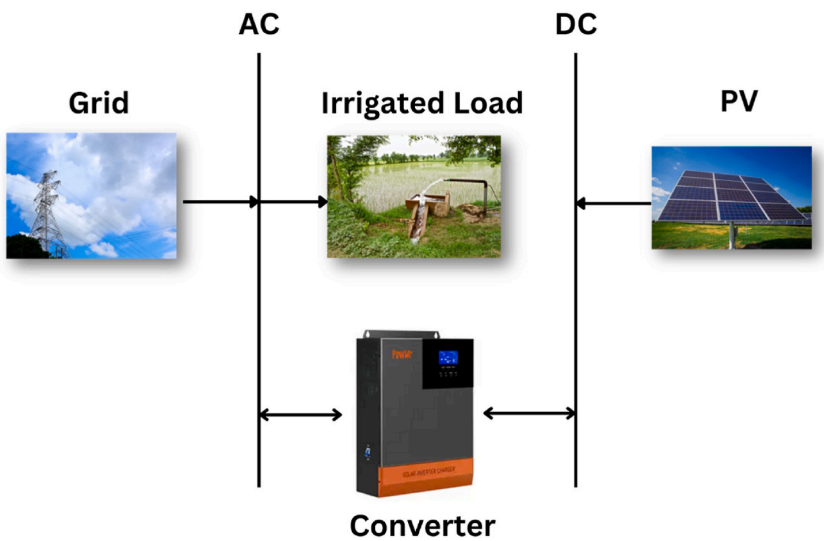

Fig. 5. Schematic diagram of the proposed optimal system.

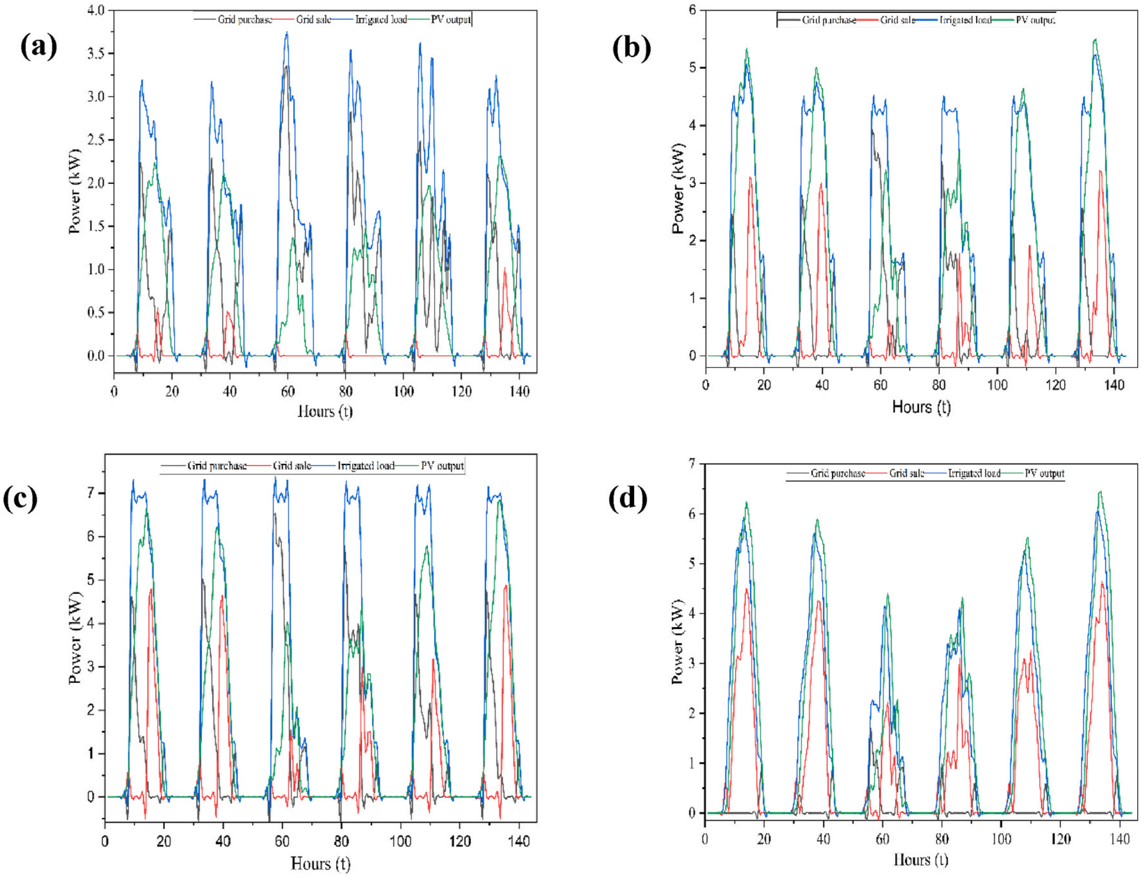

Fig. 6. Energy resource contribution behavior of the most optimal configuration; (a): Peshawar, (b): Khyber agency, (c): Mardan, (d): Charsadda.

5.1.1. *PV-battery*

In the optimization results, the PV system with battery storage was revealed to be the least feasible configuration for all the reported sites with having a COE in the range from $0.321/kWh to $0.463/kWh and acquiring a high NPC in the range from $31,501 to $158,212 as shown in Although battery storage has the potential to cater to the intermittent and variable nature of solar energy, the high initial capital cost and the replacement cost involved with the storage infrastructure renders this setup infeasible. Based on COE and NPC, a comparison study is shown in Fig. 7. Among the four sites, Charsadda and Peshawar generated the maximum and minimum solar power output. With a value of 109,651 kWh/yr and 13,859 kWh/yr, respectively.

5.1.2. *PV-utility grid$_{(P)}$*

In the proposed study, employing of PV system along with a utility grid in the peak intervals of operation experiences the COE of $0.097/kWh, $0.095/kWh, $0.096/kWh, and $0.114/kWh, for Peshawar, Khyber agency, Mardan and Charsadda as illustrated in Fig. 7. It is found that for Charsadda the COE is 14 % higher than Peshawar having the least NPC among all the sites. Moreover, in comparison to the other sites, Charsadda remained to have the highest RF with an average of 67.4 % and had the highest initial capital cost of $10,558 due to the high load.

5.1.3. *PV-utility grid $_{(P\,+\,S)}$*

The PV + $G_{(P\,+\,S)}$ system enabled with both purchase and sale is shown to be the most optimal configuration for all locations. It is worth noting that such a substantial decrease in NPC and COE is due to enabling the system to sell back the excess electricity generated by PV to the grid, consequently generating higher revenue and an increase in renewable penetration. Furthermore, it also improves the excess energy index with an average of 0.39 % for all the sites. Peshawar was revealed to be the most optimal site in terms of COE and NPC of $0.056 kWh and $7,908, respectively in contrast with the other sites. It is found that Charsadda's net present cost is greater due to its high initial capital cost.

5.1.4. *PV-diesel generator*

Winter experiences fewer sunshine hours than summer. Thus, the proposed study proved that employing DGs with PV at each site provides uninterrupted electricity during the times when PV is unable to meet the required load demand. Contrarily, during the

Table 8
Optimal configurations for all chosen regions, each with final decision indicators.

Configurations	Sites	Cost and objective parameter				Solar Energy	Grid		Renewable fraction	E. E
		NPC $	COE $	ICC $	OPC $/yr	kWh/yr	Purchase kWh	Sale kWh	%	% kWh/yr
PV-B										
	Peshawar	31,501	0.321	15,021	762	13,859	–	–	100	63.5
	Khyber Agency	88,030	0.348	49,950	1762	99,837	–	–	100	86.2
	Mardan	113,357	0.354	68,236	2088	64,442	–	–	100	75.1
	Charsadda	158,212	0.463	93,601	2989	109,651			100	84.5
PV + $G_{(P)}$										
	Peshawar	9763	0.097	3524	288	5227	1519	–	67.4	28.5
	Khyber agency	24,555	0.095	8377	749	12,465	4073	–	65.4	26.5
	Mardan	30,721	0.096	9869	965	14,778	5452	–	63.2	24.3
	Charsadda	41,444	0.114	10,558	1429	15,571	8559	–	49	28.7
PV + $G_{(P+S)}$										
	Peshawar	7908	0.056	3585	200	5229	1504	1778	76.6	0.56
	Khyber Agency	20,186	0.059	8462	542	12,466	4036	4066	74.5	0.35
	Mardan	25,826	0.061	9951	734	14,780	5423	4571	72	0.35
	Charsadda	34,487	0.068	10,631	1104	15,566	8536	6482	63.3	0.30
PV-DG										
	Peshawar	68,429	0.709	38,546	1383	59,194	–	–	65.6	92.3
	Khyber Agency	117,668	0.463	45,251	3350	66,185	–	–	60.4	82.8
	Mardan	152,729	0.533	56,857	4964	81,904	–	–	53.6	82.8
	Charsadda	270,548	0.746	102,534	7773	138,584	–	–	34	88.4
G										
	Peshawar	13,914	0.138	–	644	–	4665	–	–	–
	Khyber Agency	35,068	0.138	–	1622	–	11,757	–	–	–
	Mardan	44,224	0.138	–	2046	–	14,826	–	–	–
	Charsadda	50,027	0.138	–	2315	–	16,772	–	–	–

comparative analysis as illustrated in Table 8, due to the high diesel fuel price, O&M costs for DG are significantly greater than those of renewable energy resources, while capital costs are comparable. The relationship between NPC and COE for all the proposed sites is shown in Fig. 7, with Charsadda contributing an average of 56 % higher NPC to the Khyber agency in this configuration.

5.1.5. Grid only

The irrigated load is fed from the grid only when there is no alternative energy source available. The finding shows as illustrated in Table 8 that the grid-connected system undergoes a relatively less COE than that of feeding the load with only the G.

5.2. Environmental analysis

The presence of the system's nonrenewable components accounts for a higher level of carbon emissions as compared to a renewable component. For this purpose, PV + G $_{(P+S)}$ configuration was considered in the proposed study to perform the environmental analysis. Measuring only carbon emissions over 25 years is necessary because CO_2 contributes much more to GHG emissions than other gases. Production, operation, maintenance, and disposal of energy-related CO_2 emissions are evaluated. Life cycle emissions (LCE) have been carried out in this study on HOMER Pro software to calculate the amount of CO2 emissions that are produced by the energy used. To compute life cycle emission, the following formula has been employed as presented in Eq. (15) [42].

$$\mathrm{LCE} = \sum_{i=1}^{x} (Bi \div 1000) EI \tag{15}$$

Where x is the number of components used to simulate the system, EI (kWh) represents the energy produced and reserved in each unit or component, and Bi (tonnes CO_2-eq/kWh) presents CO_2 emissions of the lifetime period of the components of the system.

As seen from Fig. 8, the PV + $G_{(P+S)}$ configuration emits a relatively low amount of carbon emissions as compared to the G configuration. The finding shows that the amount of CO_2 produced at Charsadda and Mardan is 265.12tonnes, and 234.25tonnes for G configuration, while for the same sites, the carbon content for PV + $G_{(P+S)}$ is 134.87 tonnes and 85.64 tonnes. Similarly, CO_2 emissions accounted at Khyber Agency and Peshawar for a number of 185.75tonnes, and 73.73tonnes for the G configuration, while for the PV + $G_{(P+S)}$ configuration, produced 63.77 tonnes and 23.77tonnes. It clearly states that Charsadda and Mardan are emitting a higher amount of carbon content than that of Khyber Agency and Peshawar. The main reason for such a higher amount of carbon content at Charsadda and Mardan for PV + $G_{(P+S)}$ is due to high grid purchase power and a less installed PV system.

5.3. Sensitivity analysis

Sensitivity analysis helps in determining the impact of uncertainties and demonstrates the impact of various factors on the optimal

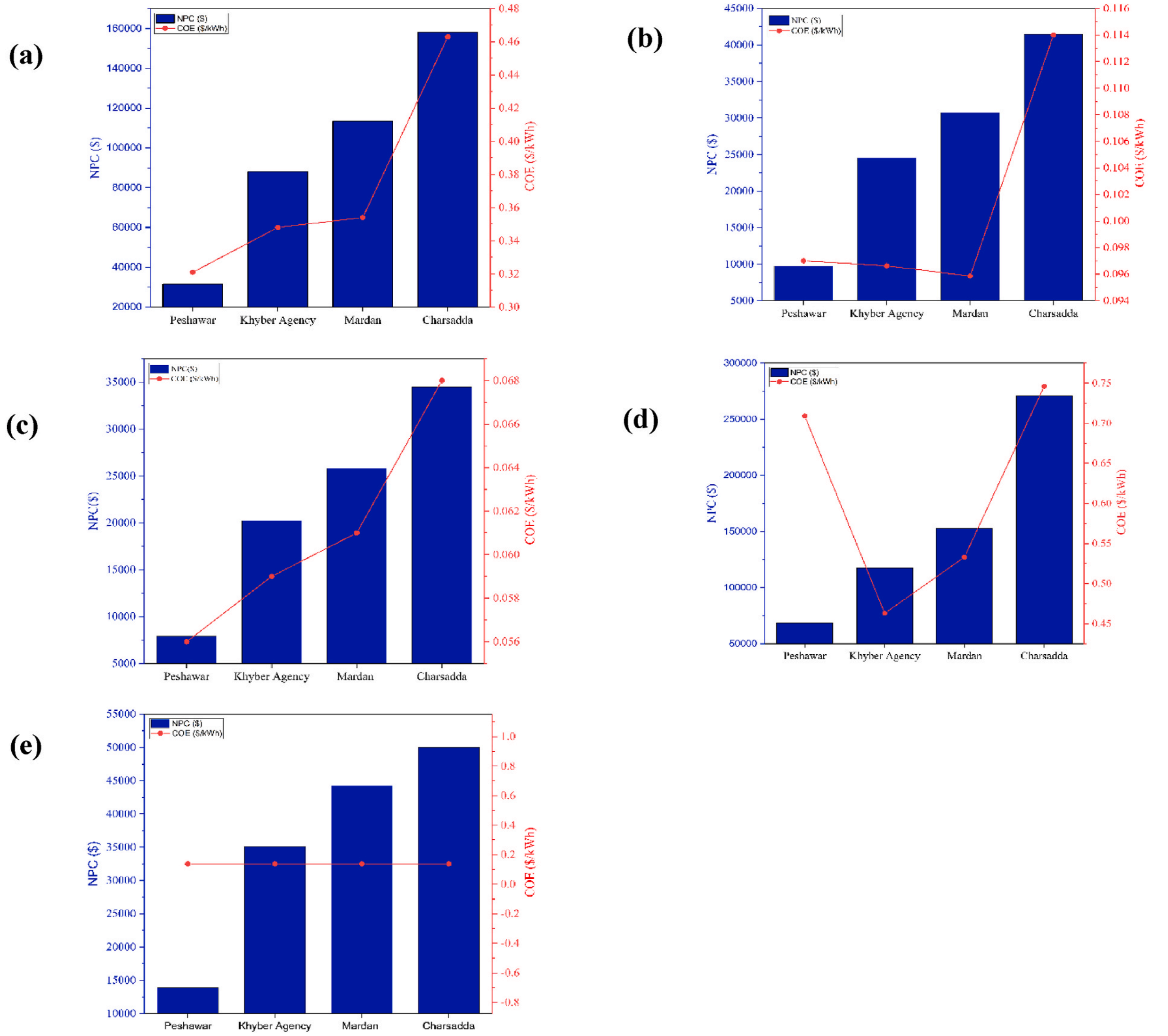

Fig. 7. Net present cost and Cost of energy of PV + G configuration, (a): PV-B, (b): PV + $G_{(P)}$, (c): PV + $G_{(P\ +\ S)}$ (d): PV-DG, (e): G.

system based on COE and NPC. In the proposed study, sensitivity analyses are performed on the most optimal configuration PV + $G_{(P\ +\ S)}$, for all four sites based on yearly average solar radiation and grid power purchase price. These factors are highly influential in affecting the economic and technical parameters of the system. To examine the behavior of the proposed configuration for the selected site Charsadda district has been taken into the study, the considered variables were varied with an expected variation of ±1 % and ±0.020 % for yearly average solar radiation and grid power purchase price respectively, for 3 distinct values. It is observed that by varying yearly average solar radiation from 4.23 kWh/m^2/day to 6.23 kWh/m^2/day both NPC and COE decreased from $36,700 to $28,016 and 0.08$/kWh to 0.051$/kWh respectively. While, on the other hand, NPC and LCOE showed a direct relation when grid power purchase price varied from $0.118/kWh to $0.158/kWh. The effects of both the varying variables on NPC and COE are represented in Fig. 9.

6. Validation and comparison

Based on the COE of the most efficient configuration (PV + $G_{(P\ +\ S)}$) of each site, the current study findings are analyzed and compared with the agriculture tariffs of the distribution companies (DISCOs) from each province and with the federal state capital. Among these DISCOs are Faisalabad Electric Supply Company (FESCO) (Punjab), Quetta Electric Supply Company (QESCO) (Baluchistan), Sukhar Electric Power Supply Company (SEPCO) (Sindh), Electric Supply Company (PESCO) (Khyber Pakhtunkhwa), and Islamabad Electric Supply Company (IESCO) (Federal state capital). The agriculture tariffs of each DISCO previously mentioned are controlled by the National Electric Power Regulatory Authority (NEPRA) and are taken into account for the comparative analysis [43].

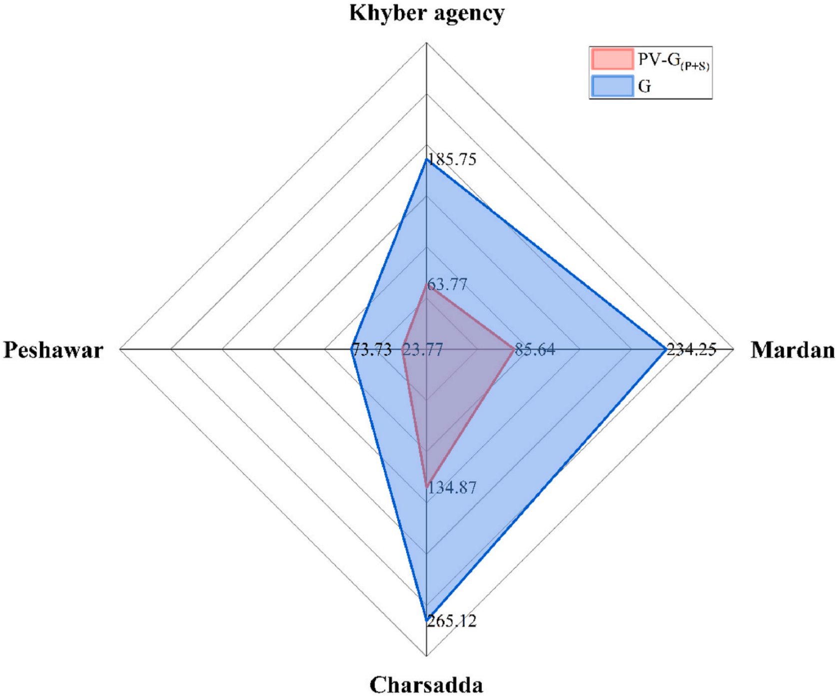

Fig. 8. Environmental analysis comparison of PV + $G_{(P+S)}$ with G for under study sites.

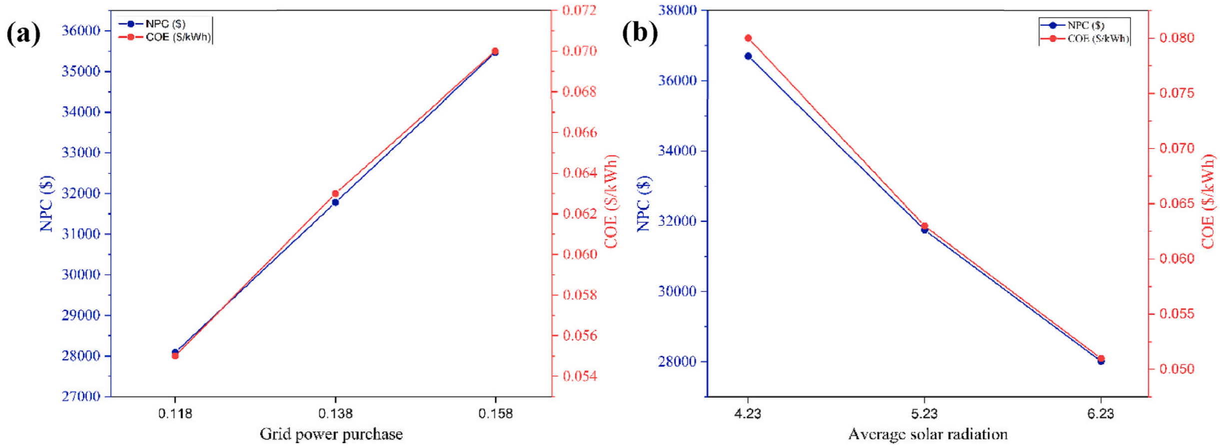

Fig. 9. Sensitivity analysis of PV + G configuration; (a): Grid power purchase (GPP), (b): Yearly average solar radiation (GHI).

Table 9
Comparative analysis of the tariffs of different DISCOs with the proposed COE optimal configuration of each selected site.

DISCO's	DISCO's Tariffs	Optimal configuration COE			
		Peshawar	Khyber Agency	Mardan	Charsadda
FESCO	0.100	0.058	0.059	0.061	0.068
QESCO	0.144				
SEPCO	0.136				
PESCO	0.138				
IESCO	0.074				

The comparison as illustrated in Table 9 shows that the proposed study is not only viable in the Khyber Pakhtunkhwa province but is also viable in the other provinces of Pakistan and can be a valuable insight for the policymakers as well.

7. Conclusions

A decision-making framework for techno-economic and environmental analysis is presented in the proposed study for four separate locations in Khyber Pakhtunkhwa, covering grid-connected and standalone PV hybrid-based systems. Several configurations were simulated on HOMER Pro software based on real-time load data for the irrigation sites along with peak tariffs acquired from Peshawar Electric Supply Company (PESCO). PV + $G_{(P+S)}$ proved to be the most optimal configuration for Peshawar, Khyber Agency, Mardan, and Charsadda with having the least COE and NPC among all other configurations with the renewable fraction of 76.6 %, %, 74.5 %, 72 % and 63.3 % and excess energy of 0.56 %, 0.35 %, 0.35 %, and 0.30 %. Moreover, sensitivity analysis on uncertainty variables such as GPP and GHI was performed based on COE and NPC for the Charsadda site with variations of ± 0.020 and $\pm$ 1.00 to examine the behavior of the system. A similar trend was observed for Peshawar, Khyber Agency, and Mardan. Environmental analysis revealed only grid configurations contributing to more carbon emission which shows that the Charsadda site highest carbon emission of 265tonnes over the useful life span of 25 years. In contrast, the PV + $G_{(P+S)}$ system proved to be the optimal configuration in terms of carbon emissions with 134.87 tons. It is worth noticing that only the Peshawar site experienced the low carbon emission of 23.77 tons. This environmental analysis was carried out for the other configuration as well and similar trends were observed. It has been observed that for all the sites, the renewable fraction has risen with an average of 71.6 % and 53.4 %, for both PV + $G_{(P+S)}$ and PV-DG configuration, thus, lowering the dependency on Grid and DG in the irrigation sector. Consequently, the transition from non-renewable to renewable sources will not only make the system economically feasible but also environmentally friendly and also prevent excessive water extraction. The proposed research could provide a viable solution for developing nations where traditional energy sources are used to supply irrigation load. Farmers stand to gain significant economic benefits from integrating PV systems with the grid, primarily through cost savings and potentially increased crop yields. By utilizing solar energy, farmers can reduce their reliance on expensive grid electricity, thus lowering their energy bills and operating costs. Additionally, net metering programs allow farmers to generate excess electricity during sunny periods and sell it back to the grid, potentially generating additional revenue. With reduced energy costs, farmers can allocate more resources towards other farm expenses or investments. Additionally, the government may offer technical assistance and capacity-building programs to help farmers effectively integrate solar energy into their agricultural operations. By aligning economic incentives with environmental sustainability goals, such policies can encourage widespread adoption of PV integration in agriculture, fostering long-term resilience and prosperity for farming communities in Khyber Pakhtunkhwa.

In the future, based on multi-year evaluations of load growth, the performance at the designing stage can be assessed. Moreover, it is recommended to make the framework more comprehensive so that it can account for more sustainable aspects, particularly socio-economic analyses.

Data availability statement

The data can be requested by contacting the authors if required.

Ethics declarations

To take part in the study, every participant gave their informed consent.

CRediT authorship contribution statement

Sheharyar Khattak: Writing – original draft. **Muhammad Yousif:** Supervision. **Shabieh Ul Hassan:** Investigation, Formal analysis. **Muhammad Hassan:** Validation. **Thamer A.H. Alghamdi:** Visualization, Funding acquisition.

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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