Sustainable Futures 10 (2025) 100826

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Analysis of renewable energy resources (RERs) under the China-Pakistan economic corridor (CPEC) initiative: A proposed solution for optimized and sustainable energy management

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ARTICLE INFO

Keywords:
China-Pakistan economic corridor (CPEC)
Economic growth
Energy management
Energy optimization
Renewable energy resources (RERs)
Smart grid technologies
Sustainable development

ABSTRACT

The western portion of Kashmir region faces challenges towards complete harness and integration of renewable energy resources (RERs) available in abundance. These challenges correlate effectively to the China-Pakistan Economic Corridor (CPEC) initiatives. To address these challenges, this article conducts a comprehensive analysis of smart grid technologies towards a possible energy solution for western Kashmir. The proposed research thoroughly examines: 1) energy generation, 2) energy consumption, and 3) energy market dynamics in the region. The findings emphasize the pivotal role of western Kashmir and highlight its substantial potential for RERs as a valuable contributor to CPEC energy initiatives. The dominance of hydroelectric power in the Alpha Case accounts for 97.6 % of total electric energy production and an impressive annual output of 100,372,080,000 kWh. This eventually demonstrates western Kashmir's capacity for generating substantial clean energy. The Beta Case portrays commendable self-sufficiency, eliminating the need for grid energy purchases and exemplifying sustainable practices. These findings offer invaluable insights to policymakers and stakeholders while providing a robust foundation for 1) effectively harnessing western Kashmir's RERs, 2) driving sustainable development, 3) fostering energy independence, and 4) positioning western Kashmir as a significant participant in the transition towards a low-carbon future and climate change.

1. Introduction

1.1. CPEC an initiative towards energy sector and sustainable development

While acknowledging the critical role of corridors as vital channels for economic and social development, China and Pakistan have initiated a significant project known as the China-Pakistan Economic Corridor (CPEC) [1,2]. This ambitious undertaking was first proposed in 2003 as part of China's broader one-belt one-road (OBOR) strategy. It symbolizes a promising pathway toward a secure and prosperous future [3,4]. CPEC promotes efficient trade and transport of goods for the Chinese people while offering numerous advantages concerning technological advancement and infrastructure development [5,6]. The energy sector is an area where CPEC has a profound impact. Aimed at tackling energy

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https://doi.org/10.1016/j.sftr.2025.100826
Received 7 April 2024; Received in revised form 14 May 2025; Accepted 7 June 2025
Available online 8 June 2025

Nomenclature

Acronyms

BESS	Battery Energy Storage Systems
BAT	Best Available Technologies
CPEC	China-Pakistan Economic Corridor
DR	Demand Response
DE	Diesel Engine
ESS	Electric Energy Storage
EV	Electric Vehicle
FC	Fuel Cell
FHV	Fuel Heating Value
GB	Gilgit Baltistan
IO	Input-Out
KKT	Karush-Kuhn-Tucker
LMP	Locational Marginal Price
LEAP	Long-range Energy Alternative Planning
MG	Microgrid
MW	Megawatt
MPC	Model Predictive Control
NPC	Net Present Cost
OBOR	One Belt One Road
O & M	Operational and Maintenance
P2P	Peer-to-Peer
PV	Photovoltaic
RE	Renewable Energy
REI	Renewable Energy Integration
RERs	Renewable Energy Resources
STC	Standard Test Condition
USD	United States Dollar
VR	Variable Renewable
WT	Wind Turbine

Symbols

PV_{eng}	PV Energy
PV_{Power}^{rat}	PV Rated Power
f_{df}	Deriving Factor
$S_{rad\,T}$	Solar Radiation
$S_{rad\,T,STC}$	Solar Radiation under STC
Cof_T	Temperature Coefficient
$Temp_{cell}$	Cell Temperature
$Temp_{cell,STC}$	Cell Temperature under STC
T_{amb}	Ambient Temperature
T_{Nom}	Nominal Temperature
$T_{a,nom}$	Ambient Temperature Under Nominal Condition
η_{eff}	Efficiency
$fun_{beta}(S_{rad})$	Function of Beta Distribution
μ	Mean
σ	Standard Deviation
P_{BESS}	Output Power of the Battery
P_{ch}	Charging Power
P_{dch}	Discharging Power
P_D	Load Demand
P_{PV}	PV Power
P_{BESS}^r	Rated Power of BESS
η_{ch}	Charging Efficiency
η_{Conv}	Efficiency of Converter
E_{ch}	Energy Charging
E_{dch}	Energy Discharging
C_{annual}	Annualized Cost
E_{gs}	Total Energy
$L_{primary}$	Total Load
L_d	Deferrable Load
$e.CO_2$	CO_2 Emissions
m_{fuel}	Fuel Volume

shortages and supporting sustainable growth, CPEC has designed and executed multiple energy projects. These initiatives are intended to diversify Pakistan's energy sources, lessen dependence on fossil fuels, and encourage the adoption of clean and renewable energy resources [7, 8]. By establishing power plants, transmission networks, and renewable energy facilities, CPEC contributes to boosting Pakistan's power generation capacity and advancing environmental sustainability. Furthermore, CPEC promotes collaboration and technology transfer in the energy sector between China and Pakistan, enabling the sharing of 1) expertise, 2) knowledge, and 3) state-of-the-art technology related to power generation, transmission, and distribution [9,10]. By enhancing Pakistan's energy infrastructure and improving the efficiency and reliability of its energy systems, CPEC plays a crucial role in addressing the country's energy issues and bolstering its economic development [11, 12].

1.2. Western portion of Kashmir region A potential hub for renewable energy resources (RERs) and CPEC imitative

Western Kashmir has considerable potential for 1) solar, 2) wind, and 3) hydro energy [13–14]. Covering an area of 13,297 km^2 and home to around 4.179 million people, western Kashmir is famous for its natural beauty and tourist destinations. Nevertheless, the area also possesses substantial untapped energy resources [15–16]. The Neelum Jhelum hydroelectric project, which has a capacity of 969 MW, was recently launched in western Kashmir as part of the comprehensive CPEC initiative. Moreover, the region hosts the Mangla Dam, which is Pakistan's second largest and the seventh largest in the world. It has an installed capacity of 1070 MW. The hilly landscape of western Kashmir aids in the flow of water from higher altitudes to lower ones while creating many opportunities for hydroelectric power production and the development of run-of-river plants. Additionally, western Kashmir takes advantage of its favourable resources for solar and wind energy [17–18]. The abundance of sunlight and strong winds provide suitable conditions for the advancement of solar and wind energy projects. By performing thorough evaluations and effectively leveraging these resources, the western part of the Kashmir region can enhance its economy and significantly contribute to the energy sector within the larger framework of the CPEC initiative [19–20].

1.3. About western Kashmir, its potential towards RE, and focus of this work

By effectively utilizing these resources through thorough analysis and strategic planning, western Kashmir can 1) drive economic growth, 2) support the energy sector within the CPEC framework, and 3) encourage sustainable development. Additionally, incorporating renewable energy sources to power electric vehicles (EVs) can reduce pollution and improve the region's visual appeal. Furthermore, with the increasing adoption of electric vehicles, western Kashmir can harvest pollution-free energy from renewable sources to fuel these vehicles. This not only lessens environmental pollution but also enhances the natural beauty of the region. This study focuses on the renewable energy resources in western Kashmir in the context of CPEC to tackle energy deficits and foster sustainable development in the energy sector.

1.4. CPEC, substantial energy potential of western Kashmir, motivation of this work, and graphical abstract

The analysis and suggested solution of this article are fuelled by a strong motivation derived from acknowledging the vast scope of the CPEC and the considerable energy potential present in the western part of the Kashmir region. CPEC, a visionary project conceived as part of China's ambitious OBOR initiative, holds great significance in facilitating 1) trade, 2) transportation, and 3) technological advancement. By diversifying Pakistan's energy mix and promoting clean and RERs, CPEC contributes towards enhancing power generation capacity and fostering environmental sustainability. Moreover, the collaboration between China and Pakistan in the energy sector fosters 1) technology transfer, 2) knowledge exchange, while enabling 3) advancements in power generation, transmission, and distribution. A set of detailed assessments and global footsteps shall be conducted while effectively utilizing the energy resources as well as integrating RE sources towards ancillary services, such as electric vehicles (EVs) [21–23], PV-driven systems [24,25], etc. This would mitigate pollution levels in the western portion of Kashmir region and enhance its aesthetic appeal. Therefore, this work aims to shed light on the untapped energy potential of western Kashmir within the context of CPEC. It also provides insights, strategies, and recommendations for 1) sustainable energy development, 2) economic growth, and 3) environmental preservation.

A graphical abstract on the representation of the contributions can be seen in Fig. 1. It outlines a compelling analysis that demonstrates how western Kashmir can make a significant contribution to meeting the region's energy demand while actively participating in ambitious CPEC energy projects. Its insights and findings, arising from the meticulous examination of resources and comprehensive analyses, hold immense potential to inform energy planning and decision-making processes within the context of the CPEC energy projects and beyond.

1.5. Literature review on RERs and their implementation in diverse geographical locations

Numerous schemes have been put forth in scholarly literature to investigate RERs in diverse geographical regions. In this context, the paper [26] focuses on developing a regional power-generation system for Gilgit Baltistan (GB) from 2016 to 2050, utilizing the Long-range Energy Alternative Planning (LEAP) model. The objective is to explore and analyze future clean pathways, considering the implications of incorporating variable renewables (VR) and best available technologies (BAT). The research [27] examined China's investments in renewable energy projects within Pakistan. It aimed to evaluate their effects on the local economy and job creation. Using Input-Output (IO) tables, the researchers found that these investments, which include 28 renewable power plants, could result in about 8905 job opportunities and generate roughly USD 39.8 million in production value across different sectors in Pakistan. Wind energy initiatives were responsible for USD 30.7 million, while solar energy projects contributed USD 9.1 million to the total production value. The article [28] explores Pakistan's considerable potential for energy production while emphasizing the deployment of 1) solar, and 2) wind power units.

A detailed assessment of appropriate sites for the installation of power generation units is also performed. The paper further outlines 1) short-term, 2) mid-term, and 3) long-term strategies, along with 4) actionable proposals. This is to tackle the ongoing power crisis in Pakistan. The research [29] provides a thorough overview of the current energy landscape, including an analysis of 1) policy influences, 2) strategic frameworks, and 3) challenges within the power sector. Additionally, the study offers suggestions for closing the electricity

Fig. 1. Graphical abstract RERs for optimized and sustainable energy management in the western portion of Kashmir region under the CPEC initiative.

supply-demand gap and establishing a sustainable electricity framework for the country. The research [30] investigates the causal link between economic growth, transport infrastructure, fuel consumption in the transport sector, and carbon emissions in Pakistan from 1971 to 2017. The findings indicate that enhancements in transport infrastructure, alongside economic growth and fuel use in the short term, correlate with increased carbon emissions.

Moreover, a two-way relationship between economic growth and infrastructure development is identified in the long run. The study concentrates on incorporating electric energy storage (EES) technologies and renewable energy resources (RERs) into power systems to improve their reliability and economic viability. The paper [31] gives a brief summary of the integration of RERs in urban settings, while considering the current global energy demands and expansion challenges. A detailed literature review highlights the worldwide energy situation and the integration of solar photovoltaic (PV) systems and battery energy storage systems (BESS). The document also looks at the diverse contexts in which RERs are implemented, particularly in grid-connected scenarios.

The paper [32] assesses the sufficiency and cost-effectiveness of distribution systems that integrate both EES and RER. A unique model predictive control (MPC)-based operational strategy is introduced to optimize energy purchase expenses while facilitating the coordination of various power sources from EES, RER, and the external grid. The article [33] presents a comprehensive model that includes key market participants, RER, and demand response (DR), considering both transmission and generation limitations. By applying the Karush-Kuhn-Tucker (KKT) conditions, the study examines the energy market and establishes criteria for the existence and uniqueness of a competitive market equilibrium. It also quantitatively evaluates the effect of wind uncertainty on this competitive market equilibrium. The article [34] discusses a dynamic model of the wholesale energy market, focusing on the uncertainties tied to renewable energy sources and the application of real-time pricing along with demand response. This model starts with a framework that integrates real-time pricing as a core state and aims to capture the dynamic relationships among generation, demand, location marginal price (LMP), and congestion price in proximity to the optimal dispatch equilibrium. The article [35] introduces an innovative operational model aimed at promoting the active participation of interconnected microgrids that RERs fully power in the transactive energy market. The primary innovation of this model is the implementation of transactive energy technology, which facilitates the establishment of a free energy trading environment within the microgrids. This local energy trading market is designed to create a dynamic energy equilibrium within the system, enhancing the effective integration and utilization of 100 % RERs. In the paper [36], a joint optimization approach is outlined to improve the planning and operation of grid-connected residential and rural microgrids (MG), which incorporate RERs and electric vehicles (EVs) while accounting for demand response programs (DRPs). The study mainly aims to achieve energy efficiency in residential homes by investigating various DRPs and integrating RERs. The incorporation of EVs into the microgrids involves the installation of PV systems, wind turbines (WT), fuel cells (FC), and diesel engines (DEs). The paper [37] presents a model that conceptualizes resource-sharing markets, including emission rights sharing, megawatt (MW) sharing, and energy storage, as extended peer-to-peer (P2P) energy-sharing markets. The research provides a comprehensive review of these resource-sharing mechanisms and their implications.

Additionally, the paper explores the cooperation between resource sharing and traditional energy sharing, highlighting the interplay and potential synergies between these approaches. Moreover, the studies on the global implementation of RERs can be seen in Table 1. Here the Table categorizes the type of loads and RERs utilized in the implementation. Moreover, it also addresses the focus of each study and the region.

1.6. Main contribution of this work

Despite the numerous schemes proposed in the existing literature, the current study encounters certain research gaps that necessitate more effective resolutions. Notably, no prior scholarly inquiry has comprehensively addressed the potential of integrating hydro, solar, and wind energy in the region of western portion of Kashmir region while considering the integration of domestic and EV loads. Furthermore, this study makes a noteworthy contribution by extensively examining the contribution of clean and green energy resources. The research paper thoroughly encompasses energy estimation, energy economics, financial considerations, and technical facets of the substantial integration of RERs. It also explores the fluctuations in RERs production throughout the diurnal and annual cycles.

Additionally, the challenges posed by domestic and EV loads are conscientiously considered, and the paper proffers optimal power-sharing strategies between the grid and RERs based on energy demand. Energy estimation, conducted under sensitivity analysis, has yielded efficacious outcomes for the region. The main contributions of this work are as follows.

- Investigating the untapped potential of western Kashmir towards hydro, solar, and wind energy sources with domestic and EV loads, an area that has remained understudied in the existing literature.
- A comprehensive and multifaceted analysis delving into crucial aspects such as 1) energy estimation, 2) energy economics, 3) financial considerations, and the 4) intricate technical challenges associated with the extensive integration of RERs, thereby meticulously examining the fluctuations in RERs production throughout the day and year while addressing the intricate challenges arising from variations in domestic and EV loads.

Table 1
Studies on global implementation of RERs.

Ref	RERs and Loads						Focus	Region
	Solar	Wind	Hydro	Others	Domestic	EVs		
[38]	(✓)	(X)	(X)	(X)	(✓)	(X)	Energy Model for emission reduction in the State of Punjab	Punjab, Pakistan
[39]	(✓)	(✓)	(X)	(X)	(✓)	(X)	Exploring the pathways toward achieving a 100 % Renewable Electricity Supply	Portugal
[40]	(X)	(✓)	(✓)	(✓)	(✓)	(X)	Comprehensive Renewable Electricity Generation System	New Zealand
[41]	(X)	(✓)	(X)	(✓)	(✓)	(X)	Transitioning towards a fully Sustainable Energy System	Ireland
[42]	(✓)	(✓)	(✓)	(✓)	(✓)	(X)	Techno-Economic Assessment and Evaluation of the Sustainability impact of Hybrid Energy Systems	GB, Pakistan
[43]	(X)	(X)	(✓)	(X)	(✓)	(X)	The Present and Future Potential of small Hydropower in Pakistan through a comprehensive survey	Pakistan
[44]	(✓)	(✓)	(X)	(✓)	(✓)	(X)	In-depth Energy System Analysis of 100 % RE Systems	Denmark
[45]	(✓)	(✓)	(✓)	(✓)	(✓)	(X)	Investigating the Impact of Renewable and Non-renewable electricity generation on Economic Growth	174 countries
[46]	(✓)	(✓)	(✓)	(✓)	(✓)	(X)	Performing Simulations to Explore Various Scenarios Involving the Implementation of 100 % Renewable Electricity	Australian

- Optimization of resource allocation by proposing sophisticated strategies for power sharing between the grid and RERs grounded in meticulous assessments of energy demand. These strategies ensure the efficient utilization of clean and green energy resources, thereby enhancing overall system performance and sustainability.
- Analysis of sensitivity is utilized to estimate energy parameters, producing accurate and effective outcomes that are specifically adapted to the distinctive traits of the region. To accomplish this, the study undertakes extensive multiyear planning that considers anticipated variations in 1) demand, 2) pricing trends, 3) electric vehicle (EV) models, 4) peak loads of EVs, and 5) operational limitations. This thorough methodology seeks to maximize techno-economic benefits over the duration of the project.
- A detailed economic analysis examining diverse facets such as 1) initial investments, 2) overall returns over the project lifespan, 3) energy savings, 4) economic growth prospects, and 5) other significant financial impacts. By considering the power generation impact of load variations (both domestic and EV), the study provides invaluable insights into effectively managing power distribution in the region.
- Assessment of the RE potential of solar, wind, and hydropower in the region, with accounting for factors such as 1) energy estimation, 2) annualized energy production, and 3) the dynamics of power fluctuations throughout the day. In a commendable display of environmental consciousness, the paper investigates and acknowledges the environmental impact associated with the substantial integration of RERs in the region, emphasizing the urgent need for clean energy initiatives.

1.7. Formation of the remaining paper

The rest of the paper is structured as follows: The methodology is represented in Section 2. This includes the demographic conditions and potential of RERs, mathematical modeling, environmental and economic model, quantitative assessment, and pseudo code of the proposed scheme. The results, comparative analysis, and discussion are made in Section 3. Finally, conclusion and policy implications are made in Section 4.

2. Methodology demographic conditions, modeling, and quantitative assessment

2.1. Demographic conditions and potential of RERs

The region of western Kashmir is a well-known territory under the control of Pakistan. Located at an elevation of 1901.26 m above sea level, western Kashmir features a humid subtropical climate. The region exhibits an average annual temperature of 19.81°C, slightly lower by approximately −1.08 % compared to the national averages of Pakistan. As for precipitation, western Kashmir typically receives an average of 140.52 mm of rainfall, distributed over 157.35 rainy days, representing around 43.11 % of the annual duration. The region exhibits an average clearness index and solar irradiance value measuring 0.607 and 5.08 kWh/m^2/day, respectively. Additionally, the prevailing wind speed in the region has been observed to be approximately 3.02 m/s.

The region is home to five prominent rivers: 1) Jhelum River, 2) Neelum River, 3) Poonch River, 4) Kunhar River, and 5) Dudhnial River. Notably, it accommodates the Mangla Dam, the second largest dam in Pakistan, and the recently completed Nelum-Jhleum project, carried out under the auspices of the CPEC. Several small-scale power projects have been installed to meet the region's energy needs, with the current commissioning of 28 hydro projects generating 2368 MW. Furthermore, 11 hydro projects with a capacity of 2795 MW are currently under construction, and there are 58 upcoming projects projected to generate 4095 MW. It is important to note that the region, characterized by its hilly terrain, possesses significant potential for harnessing solar and wind energy. The strategic placement of the Mangla Dam, combined with the region's natural topography, makes it well-suited for wind energy generation. The region comprises a network of 661,549 connections distributed across 1765 villages spanning ten districts within the state. Presently, the region procures 2042 million kWh of electricity to fulfill its energy requirements, while the region supplies 1303 million kWh. With a per capita electricity consumption of 505 kWh, the region's estimated total demand stands at 400 MW, whereas the maximum power supply available is 330 MW. Fig. 2(a)-(b) provides an overview of the demographic parameters of western Kashmir as well as the region's water resources. It showcases a dual depiction of maps. Firstly, it presents the official map of western Kashmir, offering a comprehensive overview of the region's cities and prominent geographical features. Secondly, it encompasses a specialized map focusing on the water resources within the area, encompassing rivers, lakes, and various other significant water bodies.

2.2. Mathematical modeling of components

This section concisely explains the mathematical modeling approach employed for the system components towards power management strategy [48,49]. The mathematical modeling of the photovoltaic (PV) system is elucidated through eq. (1) [50], which clearly demonstrate the dependence of PV power on the rated power, solar irradiance, and temperature of the PV cell.

$$PV_{eng} = PV^{rat}_{Power} f_{df}\left(\frac{S_{radT}}{S_{radT,STC}}\right)\left[1 + Cof_T\left(Temp_{cell} - Temp_{cell,STC}\right)\right] \tag{1}$$

where PV_{eng} is the PV energy, PV^{rat}_{Power} is the PV rated power, S_{radT} is the solar radiation, $S_{radT,\ STC}$ is the solar radiation under standard test conditions (STC), Cof_T is the temperature coefficient, $Temp_{cell}$ is the cell temperature, and $Temp_{cell,STC}$ is the cell temperature under STC conditions. Furthermore, the temperature of the PV cell is influenced by both the nominal and ambient temperatures, detailed in (2) [50].

$$Temp_{cell} = T_{amb}\left(T_{Nom} - T_{a,nom}\right)\frac{S_{rad_T}}{S_{rad_{T,STC}}}\left(1 - \frac{\eta_{eff}}{0.9}\right) \tag{2}$$

where T_{amb} is the ambient temperature, T_{nom} is the nominal temperature, $T_{a,nom}$ is the ambient temperature under nominal conditions, and η_{eff} represents efficiency. The solar radiation is defined in the form of beta distribution as follows [50]:

$$fun_{beta}(S_{rad}) = \frac{{S_{rad}}^{\alpha-1}\left(1 - S_{Rad}\right)^{\beta-1}}{\tau(\alpha)\tau(\beta)}\tau(\alpha+\beta) \tag{3}$$

where fun_{beta} is the function of beta distribution, α, and β are shape parameters that determine the shape of the distribution, and τ is gamma function. The equation for shape parameter α is represented as follows [50]:

$$\alpha = \mu\left[\frac{(1-\mu)\mu}{\sigma} - 1\right] \tag{4}$$

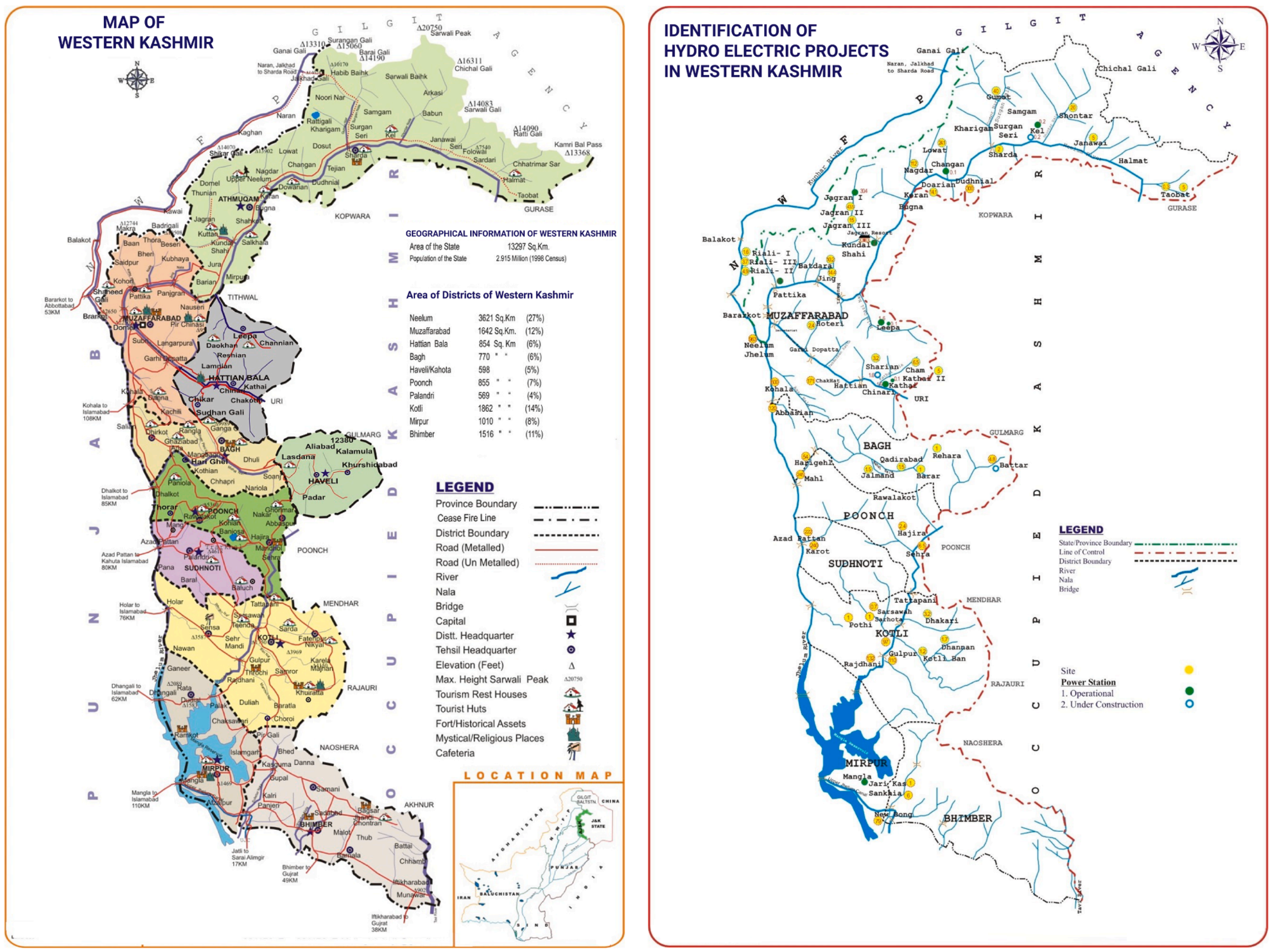
where μ is mean, and σ is standard deviation. The equation for shape parameter β is represented as follows [50]:

$$\beta = (1-\mu)\left[\frac{(1-\mu)\mu}{\sigma} - 1\right] \tag{5}$$

The P_{PV} output power of solar panels can be expressed with the help of limit conditions as follows [50]:

$$P_{PV} = \begin{cases} P^r_{PV}\frac{s}{s_r} 0 < s < s_r \\ P^r_{PV} s_r > s \end{cases} \tag{6}$$

where s_r is the solar irradiance and P^r_{PV} represents rated value of solar



(a) (b)

Fig. 2. Western Kashmir (a) geographical features, and (b) water resources [47].

irradiance.

Maintaining a stable energy balance becomes increasingly challenging with integrating renewable power sources and electric vehicles into the electric grid. This integration can result in notable system frequency fluctuations within microgrids. Power systems require additional reserves to ensure a continuous and immediate balance between power sources and loads. BESSs can contribute to frequency management by adjusting active power, thus serving as a regulating reserve and auxiliary service that mitigates frequency deviations caused by sudden variations in RE generation. Various factors, including battery configuration, backup duration, temperature, battery life, and depth of discharge, reserve power requirements, and the presence of RE sources influence the rating of a BESS. $\boldsymbol{P_{BESS}(t)}$is the power of battery energy storage system while $\boldsymbol{P_{ch}(t)}$ and $\boldsymbol{P_{dch}(t)}$ are the charging and discharging powers of the battery energy storage system. $\boldsymbol{P_{PV}(t)}$ is the output power of PV and $\boldsymbol{P_D(t)}$ represent the power demand by the load [51].

$$P_{BESS}(t) = \begin{cases} P_{ch}(t)P_{PV}(t) - P_D(t) \geq 0 \\ P_{dch}(t)P_{PV}(t) - P_D(t) < 0 \end{cases} \tag{7}$$

The charging and discharge power of BESS must exceed the nominal capacity of BESS where $\boldsymbol{P^r_{BESS}}$ is the rated power of BESS [51].

$$0 \leq P_{ch} \leq P^r_{BESS} \tag{8}$$

$$0 \leq P_{dch} \leq P^r_{BESS} \tag{9}$$

The nominal capacity of a BESS must remain lower than its corresponding charging and discharging power. Notably, a BESS can operate in either a charging or discharging state at any given time. As specified by (10) and (11), the BESS operates in the charging mode during instances of surplus power generation and switches to the discharging mode when there is an elevated energy demand. The subsequent calculations outline the precise values for the BESS's charging and discharging power.

2.2.1. Charging Mode: In the charging mode,$E_{ch}(t)$ shows energy charging while $E_{dch}(t)$ denotes energy discharging of BESS and $P_{WT}(t)$ represents the power output of the wind system. $\eta_{Conv}$is the efficiency of the converter while η_{Ch} and η_{Ch} defines charging and discharging efficiency. The state of charge of BESS is represented by $SOC(t)$ and the standard deviation is denoted through σ_1 [51].

$$E_{ch}(t) = \left(\frac{P_{WT}(t) - P_D(t)}{\eta_{Conv}} + P_{PV}(t) \right) \Delta t \eta_{ch} \tag{10}$$

$$SOC(t) = (1 - \sigma_1).SOC(t-1) + E_{ch}(t) \tag{11}$$

2.2.1. Discharging mode: the discharging mode can be represented as follows [44]

$$E_{dch}(t) = \left(\frac{-P_{WT}(t) + P_D(t)}{\eta_{Conv}} - P_{PV}(t) \right) \Delta t \eta_{dch} \tag{12}$$

$$SOC(t) = (1 - \sigma_1).SOC(t-1) - E_{ch}(t) \tag{13}$$

2.3. Environmental and economic modeling

The cost of electricity (COE) serves as an ongoing metric for comparing the economic viability of different power generation methods. While the COE is commonly defined as the minimum price at which energy should be sold to achieve financial breakeven over the project's lifespan, such an analysis necessitates the consideration of various non-financial factors such as environmental impacts and local availability. Consequently, the determination of the COE involves subjective judgments. Specifically, it is calculated by dividing the net present value of all costs incurred throughout the asset's operational life by the discounted energy production over the approximate lifespan of the asset.

Total annualized cost of the system is represented through C_{annual} while $L_{primary}$ and L_d are primary and deferable loads and E_{gs} is the total energy generation of the system [52].

$$COE = \frac{C_{annual}}{L_{primary} + L_d + E_{gs}} \tag{14}$$

Approximately 80 % of anthropogenic emissions are attributed to greenhouse gas emissions associated with energy production in both the United States and the European Union. It is noteworthy that electricity constitutes only 20 % of total energy consumption; however, it is responsible for over 40 % of all emissions. On a global scale, the combustion of fossil fuels results in the annual emission of approximately 34 billion tonnes (Gt) of CO_2. In (15), fuel heating value is denoted by FHV, carbon emission factor by CEF_{fuel}, fuel volume by m_{fuel} and X_c represent the oxidize carbon [53].

$$e.CO_2 = 3.667 \times m_{fuel} \times FHV \times CEF_{fuel} \times X_c \tag{15}$$

2.4. Quantitative Assessment and Performance Metrics of the Proposed Model.

The evaluation drivers towards sustainable adoption of renewable energy plays a key role towards development and energy security [54–57]. The proposed model in this research paper encompasses the integration of hydro, wind, PV systems, EVs, and domestic loads, which are examined through two distinct scenarios: 1) Alpha, and 2) Beta. The Alpha case represents a conservative approach, considering minimal PV and wind integration by customers, alongside domestic loads and EVs. It focuses on the installation of 4568 MW of hydro capacity, comprising 28 small dams (2368 MW) and two large power projects (2200 MW). Additionally, the Alpha scenario assumes that only 50 % of customers have installed 2 kW solar systems, while 22 % of customers have installed 1 kW wind energy systems. Furthermore, 100 MW charging stations are established for EVs in the region. As a result, the Alpha scenario entails the setup of 661,549 kW in solar power, 218,311 kW in wind power, 100 MW for PV-based charging stations, and an overall hydro capacity of 4568 MW.

Conversely, the Beta scenario investigates the highest possible integration of solar photovoltaic (PV) and wind energy, along with both current and future hydropower facilities. In this context, it is anticipated that every customer will install a 2-kW solar system, achieving a full participation rate of 100 % for solar energy adoption. Furthermore, it is projected that 50 % of customers will implement 1 kW wind energy systems, leading to a total installation of 330,774 kW. The Beta scenario includes all hydropower plants that are currently operational, underway, or planned, resulting in a significant hydroelectric capacity of 11,458 MW. A detailed analysis and calculations have been performed for both the Alpha and Beta scenarios, allowing a comprehensive evaluation of the various potential outcomes and effects connected to different levels of renewable energy integration (REI) in the area.

By exploring these differing scenarios, this paper offers important insights into the best strategies for deploying renewable energy resources (RERs), along with economic factors and environmental consequences. The thorough analysis carried out in this research covers 1) energy forecasting, 2) financial assessments, 3) technical challenges, and 4) evaluations of energy demand. The results from this study aim to address existing research deficiencies and aid in the progress of sustainable energy systems in the region, ultimately fostering a cleaner and more sustainable future. Fig. 3 depicts the proposed model of renewable energy integration, which includes 1) hydro, 2) wind, 3) solar PV, 5) electric vehicles (EVs), and 6) household energy consumption.

2.4. Pseudo code for the proposed optimized and sustainable energy management system

The pseudo code shown in Table 2 below is designed to explain the process of the algorithm. Variables are initialized from lines # 2 to 24 in which different scenarios are considered, including PV energy, PV-rated power, solar radiation, temperature coefficient, cell temperature, shape parameters, output power, and fuel volume.

At line # 25 to 27, it calculated PV energy. This is followed by calculation of solar radiation (line # 28 to 30), output power of solar (line # 31 to 33), and batter storage system (line # 34 to 36). For charging and discharging mode, calculation is made on line # 37 to 39. For cost of electricity, calculation is made on line # 40 to 42. The output/return of this proposed code is represented at line # 43.

3. Results, comparative analysis and discussion

The following passage offers a summary of the results related to energy economics and cost assessment. Moreover, it includes aspects of power distribution and energy measurement. It also examines the financial and ecological impacts tied to the deployment of the system, in addition to the strategic planning involved in energy distribution throughout various times of the day and year.

This section is organized by addressing: 1) a comparative cost-benefit analysis of renewable energy technologies, 2) an exploration of the dynamics of energy generation and consumption, 3) an investigation into the seasonal trends of renewable energy resources, 4) the operational characteristics and levels of integration of power generation systems, 5) the dynamics of energy markets and interactions with the grid, 6) the environmental consequences and comparative assessment of power generation, and 7) progress in renewable energy research and a comparative overview.

3.1. Comparative cost-benefit analysis of RE technologies

The subsequent paragraph provides a summary of energy economics. This includes 1) the capital expenditures for resource setup, 2) replacement expenses throughout the project lifecycle, 3) operational and maintenance costs, in addition to 4) salvage expenses.

To establish a 100MW charging station in the region, an investment of $35 million is required. Installing power storage devices alongside the solar system calls for an initial budget of approximately $1698.46 million. Replacing the BESS every 10 years costs $1500.49 million, operational and maintenance expenses of $147.63 million, and a salvage cost of $203.44 million. Although the grid does not entail any initial expenses, it carries an operational and maintenance cost of $4007.66 million. Upgrading and replacing hydropower plants necessitates a budget of $1412.44 million, with operational and maintenance costs totaling around $147.63 million and a salvage cost of $191.50 million. For solar system installations intended for domestic purposes, the initial investment required is a modest $231.54 million. The installation of converters in conjunction with the solar system incurs a budget of $228.46 million. In the alpha scenario, wind energy installation demands $76.41 million, with an operational and maintenance cost of approximately $0.28 million. The total initial cost for installing all resources in the alpha case amounts to $3868.68 million, while the

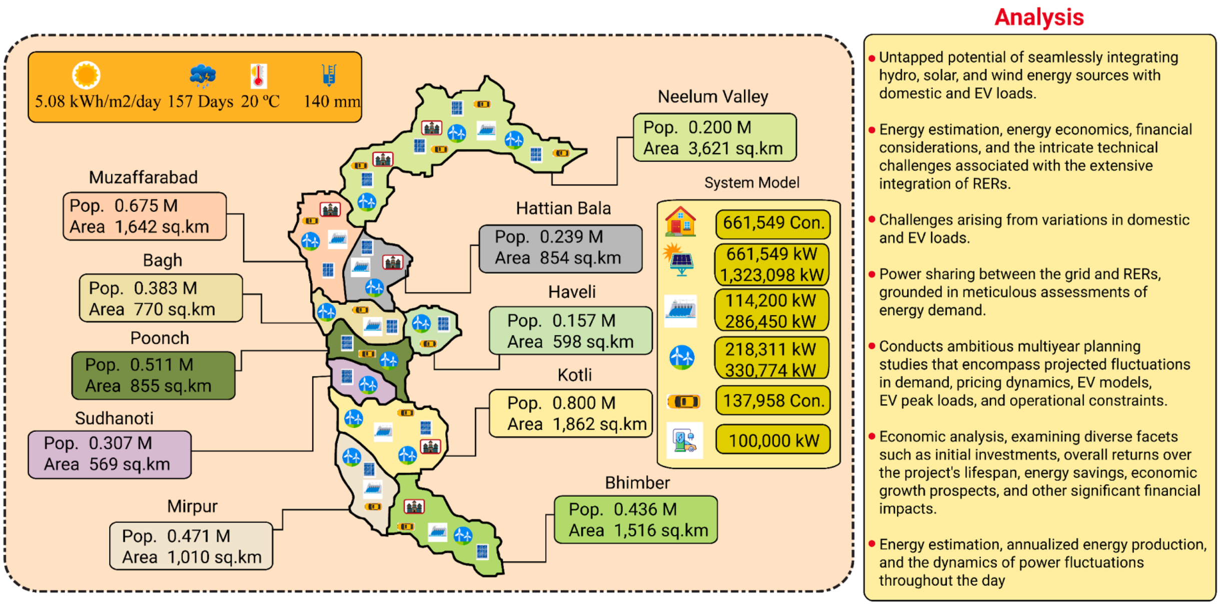


Fig. 3. Proposed model for renewable energy integration (REI) Hydro, wind, PV, EV, and domestic loads.

Table 2
Pseudocode for the proposed scheme.

Algorithm: Optimized and sustainable energy management system
Initialize:
PV_{eng}, % PV energy
PV^{rat}_{Power}, %PV rated power
$S_{rad\,T}$, % solar radiation
$S_{radT,\ STC}$, % solar radiation under standard test conditions (STC)
Cof_T, % temperature coefficient
$Temp_{cell}$, % cell temperature
T_{amb}, %% ambient temperature
T_{nom}, % nominal temperature
$T_{a,nom}$, %% ambient temperature under normal conditions
S_{rad}, % solar radiation
α, β, τ, % shape parameters
P_{PV}, % output power of solar panel
P_{WT}, % output power of wind system
s_r, %% solar irradiance
P^r_{PV}, %% rated value of solar irradiance.
s_r, % solar irradiance
P^r_{BESS}, % rated power of BESS
E_{ch}/E_{dch}, % energy charging/discharging
σ_1, % standard deviation
FHV, fuel heating value
CEF_{fuel}, % carbon emission factor
m_{fuel} . % fuel volume
X_c, % oxidize carbon
For PV Energy
Calculate PV_{eng} (1), $Temp_{cell}$ (2)
End
For Solar Radiation
Calculate S_{rad} (3), α (4), β (5)
End
For Output Power of Solar Panel
Calculate P_{PV} (6)
End
For Battery Energy Storage System
Calculate P^r_{BESS} (7,8,9)
End
For Charging/Discharging Mode
Calculate E_{ch} (10), E_{dch} (12), SOC (11,13)
End
For Cost of Electricity
Calculate COE (14), $e.CO_2$ (15)
End
Return (PV_{eng}, S_{rad}, P_{PV}, P^r_{BESS}, E_{ch}, E_{dch}, COE)

replacement cost is approximately $3009.86 million. Interestingly, the operational and maintenance cost of the entire system is negative, indicating a surplus of energy sold back to the grid, generating revenue. The project total cost over 25 years reaches approximately $3337.60 million. Fig. 4 analyzes the total cost associated with the proposed energy project over a 25-year duration, specifically focusing on the alpha scenario. Table 3 presents detailed information on the capital expenditure, replacement costs, operational and maintenance (O & M) expenses, and salvage expenditure about the alpha scenario of the energy project.

Fig. 5 analyzes the total cost associated with the proposed energy project over a 25-year duration, specifically focusing on the beta scenario. Table 4 presents a concise breakdown of costs associated with various power generation resources in the beta case. The charging station carries a capital cost of $35.00 million, without any replacement cost. It incurs an operational and maintenance cost of $12.93 million and has no salvage cost. The charging station's net present cost (NPC) is $35,012.93 million. Power storage requires a capital investment of $1896.93 million and incurs a replacement cost of $1675.82 million. However, it demonstrates a negative operational and maintenance cost of -$227.21 million, indicating revenue generation. The salvage cost is $0.00, resulting in an NPC of $4162,955.58 million. The grid has no capital or replacement cost but carries a negative operational and maintenance cost of -$22,648.99 million, leading to a negative NPC of -$22,648,986.34 million. Hydro power entails a capital cost of $4010.30 million and a replacement cost of $3542.85 million. The operational and maintenance cost amounts to $370.31 million, while the salvage cost is -$480.35 million. The NPC for hydro power is $7443,109.21 million. Solar installations require a capital investment of $463.08 million and do not involve any replacement cost. The operational and maintenance cost is $171.04 million, with no salvage cost. The NPC for solar Installations is $463,255.34 million. Converters involve a capital investment of $426.93 million and a replacement cost of $181.13 million. They do not entail any operational and maintenance costs, and the salvage cost is -$34.09 million. The NPC for converters is $573,972.94 million. Wind power incurs a capital cost of $115.77 million, with no replacement cost. It has an operational and maintenance cost of $427.61 million, and no salvage cost. The NPC for Wind power is $116,198.51 million. The total infrastructure cost, encompassing all resources, includes a capital investment of $6948.01 million and a replacement cost of $5399.80 million. It demonstrates a negative operational and maintenance cost of -$21,460.65 million and a negative salvage cost of

-$741.65 million. The overall NPC for the entire infrastructure is -$9854,481.83 million.

This section provides important insights into different elements of power generation resources. It explores economic factors by examining 1) capital expenditures, 2) replacement costs, 3) operational and maintenance fees, and 4) salvage values. Importantly, the results reveal a noteworthy finding concerning revenue generation, shown by the negative operational and maintenance costs seen in power storage facilities in both the alpha and beta scenarios. Additionally, it emphasizes the significance of selling surplus energy to generate income. These insights greatly enhance the understanding of both traditional and novel strategies in the power generation sector, offering substantial information on economic dynamics and potential revenue opportunities.

3.2. Investigating and exploring energy generation and consumption dynamics

The results section provides a detailed examination of the data collected from the study, which is outlined in the Table. The PV installation demonstrated a significant output of 2239,658,814 kWh/year, representing 2.18 % of the overall total. Meanwhile, the charging station contributed 169,273,842 kWh/yr, representing a mere 0.165 % of the overall production. The wind source yielded 43,853,739 kWh/yr, constituting a meager 0.0426 % of the total. The results section presents a comprehensive analysis of the data obtained from the study, as summarized in the Table. The PV installation exhibited a substantial production of 2239,658,814 kWh/yr, accounting for 2.18 % of the total.

Meanwhile, the charging station contributed 169,273,842 kWh/yr, representing a mere 0.165 % of the overall production. The wind source yielded 43,853,739 kWh/yr, constituting a meager 0.0426 % of the total. Conversely, hydroelectric power became the primary source, producing an impressive 100,372,080,000 kWh annually, representing 97.6 % of the overall output. The analysis of consumption metrics revealed that the AC load reached 39,719,221,452 kWh per year, making up 81.9 % of total consumption. The surplus electricity amounted to 54,345,653,703 kWh per year, which corresponded to 52.9 % of the total. Notably, the renewable share achieved an exceptional score of 100 %.

Additionally, grid sales totaled 8759,991,240 kWh per year, constituting 18.1 % of total consumption. In conclusion, the aggregated data illustrated a total production of 102,824,866,395 kWh annually, derived from various energy sources, while overall consumption was recorded at 48,479,212,692 kWh per year. These results offer significant insights into the patterns of energy production and consumption within the specific context of the alpha case. Tables 5 and 6 deliver a detailed analysis of energy production and consumption in the Alpha and Beta cases, highlighting the contributions from PV, charging stations, wind, and hydro generation.

The results obtained from the beta case, as presented in the Table, reveal significant insights into the energy dynamics of the studied context. The PV installation demonstrated 1119,829,407 kWh/yr production, accounting for 2.70 % of the total production. Similarly, the charging station contributed 169,273,842 kWh/yr, representing 0.409 % of the overall production. The wind source provided 28,943,489 kWh/yr, constituting a mere 0.0699 % of the total production. However, hydroelectric power emerged as the primary contributor, generating a substantial 40,015,680,000 kWh/yr, accounting for 96.6 % of the total production. On the consumption side, the AC primary load accounted for 39,719,221,452 kWh/yr, representing 96.0 % of the total consumption. The renewable fraction attained an impressive 99.8 %. Notably, grid purchases amounted to 92,293,688 kWh/yr, constituting a mere 0.223 % of the total consumption, while grid sales reached 1642,343,811 kWh/yr, accounting for 3.97 % of the total consumption. In summary, the collective data showcased a total production of 41,426,020,426 kWh/yr, encompassing various power sources, while the total consumption amounted to 41,361,565,263 kWh/yr. These findings offer valuable insights into the beta case's energy production and consumption patterns, enabling a deeper understanding of the system dynamics.

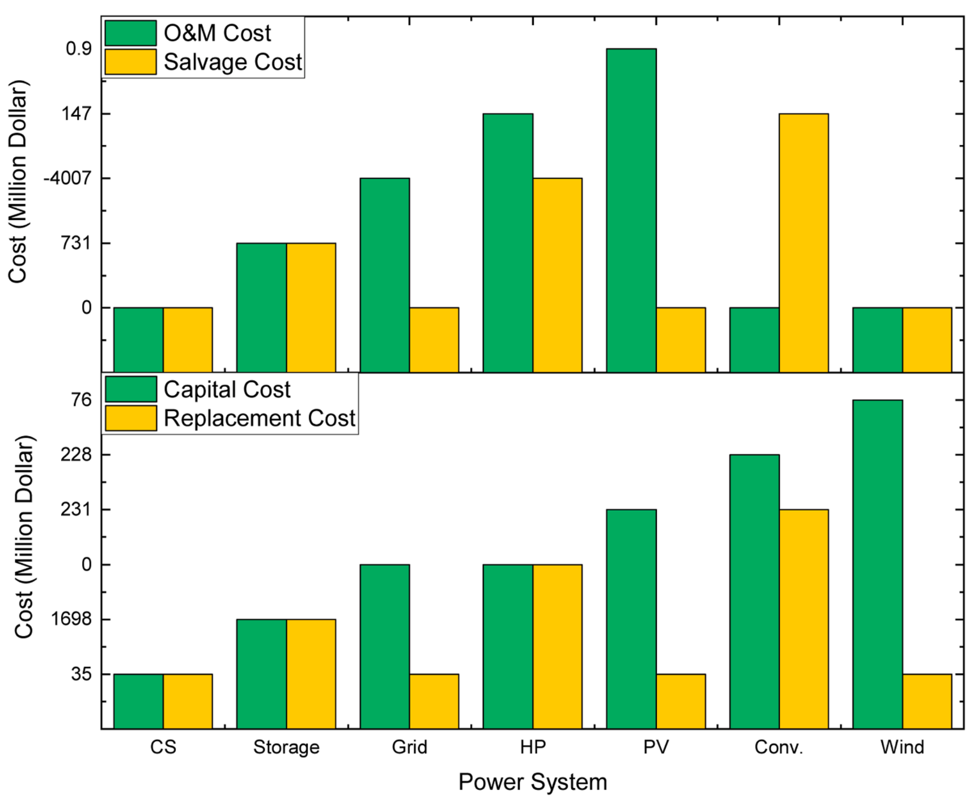


Fig. 4. Total cost assessment of the proposed energy project over a 25-year duration (alpha scenario).

Table 3
Capital expenditure, replacement costs, operational and maintenance expenses, and salvage expenditure (alpha scenario).

Power System	Capital Cost (million)	Replacement Cost (million)	O&M Cost (million)	Salvage Cost (million)	NPC (million)
Charging Station	$35.00	$0.00	$0.01	$0.00	$35.01
Power Storage	$1698.46	$1500.49	$731.90	-$203.44	$3727.41
Grid	$0.00	$0.00	-$4007.66	$0.00	-$4007.66
Hydro Power	$0.00	$1412.44	$147.63	-$191.50	$2967.37
Solar Installations	$231.54	$0.00	$0.09	$0.00	$231.63
Converters	$228.46	$96.93	$0.00	-$18.24	$307.15
Wind	$76.41	$0.00	$0.28	$0.00	$76.69
Whole Infrastructure Cost	$3868.68	$3009.86	-$3127.75	-$413.19	$3337.60

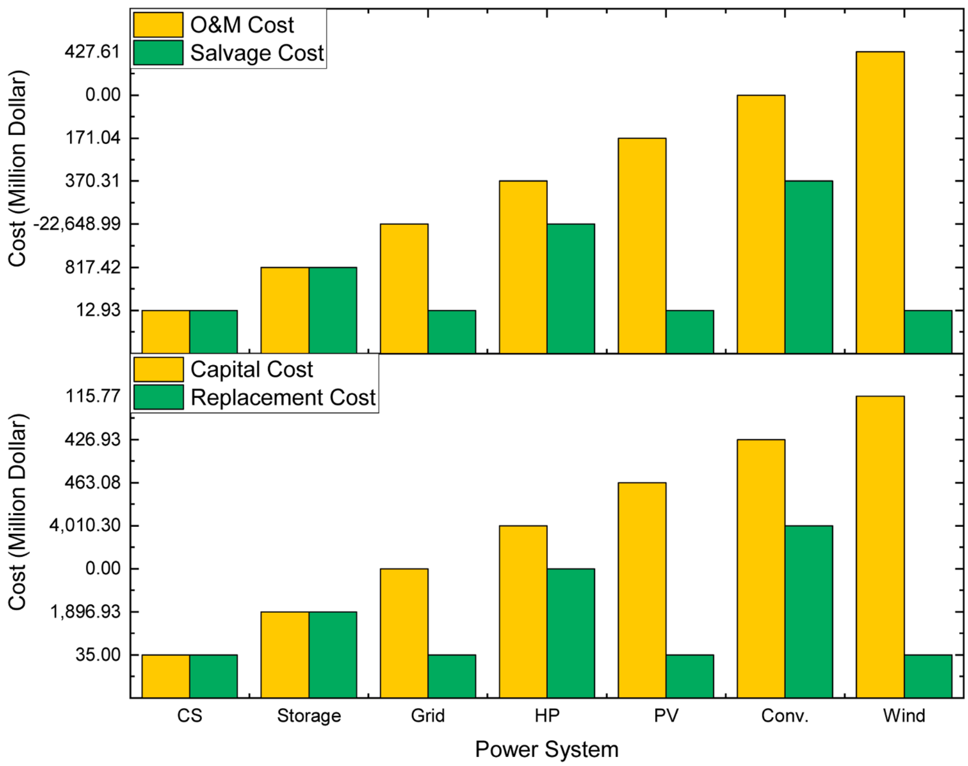


Fig. 5. Total cost assessment of the proposed energy project over a 25-year duration (beta scenario).

Table 4
Capital expenditure, replacement costs, operational and maintenance expenses, and salvage expenditure (Beta Scenario).

Power System	Capital Cost (million)	Replacement Cost (million)	O&M Cost (million)	Salvage Cost (million)	NPC (million)
Charging Station	$35.00	$0.00	$12.93	$0.00	$35,012.93
Power Storage	$1896.93	$1675.82	$817.42	-$227.21	$4162,955.58
Grid	$0.00	$0.00	-$22,648.99	$0.00	-$22,648,986.34
Hydro Power	$4010.30	$3542.85	$370.31	-$480.35	$7443,109.21
Solar Installations	$463.08	$0.00	$171.04	$0.00	$463,255.34
Converters	$426.93	$181.13	$0.00	-$34.09	$573,972.94
Wind	$115.77	$0.00	$427.61	$0.00	$116,198.51
Whole Infrastructure Cost	$6948.01	$5399.80	-$21,460.65	-$741.65	-$9854,481.83

The summarized findings of the two paragraphs reveal several notable novelties within the research study. These findings reinforce the viability and effectiveness of RE systems in the energy production landscape. Moreover, the minimal grid purchases and the significant grid sales signify a reduced dependence on external energy sources and the potential for energy surplus within the system. Overall, the research study contributes to understanding RE utilization, revenue generation potentials, and the importance of integrating sustainable energy resources into the energy mix.

3.3. *Investigating the seasonal dynamics of RERs*

The evaluation of hourly energy shares from various renewable energy resources (RERs) while encompassing domestic photovoltaic (PV) systems in both alpha and beta scenarios. Charging stations and wind energy in those same contexts offer significant insights into the patterns of use and distribution of clean energy sources. Analysing the monthly power shares reveals fascinating dynamics in energy production and availability. In January, the energy shares from domestic PV systems remained low throughout the day, indicating minimal solar energy production. Conversely, February saw a marked rise in domestic PV

Table 5
Comprehensive energy production and consumption analysis in the alpha case: PV, charging station, wind, and hydro contributions.

Source	Production (kWh/yr)		Parameters	Consumption (kWh/yr)	
	kWh/yr	%		kWh/yr	%
PV Installation	2239,658,814	2.18	AC Load	39,719,221,452	81.9
Charging Station	169,273,842	0.165	Excess Electricity	54,345,653,703	52.9
Wind Source	43,853,739	0.0426	Renewable Fraction	100	%
Hydropower	100,372,080,000	97.6	Grid Sales	8759,991,240	18.1
Total	102,824,866,395	100	Total	48,479,212,692	100

Table 6
Comprehensive energy production and consumption analysis in the beta case: PV, charging station, wind, and hydro contributions.

Source	Production (kWh/yr)		Parameters	Consumption (kWh/yr)	
	kWh/yr	%		kWh/yr	%
PV Installation	1119,829,407	2.70	AC Primary Load	39,719,221,452	96.0
Charging Station	169,273,842	0.409	Renewable Fraction	99.8	%
Wind Source	28,943,489	0.0699	Grid Purchases	92,293,688	0.223
Hydropower	40,015,680,000	96.6	Grid Sales	1642,343,811	3.97
Total	41,426,020,426	100	Total	41,361,565,263	100

energy shares, especially in the beta region, pointing to enhanced solar irradiation and increased energy generation capabilities. March experienced variations in energy shares from domestic PV, with distinct peaks during midday hours corresponding to sunlight availability. The energy shares from PV-based charging stations steadily increased, reflecting improvements in their performance and contributions to the overall energy composition. April experienced a slight reduction in domestic PV energy shares, while wind energy shares displayed intermittent fluctuations, likely influenced by changes in wind speeds and atmospheric conditions. In May, domestic PV energy shares surged during midday, underscoring the considerable potential of solar energy generation. The power shares from charging stations remained stable, illustrating their dependability and consistent role in the energy system. Wind energy shares continued to show variability, reflecting the inherent unpredictability of wind resources. In June, domestic PV energy shares maintained robust levels during daylight hours, confirming the reliable generation of solar energy. Charging station energy shares stayed stable, highlighting their consistent performance, while wind energy displayed steady patterns, indicating a foreseeable input to the energy mix. Fig. 6 illustrates the temporal variations and contributions of RERs in the alpha and beta scenarios, focusing on energy shares from domestic PV, charging stations, and wind energy from January to June.

The assessment of hourly energy shares from numerous RERs, including domestic PV systems in both alpha and beta instances, charging stations, and wind energy within these cases, provides essential insights into the dynamics of energy generation and availability. A seasonal analysis of power shares unveils intriguing trends in energy production and accessibility. During July, the energy shares from domestic PV and wind energy remained relatively low, signifying limited solar and wind energy generation. However, August experienced a significant boost in energy shares from domestic PV, particularly in the beta region, indicating improved solar irradiation and increased energy production. Power shares from charging stations also saw substantial growth, reflecting heightened utilization. September showcased ongoing increases in energy shares from both domestic PV and charging stations, emphasizing the growing adoption of renewable energy for electric vehicle (EV) charging. Wind energy also played a role in the overall energy shares during this time. October recorded a further rise in energy shares from both domestic PV and wind energy, highlighting the potential of these renewable sources. The energy shares from charging stations remained steady, signalling a consistent demand for EV charging. November presented fluctuating energy shares from various sources, with contributions from domestic PV, wind energy, and charging stations enriching the energy mix. December mirrored this trend, with domestic PV and wind energy continuing to significantly contribute to clean energy production, while charging stations supported the EV charging infrastructure. Fig. 7 depicts the temporal variations and contributions of RERs in both alpha and beta scenarios, emphasizing energy shares from domestic PV, charging stations, and wind energy from July to December.

These results highlight the necessity of resource assessment, infrastructure advancement, and strategic planning to fully optimize the use of renewable energy sources. They offer valuable insights for policymakers, energy planners, and stakeholders aimed at achieving a sustainable energy future by leveraging the full potential of a diverse array of renewable resources.

3.4. Operational characteristics and penetration levels of power generation systems

The results section of the research paper presents a comprehensive analysis of various parameters related to energy production from different sources. Starting with domestic PV installations, the rated capacity is reported as 661,549 kW, with a mean power output of 127,834 kW and a corresponding mean energy output of 3068,026 kWh per day. Charging stations, on the other hand, have a rated capacity of 100,000 kW, resulting in a mean power output of 19,323 kW. Wind production exhibits a capacity factor of 1.51 %, leading to a total production of 28,943,489 kWh per year. However, it is noteworthy that specific information regarding mean energy output and capacity factor is not available for wind production. In contrast, hydropower stands out as the dominant contributor, with a substantial rated capacity of 4568,000 kW and a capacity factor of 100 %. This can also be seen in Table 7.

Consequently, hydropower achieves a remarkable total production of 40,015,680,000 kWh per year. The minimum and maximum output values for each source indicate the range of power variation, with hydropower maintaining a constant output at its maximum capacity. The penetration rates provide insights into the proportion of each energy source's contribution to the overall energy landscape, with hydropower slightly surpassing 100 % due to its consistent generation. Additionally, the hours of operation indicate the length of power generation activities, with hydropower functioning for a complete 8760 h annually. Finally, the levelized cost figures illustrate the expense per energy unit produced, showing domestic PV and charging stations with a 1) levelized cost of $0.0160, 2) wind energy at $0.205, and 3) hydropower at the lowest cost of $0.00574. These in-depth findings provide insights into the 1) capacities, 2) variations, 3) penetration rates, 4) operational hours, and 5) cost aspects connected to various energy sources, while

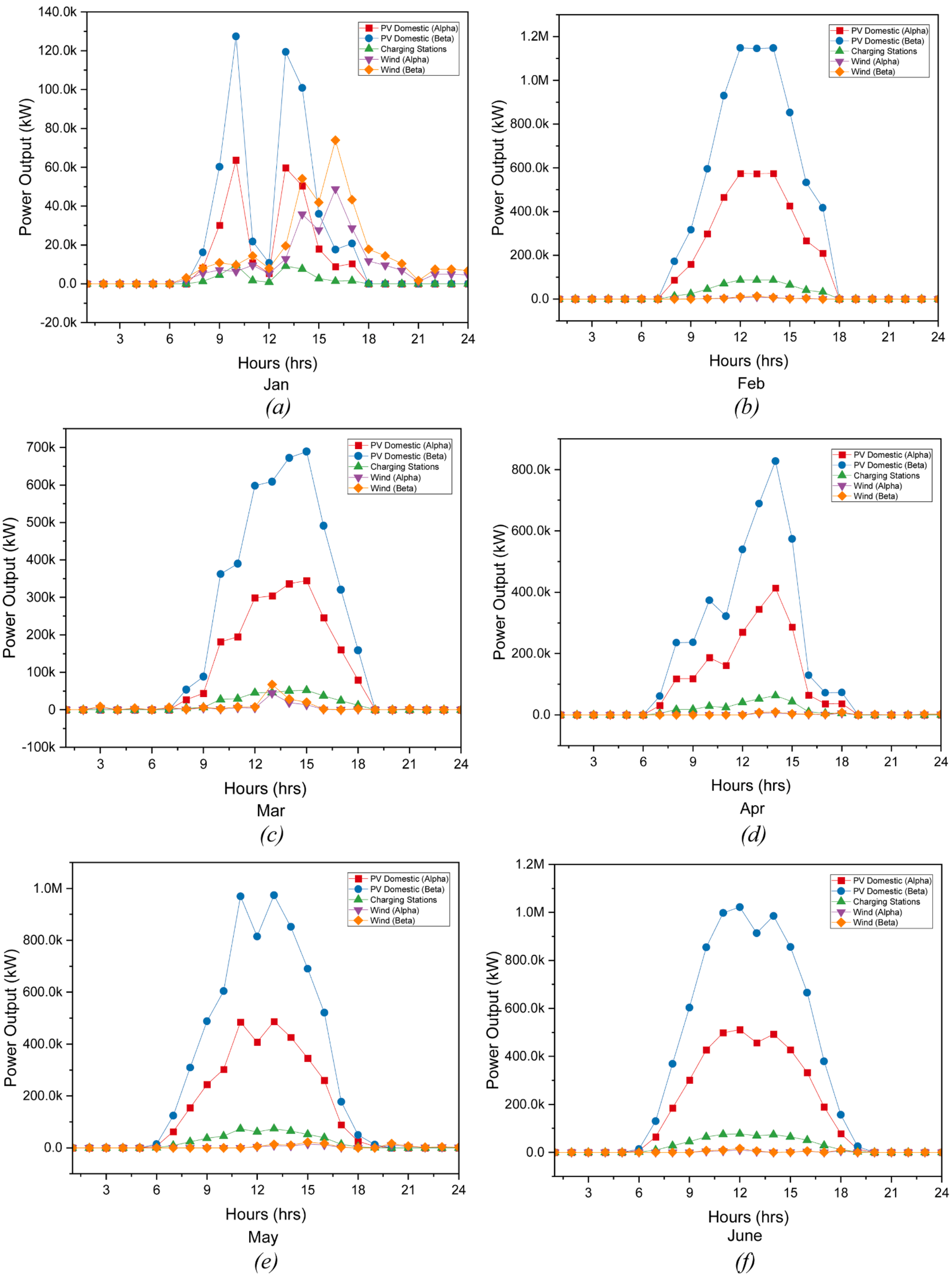


Fig. 6. Temporal variations and contributions of RERs in the alpha and beta cases: Power shares from domestic PV, charging stations, and wind energy (a)-January, (b)-February, (c)-March, (d)-April, (e)-May, and (f)June.

enhancing the overall understanding of the energy production landscape. Table 8 offers a comprehensive analysis of energy production parameters. This includes 1) rated capacities, 2) average power outputs, 3) total production amounts, 4) capacity factors, 5) minimum and maximum outputs, 6) penetration rates, 7) operational hours, and 8) levelized costs for domestic PV, charging stations, wind, and hydropower.

3.5. Energy market dynamics and grid interactions

The evaluation of energy transactions between the Alpha and Beta scenarios over the year offers significant insights into the dynamics of energy buying and selling, as well as the overall energy balance with the grid. In the Alpha Case, the volume of energy procured from the grid fluctuated monthly, ranging from 10,030,700 kWh in January to 8772,462 kWh in December. In contrast, the Beta Case reported no energy purchases from the grid during the entire year, signifying complete self-sufficiency in energy production. For energy sales, the Alpha Case reflected steady selling patterns, with figures varying from 125,239,000 kWh in January to 121,050,000 kWh in December. Meanwhile, the Beta Case maintained a constant energy sales figure of 743,99,000 kWh throughout the year. When it comes to net energy acquired, the Beta

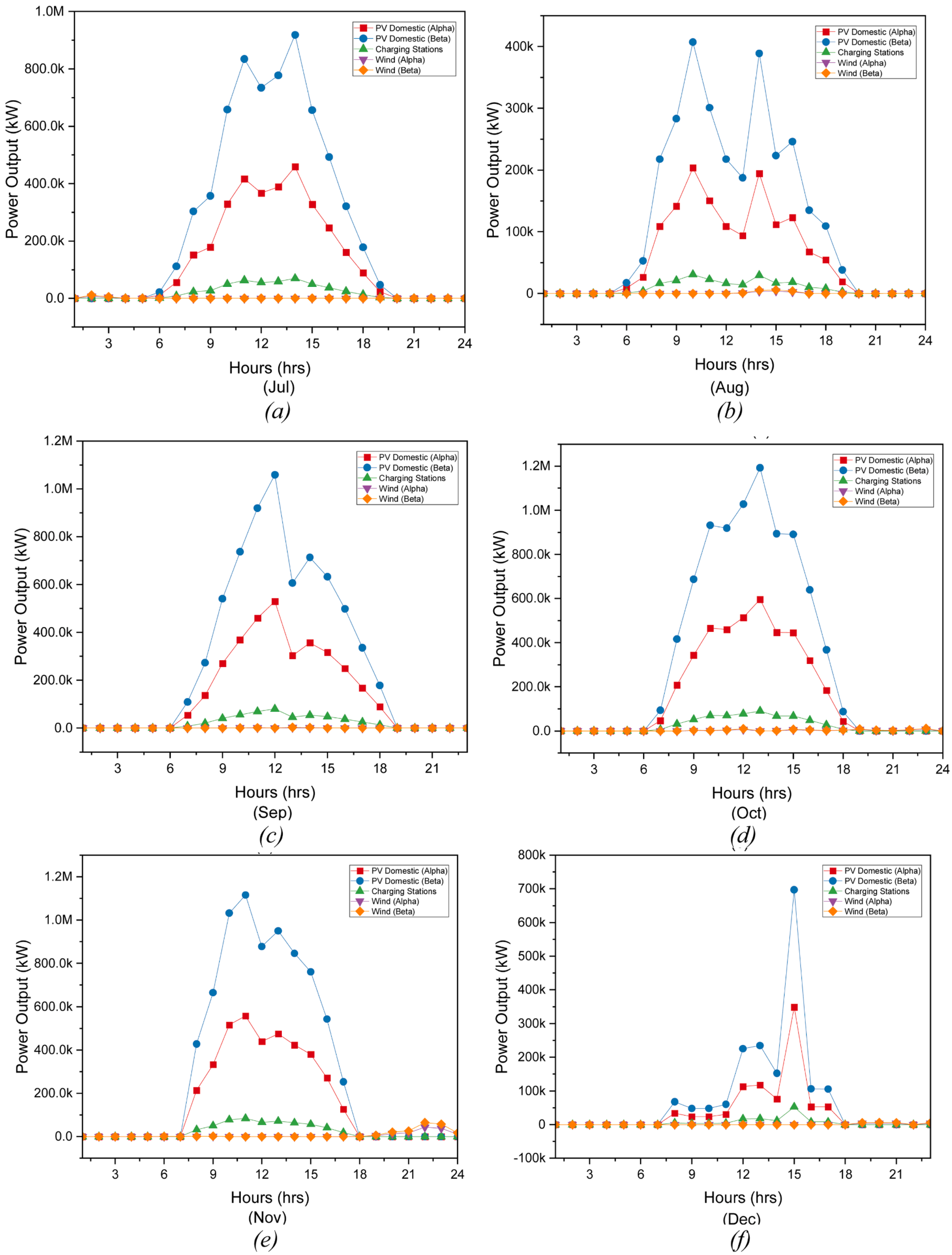


Fig. 7. Temporal variations and contributions of RERs in the alpha and beta cases: Power shares from domestic PV, charging stations, and wind energy (a)-July, (b)-August, (c)-September, (d)-October, (e)-November, and (f)-December.

Case persistently recorded negative values, showcasing excess energy production, whereas the Alpha Case consistently depended on net energy purchases from the grid. These results underscore the energy independence attained in the Beta Case, where the energy generated from renewable sources surpassed consumption, leading to a surplus that was sold back to the grid.

On the other hand, the Alpha Case had a stronger reliance on grid energy to satisfy its needs, highlighting a greater dependence on external energy resources. These findings stress the significance of optimizing renewable energy generation and adopting energy management practices to create a more sustainable and self-sufficient energy system. Refer to Fig. 8 for a detailed summary of energy transactions, encompassing purchases, sales, and the net energy balance between the Alpha and Beta scenarios throughout the year.

Table 7
Comprehensive analysis of energy production parameters: Domestic PV, charging stations, wind, and hydro power (alpha case).

Parameters	Domestic PV	Charging Stations	Wind Production	Hydro Power
Rated Capacity (kW)	661,549	100,000	218,331	4568,000
Mean Power Output (kW)	127,834	19,323	3304	4568,000
Mean Energy Output (kWh/d)	3068,026	463,764	-	-
Capacity Factor (%)	19.3	19.3	1.51	100
Total Production (kWh/yr)	1119,829,407	169,273,842	28,943,489	40,015,680,000
Minimum Output (kW)	0	0	0	4568,000
Maximum Output (kW)	660,601	99,857	165,524	4568,000
Penetration (%)	2.82	0.426	0.0729	101
Hours of Operation (hrs/yr)	4385	4385	3615	8760
Levelized Cost ($)	0.0160	0.0160	0.205	0.00574

Table 8
Comprehensive analysis of energy production parameters: Domestic PV, charging stations, wind, and hydro power (beta case).

Parameters	Domestic PV	Charging Stations	Wind Production	Hydro Power
Rated Capacity (kW)	1323,098	100,000	330,774	11,458,000
Mean Power Output (kW)	255,669	19,323	5006	11,458,000
Mean Energy Output (kWh/d)	6136,052	463,764	-	-
Capacity Factor (%)	19.3	19.3	1.51	100
Total Production (kWh/yr)	1119,829,407	169,273,842	43,853,739	100,372,080,000
Minimum Output (kW)	0	0	0	11,458,000
Maximum Output (kW)	660,601	99,857	250,794	11,458,000
Penetration (%)	2.82	0.426	0.110	253
Hours of Operation (hrs/yr)	4385	4385	3615	8760
Levelized Cost ($)	0.0160	0.0160	0.205	0.00574

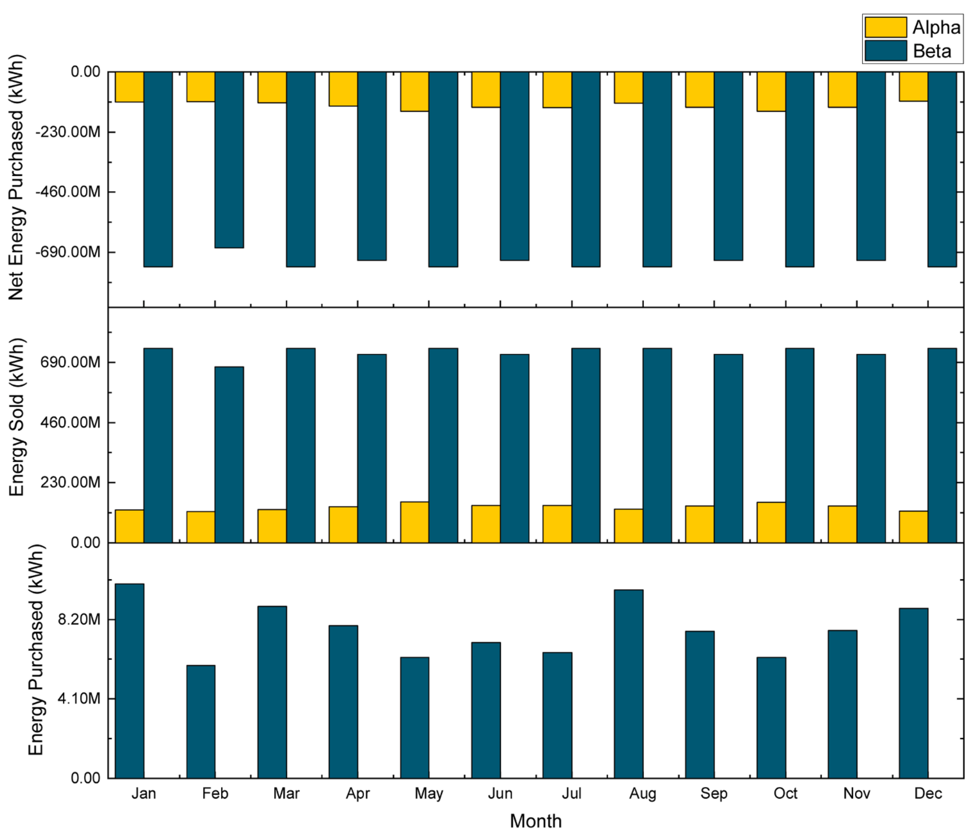


Fig. 8. Energy transactions and net energy balance between alpha and beta cases: Purchases, sales, and net energy balance with the grid throughout the year.

3.6. Environmental implications and comparative analysis of power generation

The analysis of emission data from the Alpha and Beta scenarios highlights notable disparities in the environmental effects of power generation. In the Alpha Case, carbon dioxide emissions totalled 58,329,611 kg annually, making a significant contribution to greenhouse gas emissions. Nevertheless, there were no measurable emissions of carbon monoxide, unburned hydrocarbons, or particulate matter, indicating effective combustion methods and successful measures to reduce air pollution. Sulfur dioxide emissions were recorded at 252,885 kg per year, reflecting a moderate level of sulfur contamination, while nitrogen oxide emissions reached 123,674 kg per year, emphasizing the discharge of these pollutants into the atmosphere. Conversely, the Beta Case showcased an outstanding accomplishment with zero emissions in all pollutant categories, including 1) carbon dioxide, 2) carbon monoxide, 3) unburned hydrocarbons, 4) particulate matter, 5) sulfur dioxide, and 6) nitrogen oxides. These results demonstrate the utilization of advanced emission control technologies and cleaner energy alternatives, resulting in a significant decrease in environmental impact and a stronger commitment to sustainable practices. The juxtaposition of the Alpha and Beta cases highlights the necessity of enforcing strict emission regulations and shifting towards low-carbon and zero-emission energy systems to address climate change and safeguard the environment.

Table 9
Comparative analysis of renewable energy studies.

Aspect	Existing Research [38–46]	Proposed Research
Geographical Focus	Diverse, including Portugal, New Zealand, Ireland, Gilgit-Baltistan (Pakistan), Pakistan, Denmark, a global analysis, and Australia.	Western Kashmir region, focusing on integration with CPEC initiatives.
RE Sources	Varied, including hydro, wind, solar, biomass, and ocean waves.	Emphasis on hydroelectric power (97.6 % of total electric energy), smart grid technologies, PV and wind technologies which are suitable for the region.
Energy System Focus	Mostly focused on electricity production and the transition to RE for electricity.	Broader focus, including energy generation, consumption, and market dynamics within the specific context of western Kashmir and its role in CPEC initiatives.
Key Challenges Addressed	Challenges specific to each region, such as dependency on fossil fuels, grid integration of renewables, and electrification issues.	Specifically addresses the challenges of harnessing and integrating RERs in western Kashmir, in the context of regional political and economic dynamics.
Technological Scope	Varied: from simple renewable integration to complex systems like hybrid energy systems and storage solutions.	Primarily focuses on smart grid technologies as a means to integrate RERs effectively in western Kashmir.
Policy and Stakeholder Relevance	Generally focused on technical solutions with some policy implications.	Directly addresses policy makers and stakeholders, emphasizing the role of western Kashmir in sustainable development, energy independence, and climate change initiatives within the CPEC framework.
Innovation and Uniqueness	Each study presents unique solutions and analyses for specific regional challenges.	Presents a unique case study of western Kashmir's potential in RERs within the broader geopolitical and economic context of the CPEC, highlighting its role in regional energy dynamics. Offers a novel approach by integrating political, economic, and technological aspects.
Outcomes and Implications	Varied, depending on the region and focus of the study. Typically, proposals for increasing REI and suggestions for policy and infrastructure changes.	Provides a detailed and region-specific roadmap for energy independence and sustainable development in western Kashmir, with implications for regional stability and economic growth within the CPEC framework. Emphasizes the opportunity for substantial clean energy production and serves as an example of sustainable energy practices in the area.

3.7. Advancements in RE research: A comparative overview

The proposed research on RE in western Kashmir stands out from existing studies >[38–46] due to its unique regional focus on the geopolitically significant CPEC (Table 9). Unlike other studies that often concentrate on specific renewable sources or technical aspects, this research offers a comprehensive analysis includes 1) energy generation, 2) consumption, and 3) market dynamics, with a particular emphasis on 4) smart grid technologies. This approach not only addresses the technical aspects of energy integration but also aligns closely with policy-making and strategic initiatives. The study's focus is on hydroelectric power, PV, and wind energy and its implications for sustainable development. The study also explores energy independence in western Kashmir positions as a novel and significant contribution to the field. This offers actionable insights for stakeholders and potentially serving as a model for other regions with similar challenges.

4. Conclusion and policy implications

In conclusion, the proposed research provides essential insights into the potential of renewable energy (RE) systems, as demonstrated through an in-depth analysis of the Alpha and Beta cases. The study highlights the prevalence of hydroelectric power in the Alpha Case, which constitutes an impressive 96.6 % of total energy generation. This showcases the significance of utilizing water resources for sustainable energy. Conversely, the Beta Case illustrates self-reliance and a variety of RE applications, with substantial contributions from solar and wind energy.

Moreover, the significance of domestic photovoltaic (PV) installations is emphasized, revealing the potential for a considerable rise in energy share during peak demand times. The examination of wind energy highlights the inherent variability of this resource, indicating the necessity for careful strategizing in energy mix determinations. The levelized cost assessment in the research indicates that RE is competitively favorable, especially in relation to domestic PV and charging infrastructure. Importantly, the substantial energy sales reported by the Beta Case highlight the prospects for energy autonomy and the complexities of grid interactions. The study also focuses on the environmental effects of various energy systems. The Beta Case's achievement of zero emissions across all pollutant categories underscores the ecological advantages of clean energy sources and innovative emission control technologies.

In summary, the findings provide compelling evidence for the viability and effectiveness of RE systems in the western Kashmir region. These insights can be utilized by policymakers, energy planners, and stakeholders to foster RE adoption, formulate effective energy strategies, and contribute to mitigating climate change within the CPEC framework. Achieving this requires an integrative approach involving diverse renewable resources, optimization of resource utilization, and efficient energy management strategies.

CRediT authorship contribution statement

Anis Ur Rehman: Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ishaq G. Muhammad Alblushi:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Formal analysis, Data curation. **Haris M. Khalid:** Writing – original draft, Supervision, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Zafar Said:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Abdulla Ismail:** Writing – review & editing, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **S.M. Muyeen:** . **Hakan F. Oztop:** Writing – review & editing, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Almoataz Y. Abdelaziz:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

The authors declare that there are no following financial interests/ personal relationships which may be considered as potential competing interests.

Funding statement

There is no funding body for this work.

Additional information

No additional information is available for this paper.

Data availability

Data will be made available on request.

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