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Green energy systems for powering electric vehicles considering telecommunication system with case study of Pakistan

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Abstract. The objective is to analyze the sustainability and efficiency of Pakistan's telecommunication sector by developing a framework for base transceiver stations integrating renewable energy and charging stations. Various renewable energy sources such as solar, wind, biomass and hydropower were considered as the object of research. The following methodological steps were implemented in this work: site analysis; determination of optimal sizing of plants, energy storage systems and electric vehicle charging stations; cost-benefit analysis methods; greenhouse gas emissions estimation; and system design methods for integrating selected renewable energy sources and energy storage solutions, taking into account the operational requirements of the base transceiver stations. It is found that switching to hybrid renewable energy systems can significantly reduce dependence on diesel generators. It is shown that operating costs can be reduced by more than 80% compared to conventional diesel-fueled systems. Also, the introduction of hybrid renewable energy sources can lead to significant reductions in CO_2 emissions. The integration of battery storage systems has been shown to improve the reliability of energy supply by ensuring uninterrupted operation during periods of high demand and blackouts. The proposed structure scheme for base transceiver stations is designed to accommodate future growth in the share of electric vehicles and technological advancements in renewable energy and electric vehicle charging. By prioritizing the integration of renewable technologies along with charging station infrastructure, telecom service providers in Pakistan can reduce their carbon footprint and operational costs. This approach not only addresses the unpredictability of the electricity grid, especially in rural areas, but also positions the telecoms sector as an active participant in global efforts to combat climate change.

Keywords: electric vehicle charging stations, base transceiver stations, battery storage system, technical, economic and environmental assessment, renewable framework

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ЭНЕРГЕТИКА

Научная статья
УДК 621.31

Зелёные энергетические системы для электромобилей с учётом телекоммуникационной системы на примере Пакистана

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Резюме. Цель – анализ устойчивости и эффективности телекоммуникационного сектора Пакистана путем разработки структуры для базовых приемопередающих станций, объединяющих возобновляемые источники энергии и зарядные станции. В качестве объекта исследований рассматривались различные возобновляемые источники энергии, такие как солнце, ветер, биомасса и гидроэнергия. В работе реализованы следующие методологические этапы: анализ местности; определение оптимальных размеров установок, систем накопителей энергии и станций зарядки электромобилей; методы анализа затрат и выгод; оценка выбросов парниковых газов; методы проектирования системы для интеграции выбранных возобновляемых источников энергии и решений по хранению энергии с учетом эксплуатационных требований базовых приемопередающих станций. Установлено, что переход на гибридные системы возобновляемой энергии может значительно снизить зависимость от дизельных генераторов. Показано, что эксплуатационные расходы могут быть снижены более чем на 80% по сравнению с традиционными системами, работающими на дизельном топливе. Также внедрение гибридных возобновляемых источников энергии может привести к значительному сокращению выбросов CO_2. Показано,

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что интеграция систем хранения аккумуляторов повышает надежность энергоснабжения, обеспечивая бесперебойную работу в периоды высокого спроса и отключения электроэнергии. Предложенная схема структуры для базовых приемопередающих станций разработана с учетом будущего роста доли электротранспорта и технологических достижений в области возобновляемых источников энергии и зарядки электромобилей. Отдавая предпочтение интеграции возобновляемых технологий наряду с инфраструктурой зарядных станций, поставщики телекоммуникационных услуг в Пакистане могут сократить углеродный след и эксплуатационные расходы. Такой подход не только решает проблемы, связанные с непредсказуемостью электросетей, особенно в сельских регионах, но и позиционирует телекоммуникационный сектор как активного участника глобальных усилий по борьбе с изменением климата.

Ключевые слова: зарядные станции электромобилей, базовые приемопередатчики, накопители энергии, технико-экономическая и экологическая оценка, возобновляемые источники энергии

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INTRODUCTION

A key element of economic growth and development is electricity. Consequently, a nation's ability to use energy is a must for its development. The telecom industry needs electricity to deliver reliable services to potential customers. The significant increase in the use of wireless communication networks in recent years is supported by a number of indicators, including the COVID-19 pandemic. Since many businesses and organizations now want their employees to work from home or finish their coursework online, wireless communication is more crucial than ever in the modern world. Man-made greenhouse gas emissions need to be decreased in light of the growing body of evidence demonstrating the effects of climate change on a global scale [1].

Cellular network operators must construct more telecommunication towers to meet the growing demand for telecom services in order to improve transmission and provide extensive coverage [2]. In rural areas with unpredictable grid electricity, telecom companies have challenges. Diesel generators (DG) are required when demand is high, increasing CO_2 (GHG) emissions and exacerbating the effects of global warming. Renewable energy sources like solar, wind, biomass, hydro, and tidal are essential for driving telecom towers [2]. Diesel oil accounts for over 80% of energy costs for off-grid tower locations, making it the main expense. Effective design, upkeep, and technical development are crucial for the highest return on investment, accounting for factors such as emissions, energy efficiency, and operational scenarios [3].

Two tactics to assist reduce global warming include promoting energy-efficient devices and raising consciousness of the consequence of reducing power consumption in hometowns and the telecom industry. Numerous scholars are trying to find solutions to these problems in different ways. Promoting renewable energy resources is the most reliable, cost-effective, environmentally pleasant, and well-liked alternate strategy. In an attempt to improve long-term energy supply systems, a lot of emphasis has been paid to the development of different renewable energy sources. Hybrid renewable energy sources (HRES) are dependable, carbon dioxide-free systems that successfully lessen dependency on a single renewable resource in areas with limited natural resources [4]. Integrating renewable energy sources is an emission-free method of producing energy that supports a district's geography and functions as a dependable prospective energy source for remote generating applications, claim [5, 6]. Large-scale wind, solar, and residential PV installations are all comprised in the renewable energy capacity shown. The production collects extra power from the grid throughout the day and releases it at night since most residential PV systems are on-grid systems. HRES can be operated individually for each household or in microgrids (MGs), that link many homes to create a power grid, in remote areas wherever grid extension is not practical [7–9]. The recent literature is shown in Table 1.

Interest in HRES has increased as a result of the fast-increasing demand for energy, environmental concerns, the depletion of fossil resources, fluctuating energy prices, and the need to power off-grid equipment. However, cultural, economic, environmental, and technical factors need to be taken

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Table 1. Recent works on technical, economic and environmental assessment
Таблица 1. Последние работы по технико-экономической и экологической оценке

No.	Location	BTS sites	Method	Technical characteristic components					Objective functions and explicitly considered variables				Load type
				PV	WE	DG	EV	BA	LCOE	IRR	ROI	SA	
1	Australia [10]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✘	✔	IL
2	Cameroon [11]	✘	HOMER	✔	✔	✔	✘	✘	✔	✔	✘	✘	DOMS
3	Iran [12]	✘	IGOA	✔	✔	✘	✘	✔	✔	✘	✘	✔	COM
4	India [13]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✘	✔	DOM
5	Nigeriya [14]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✘	✔	DOM
6	India [15]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✘	✔	AGR
7	India [16]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✘	✔	RSD
8	Pakistan [17]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✘	✔	COM
9	Bangladesh [18]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✘	✔	RSD
10	India [19]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✘	✔	RSD
11	Tunisia [20]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✘	✔	COM
12	Saudi Arabia [21]	✘	HS, PSO	✔	✔	✔	✘	✔	✔	✔	✘	✔	DOM
13	Egypt [22]	✘	HOMER	✔	✔	✘	✘	✘	✔	✘	✘	✘	COM
14	India [23]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✘	✔	COM
15	China [24]	✘	HOMER	✘	✔	✔	✘	✔	✔	✔	✔	✔	IND
16	Thailand [25]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	IL
17	Iraq [26]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✔	✔	RSD
18	Europe [27]	✘	GA, PSO	✔	✔	✘	✘	✔	✔	✘	✘	✔	DOM
19	Africa [28]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	DOM
20	India [29]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✔	✔	DOM
21	South Korea [30]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	COM
22	Saudi Arabia [31]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	IND
23	China [32]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✔	✔	IL
24	India [33]	✘	GA, PSO	✔	✔	✔	✘	✔	✔	✔	✘	✔	AGR
25	Pakistan [34]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✔	✔	DOM
26	Turkey [35]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	RSD
27	Saudi Arabia [36]	✘	HOMER	✔	✔	✘	✘	✘	✔	✘	✔	✘	COM
28	Bangladesh [37]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	DOM
29	Northeast India [38]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	DOM
30	South Korea [39]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	COM
31	Southern Turkey [40]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	RSD
32	Saudi Arabia [41]	✘	HOMER	✔	✔	✘	✘	✔	✔	✘	✔	✔	DOM
33	Pakistan [42]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✔	✔	AGR
34	India [43]	✘	HOMER	✔	✘	✘	✘	✘	✘	✘	✘	✘	DOM
35	Namibia [44]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	RSD
36	East Malaysia [45]	✘	HOMER	✔	✘	✘	✘	✔	✘	✘	✔	✔	DOM
37	Colombia [46]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	DOM
38	Yamen [47]	✘	HOMER	✔	✔	✔	✘	✘	✔	✔	✔	✘	DOM
39	Malaysia [48]	✘	HOMER	✔	✘	✔	✘	✔	✘	✔	✔	✔	DOM
40	Iran [49]	✘	HOMER	✔	✔	✔	✘	✔	✔	✔	✔	✔	IND
41	Chile [50]	✘	HOMER	✘	✔	✘	✘	✘	✔	✘	✔	✘	RSD
42	Saudi Arabia [51]	✘	PSO	✔	✔	✘	✘	✔	✔	✘	✘	✔	DOM
43	Australia [52]	✘	PSO	✔	✔	✘	✘	✘	✔	✘	✘	✘	DOM
44	**Proposed Study (Pakistan)**	✔	**HOMER**	✔	✔	✔	✔	✔	✔	✔	✔	✔	**TELEC**

Note: **SA** – Sensitivity analysis, **PV** – Photo-voltaic, **DG** – Diesel generator, **EV** – Electric vehicle charging station, **IRR** – Internal rate of return, **IL** – Island load, **DOM** – Domestic, **COM** – Commercial, **AGR** – Agricultural, **RSD** – Residential, **IND** – Industrial; **TELEC** – Telecom base transceiver station (BTS) load, **WE** – Wind energy, **BA** – Battery, **LCOE** – Levelized cost of energy.

into account for an HRES design to be really sustainable. Creating a successful HRES dispatch plan also requires comparing various dispatch strategies in terms of technological, economical, ecological, and social concerns. In addition to reducing stakeholder costs associated with managing load demand, this initiative seeks to improve social standing and reduce environmental degradation. The authors were motivated to conduct additional study and write a paper on the topic by the hybrid renewable energy system's integrated techno-economic-environmental-socio-technical design with an appropriate dispatch strategy for telecommunication demands. The techno-economic-environmental analysis of integrating renewable resources (solar, wind, biomass, and hydro) with electric vehicle charging stations and battery storage systems with base transceiver stations in Pakistan's telecom industry forms the basis of this proposed study's detailed review.

OVERVIEW OF ASSESSMENT METHOD

The details assessment method is explained below.

Step 1: Optimal sizing of HRES system:

– design components of proposed hybrid BTS system;

– simulation computer tools required to optimize renewable resources.

Step 2: Results and Discussion:

– optimization outcomes of standalone and On-Grid EV's based hybrid BTS sites;

– optimal renewable resources and energy storage to optimized HRE Plants.

Step 3: Conclusion.

OPTIMZAL SIZING OF HRES SYSTEM

Some of the ideal size issues linked with HRES systems include approximating the system parmeters and components with the highest capacity while also taking feasibility and reliability restrictions into consideration. It is observed that this research is predicated on the implementation of HRES grids and only optimal generating and storage unit sizing is taken into account through the use of optimization techniques [53, 54]. In this scenario, governments often plan and build HRES networks. As a result, the distribution of grid installation on HRES systems is not sufficiently well-documented for cost analysis. Additionally, producing and storage facilities are usually located near rural regions, therefore the HRES grid is far less expensive than traditional power networks [55].

Design components of proposed hybrid BTS system. In this proposed study, multiple cites of BTS are taken from all over the Pakistan including north, south and central region. Therefore, the existing BTS have only diesel generator and battery bank. While the proposed BTS have renewable resources (wind, solar, biomass and hydro) with electric vehicle charging stations and battery storage system. The comparison of components of existing and proposed BTS sites are shown in Table 2. The existing and proposed BTS infrastructure is shown in Fig. 1.

The detail components of HBTS system are shown in Fig. 2. The advantages and disadvantages of renewable resources are shown in Table 3.

Simulation computer tools required to optimize renewable resources. The challenges confronting the energy industry are complex and interrelated. Energy modeling methods help solve problems in the energy business. Many tools with a wide variety of uses, ranges, and scopes are available. The correct tool can accomplish the intended energy aims, even though no energy tool can address every problem facing the sector. A mechanism that may combine all renewable resources in a more long-term way and have techno-economic-environmental analysis at least at the national level was required for this research project. The specific features of a number of tools are listed below in Table 4.

Table 2. Comparison of existing and proposed BTS system components
Таблица 2. Сравнение компонентов существующей и предлагаемой системы BTS

	Diesel generator	Battery storage system	On-grid	Solar	Wind	Biomass	Hydro	EV charging station
Existing System	✔	✔	✘	✘	✘	✘	✘	✘
Proposed System	✔	✔	✔	✔	✔	✔	✔	✔

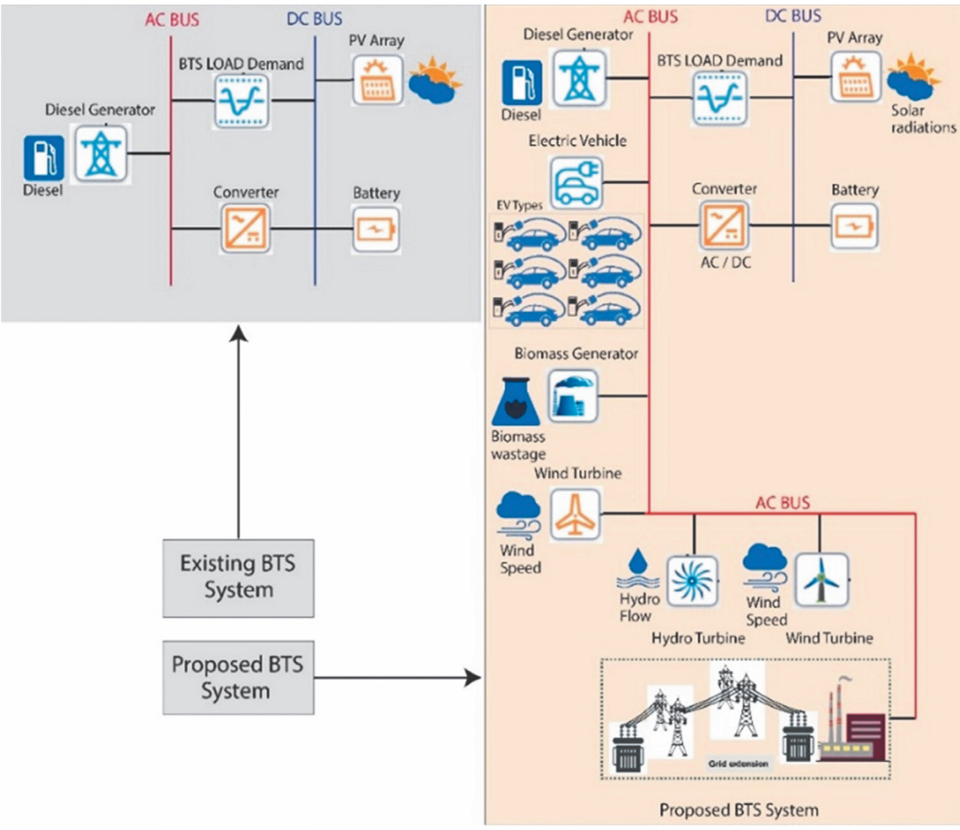

Fig. 1. *Proposed BTS system infrastructure*
Рис. 1. *Инфраструктура предлагаемой системы BTS*

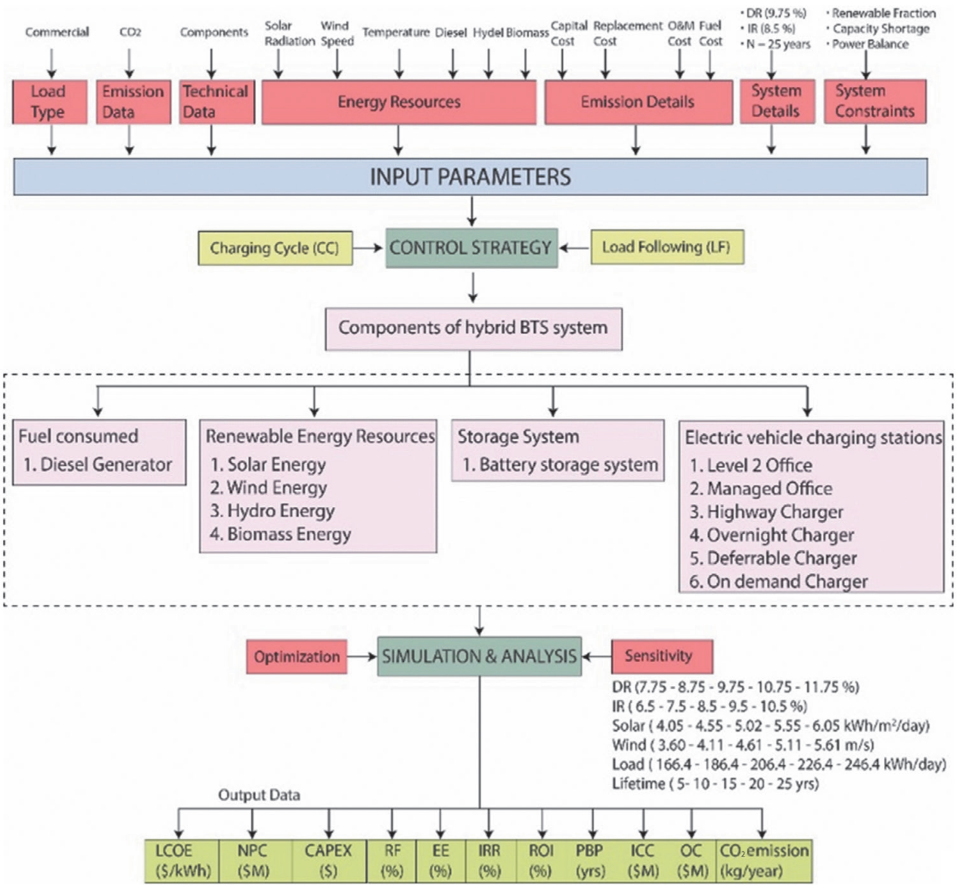

Fig. 2. *Proposed HBTS system components*
Рис. 2. *Компоненты предлагаемой системы HBTS*

Table 3. Advantages and disadvantages of renewable resources
Таблица 3. Преимущества и недостатки возобновляемых ресурсов

Renewable energy sources	Global share	Advantages	Disadvantages	Top countries
Solar Energy [56, 57]	24.70%	• Economical • Low maintenance • Longer life • Easy installation • Technical maturity	• Larger land acquisition • Toxic material deposition • Relative lower efficiency • High initial costs • Intermittent • Susceptible to storms	• Japan • China • Germany • United States
Wind Energy [58, 59]	25.26%	• High efficiency • Greater technical maturity • Easy installation over land and water • Lower environmental impact • Reduce dependency on fossil fuels • Minimal water usage	• Larger land acquisition • Intermittency and reliability issues • High initial costs • Noise and visual impact • Wildlife impact • Difficult to transport	• United States • China • India • Germany
Biomass Energy [56, 57]	9–10%	• Reliable and Sustainable • Versatile Energy source • Sustenance rural economies • Less dependency on fossil fuels • Compatible with existing infrastructure • Higher efficiency • Reduction of waste material	• Carbon emissions • Deforestation and habitat use • Land and water resource use • Lower energy density • Air pollution • High cost for large scale production • Seasonal availability and storage	• United States • China • Brazil • Germany • India • Sweden • Finland
Hydro Energy[3] [60]	44.47%	• Renewable and reliable • Low greenhouse gas emission • High energy efficiency • Flexible and adjustable power • Supports water management and irrigation • Long lifespan • Low operating costs	• Flood and erosion • Displacement of communities • High initial costs • Risk of drought and water dependency • Lon construction time • Potential for methane emission	• China • Brazil • Canada • United States • Russia • India • Norway

Table 4. A detailed overview of simulation tools to optimize renewable resources use
Таблица 4. Подробный обзор инструментов моделирования, используемых для оптимизации использования возобновляемых ресурсов

Tool name	Developer	Time-step	Analysis type	Accessibility
AEOLIUS	Karlrsuhe	Minutes	Simulation only	Commercial
Balmorel	Individual	Hourly	Simulation, Balancing & Optimization	Free
CREST	NREL	Hourly	Optimization only	Free
DER-CAM	Micro grid team, Berkeley lab	Hourly	Optimization & Balancing	Free
EnergyPLAN	Aalborg University, Denmark	Minutes	Simulation only	Commercial
E4cast	ABARE	Yearly	Optimization & Balancing	Commercial
ENPEP	National Laboratory, USA	Yearly	Balancing only	Free
EVST	NREL	Hourly	Simulation & Optimization	Paid
EMPS	SITEF	Weekly	Simulation & Optimization	Commercial
Gatecycle	GE	Hourly	Simulation Only	Paid
GridLAB-D	PNNL	Seconds	Simulation only	Free
HOMER	NREL	Hourly	Simulation & Optimization	Free + Paid
Helioscope	Folsom Labs	Minutes	Simulation & Balancing	Paid
INFORSE	Europe Secretariat	Yearly	Balancing & Optimization	Paid

[3]Electricity from renewable resources: status, prospects, and impediments // Internet Archive. Available from: https://archive.org/details/electricityfromr0000nati/page/n7/mode/2up [Accessed 30th September 2023].

Продолжение табл. 4

IKARUS	Institute of Energy Research	Yearly	Optimization only	Commercial + Free
Invert	EEG	Yearly	Simulation & Optimization	Free
Kom Mod	Fraunhofer IES	Hourly	Simulation only	Unknown
LEAP	Stockholm Institute	Monthly & Daily	Simulation & Optimization	Paid
MESSAGE	IIASA	5 years	Optimization & Balancing	Free
Mesap PlaNet	IER	Any	Simulation & Optimization	Commercial
NEMS	EIA	Weekly	Balancing only	Free
PVWatts	NREL	Hourly	Simulation only	Free
PVsyst	PVsyst SA	Minutes	Simulation only	Free
PERSEUS	Karlsruhe University	Typical days	Simulation & Balancing	Free + Paid
ProdRisk	SINTEF	Hourly	Simulation & Optimization	Commercial
RETScreen	CEDRL	Hourly	Simulation & Balancing	Free
REopt	NREL	Hourly	Simulation & Optimization	Free
ReEDS	NREL	Yearly	Simulation only	Free
SAM	NREL	Hourly	Simulation & Optimization	Free + Paid
SimREN	iSUSI	Minutes	Simulation only	Paid
WASP	IAEA	Yearly	Simulation & Optimization	Commercial + Free
Windographer	AWS true power	Hourly	Simulation & Optimization	Paid
Windpro	EMD international	Hourly	Simulation & Optimization	Paid

RESULT & DISCUSSION

In this section, result and discussion of proposed study is described. This section is separated into two sessions, one is "Optimization outcomes of Standalone and On-Grid EV's Based Hybrid BTS Sites" and second is "Optimal renewable resources and energy storage to optimized HRE Plants".

Optimization outcomes of Standalone and On-Grid EV-based Hybrid BTS Sites. It can be seen that, in this planned study, the 42 BTS sites from all over Pakistan is selected. It is evident that all objective functions (LCOE, ICC, NPC, and OC) and financial parameters (IRR, ROI, and PBP) are fulfilled following the combination of renewable resources (solar, biomass, hydro, and wind energy) with battery bank. The optimized output of standalone hybrid BTS sites are shown in Table 5.

The objective and financial parameters achieved by On-Grid EV's based hybrid BTS sites are revealed in Table 6. It can be seen that after integrating different types of electric vehicle charging stations and renewable resources (wind and solar) with battery storage system and grid, all objective and financial parameters are achieved.

Table 5. Optimized output parameters of standalone hybrid BTS sites
Таблица 5. Оптимизированные выходные параметры автономных гибридных BTS площадок

BTS site names	Objective parameters				Financial parameters			Renewable resources and storage system					On-grid and EV charging stations	
	LCOE	ICC	OPC	NPC	IRR	ROI	PBP	PV	Wind	Biomass	Hydro	Battery	On-Grid	EV's
Chakwal	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Islamabad	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Jhelum	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Rawalpindi	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Talagang	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Taxila	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Bajaur	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Dir	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Mardan	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Chitral	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✔	✘	✘
Swat	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘

Продолжение табл. 5

Kohat	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Nowshera	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Buner	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Peshawar	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Abbottabad	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Kohistan	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Mansehra	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Gilgit	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Mingora	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Malakand	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Kamri	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✘	✘
Mirpur	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✘	✔	✘	✘
Muzaffarabad	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✘	✔	✘	✘
Lahore	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Sheikhupura	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Bhakkar	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Khushab	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Mianwali	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
DG Khan	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Layyah	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘	✘
Karachi-I	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✘	✘
Karachi-II	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✘	✘
Badin	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✘	✘
Hyderabad	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✘	✘
Mirpur Khas	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Ghotki	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Rajan Pur	✔	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✔	✘	✘
RahimYar Khan	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Sukkur	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Gawadar	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘
Quetta	✔	✔	✔	✔	✔	✔	✔	✔	✘	✘	✘	✔	✘	✘

Table 6. Objective and financial parameters of On-grid EV-based hybrid BTS sites
Таблица 6. Объективные и финансовые параметры гибридных BTS площадок на базе On-grid EV

BTS site names	Objective parameters				Financial parameters			On-grid and EV charging stations				
	LCOE	ICC	OPC	NPC	IRR	ROI	PBP	PV	Wind	Battery	On-Grid	EV's
Islamabad	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Jhelum	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Bajaur	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Kohat	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Peshawar	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Abbottabad	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Mingora	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Muzaffarabad	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Lahore	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Mianwali	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Karachi-I	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Badin	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Hyderabad	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Rajan Pur	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔
Quetta	✔	✔	✔	✔	✔	✔	✔	✔	✘	✔	✔	✔

Optimal renewable resources and energy storage to optimized HRE Plants. In addition to computer software, authors have produced a number of novel models to address situations in which computer tools are not relevant. These models include a variety of commonly reviewed algorithms, such as GA, MCA, PSO, FL, or a combination of these approaches. Table 7 provides a summary of all the research based on these mathematical techniques. The advantages of these cutting-edge techniques are not thoroughly discussed in this article because it concentrated more on the computer tools method.

In conclusion, different techno-economic [64] assessment methods are needed for HRES at the national, regional, and building scales since analytical criteria and concerns vary from scale to scale. Therefore, this paper suggests a framework for the HRES techno-economic analysis shown in Fig. 3, based on scale characteristics and research emphases. The following is an explanation of some promising approaches along with the associated inputs and outputs. The analysis takes a more macroscopic approach when examining systems at the national or international level. For example, it focuses more on whether the associated emissions and technology can meet the needs of national development, but it aims for less cost-effective outcomes. Because money is not a major issue for a nation when compared to a local location. Rather, socioeconomic viability is gathered as a crucial metric. Therefore, it is important to consider conditions such as LCOE, import/export policies, carbon taxes, and incentive programs beforehand. Furthermore, the most important technological restricting elements to be taken into account are the availability of resources (such as acquisition difficulty) and the possibility for RE use.

In this paradigm, regional systems are separated into two groups: those in state, federal, government property, cities, and industry, and those in remote, domestic, or island locations. The former is incorporated into the framework at the national level because they still have substantial territories. However, as they are all part of stand-alone systems, the latter always employ techniques and technologies similar to those used by building systems. A few factors should receive extra attention since techno-economic analysis for HRES in buildings requires solid and comprehensive system designing, in contrast to systems. First, it is crucial to research the weather because the available renewable resources are always changing. The installation specifications of certain components,

Table 7. A detailed description of technical and economic studies with developed models/algorithms
Таблица 7. Подробное описание технико-экономических исследований с разработанными моделями/алгоритмами

Location	Selected renewable sources	Proposed approach	Selected algorithms	Objective functions	Ref.
Germany	Solar & Hydro	REMoD-D	Mathematical numeric optimizer	Annual cost	[61]
Ontario	Solar, Wind, Hydro, Hydrogen & Biomass	Silver model	Linear optimization	Total generated cost	[62]
Japan	Solar & Wind	Top-down	–	–	[63]
Agricultural	Solar & Biogas	Homan method [65]	Net present value method	NPV	[65]
Public building	Solar	–	MATLAB Algorithm	Life cycle cost	[66]
City	Solar & Wind	Computer program	–	Total cost	[67]
India	Solar, Wind, Hydro, Biomass and Hydrogen	Multi-node	–	Total cost	[68]
Residential	Solar, Wind & Hydrogen	Optimization model	GA & PSO	Total cost	[69]
New Zealand	Geothermal, Wind, Hydro & Biomass	Analytical approach	–	Energy Spillage	[70]
City	Solar & Battery	–	Differential evolution	LCOE & LCC	[71]
Commercial	Solar, Wind & Battery	–	Firefly inspired	COE	[72]
Industrial	Solar, Wind & Battery	–	Multi-objective grey wolf	COE	[73]
Australia	Solar, Wind, Hydro, Biomass & Geothermal	Computer program	–	Energy consumption	[74]

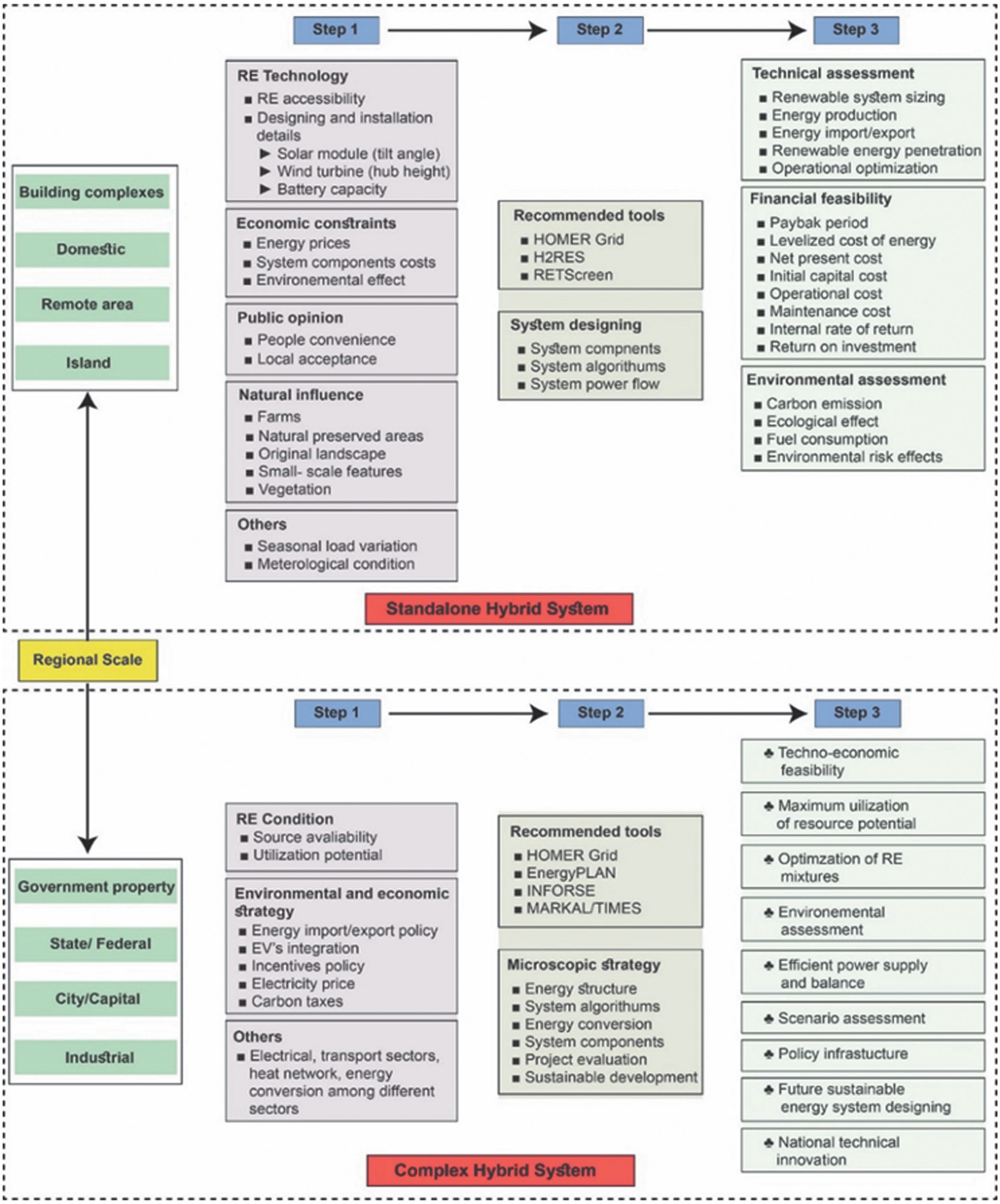

Fig. 3. *Proposed framework for a standalone system and a complex hybrid system*
Рис. 3. *Предлагаемая структура для автономной и сложной гибридной систем*

such as the number and slope angle of PV, the number and hub height of WT, the options for battery capacity, etc., are also crucial considerations.

Second, the primary financial limitations are the costs of system equipment and local energy prices. Thirdly, natural influence should be taken into account when installing RE projects. This means that original structures such as farms, plants, landscapes, natural conserved areas, or small-scale elements (for islands) shouldn't be destroyed.

Furthermore, the foundation of RE projects is local support and public acceptance. Another important consideration is the target people's comfort and convenience, as designed systems are meant to serve them. In particular, while creating systems for resorts, the original landscape and tourism development should not be compromised. Not to be overlooked is the seasonal load change brought on by the tourist peak. One can choose the points that meet the specific analysis and determine the aforementioned spatial scale requirements before beginning to examine a system. The most suggested tools, HOMER, RETScreen, and H2RES, can then be used to acquire detailed output results that include economic, technical, and environmental performance. Generally speaking, this architecture consists of three processes for systems, whether they are large-scale or standalone. First, the key characteristics and needs of a certain system type and spatial scale are noted. The best models or tools are then recommended. The techno-economic evaluation may finally be carried out in its entirety thanks to the encouraging simulation findings and outputs that were offered in the framework's last step. The suggested tools can effectively support HRES on their respective scales within this framework [75].

Through scenario analysis, energy balance, system configuration optimization, relevant indicator calculation, etc., they are utilized to solve techno-economic assessment problems in an efficient manner. Numerous applications mentioned in this study and on these six tools' official website demonstrated their exceptional capacity to direct practices. Therefore, the suggested framework is successfully validated using the aforementioned workable tools in addition to the real inputs taking into account the numerous limiting considerations mentioned at the outset. In addition to helping system designers understand potential carelessness and other factors that should be taken into account when developing diverse energy systems, it can offer a very efficient means of doing future research in the field of HRES techno-economic analysis at various spatial levels.

CONCLUSION

Growing demand for power Providing consistent electricity to connected loads is becoming more challenging due to the sporadic nature of individual renewable resources. The intermittent nature of HRES may be addressed by an efficacious and enduring energy storage system, which lowers maintenance costs and, consequently, the overall operating expenses of the system. However, when paired with storage bank system, hybridization can help mitigate the sporadic nature of HRES. Flywheels, compressed air energy storage, hydrogen fuel cells, super capacitors, super conducting magnetic energy storage, pumped hydro energy storage, and battery storage systems are some of the energy storage options offered by HRES. Compared to a battery and other storage systems, the integrated system delivers improved round-trip efficiency, increased reliability of the power supply, reduced revenue losses, cost savings, a low investment cost, maximum accessible energy, a longer lifespan, and less greenhouse gas emissions. According to earlier research, two of the most useful HRES storage options are freshwater resources.

The following ideas have been put up to conquer the previously described confrontation to the ideal sizing of HRES acceptance with ESS combination:

- The present state of HRES technology, when combined with ESS, may cover several problems with the earlier technology, such as capacity, competence, and dependability. The extent to which this innovation will be further developed for upcoming usage in MG technology has been selected. Energy sizing, cost, safety, and efficacious management are becoming the attention of study.
- For the components of the HRES and ESS systems to scale adequately, intelligent procedures (meta-heuristic approaches) must be collective used with the right control settings, or more efficacious methods must be established. It might be argued that the hybrid GWOPSO optimization approaches are the finest at accomplishing the objective of an ESS in combination with a reliable, cost-effective, and ecologically friendly HRES.
- HRES needs an ESS that associates the features of a high-power and energy storage system in order to decrease power quality problems and improve system stability and reliability. High-energy ESS devices react more slowly and have a longer lifespan, whereas high-pow-

er devices assistance temporarily from rapid reactions at high rates. Combining both of these ESS types could result in improved power quality with connected loads.

According to many study results, FITs for loads in grid-connected HRES must be achieved by supplying excess energy to the grid. Consequently, a greater proportion of HRES currently use renewable sources. In order to lower power costs and generate revenue for the municipal, the FIT enables users to sell their excess energy to the grid. To optimize component size based on emission, reliability, and economic functions, new software tools and meta-heuristic optimization methodologies are required. Meta-heuristic optimization methods work better for scaling HRES. However, current software tools, including the HOMER software, are incompetent to address multi-objective problems. It is also difficult to deploy demand-side management response systems using this software. After that, software may be used, allowing designers to more freely size HRES systems.

The summary of prospective research projects of techno-economic evaluation in HRES for all spatial scales based on the gaps and current research progress is explained below:

- Setting a maximum limit for the share of possible RE is crucial to preventing excess energy output during the integration of RE sources into a system. Currently, there are a few indicators that quantify this limit, but the most of them were created for EnergyPLAN software assessments. One goal to be accomplished in the future is to define more types of measurement indexes that apply to various tools.
- At the moment, self-built analysis models and programs are highly independent but insufficiently flexible. Usually, authors who are in their own region at comparable spatial scales invent them first, then use them. To build on their advantages and increase their adaptability, these various models and programs can be integrated and used in various case studies in subsequent projects.
- Develop a set of comprehensive assessment metrics suitable for HRES at all sizes, from building to global. Create an integrated techno-economic evaluation system or HRES model for all scales to improve assessment's efficiency and convenience.

References

1. Abdulmula A.M.O., Sopian K.B., Kazlizan A., Lim Chin Haw. Performance evaluation of standalone double axis solar tracking system with maximum light detection MLD for telecommunication towers in Malaysia. *International Journal of Power Electronics and Drive Systems*. 2019;10(1):444-453. https://doi.org/10.11591/ijpeds.v10n1.pp444-453.
2. Amutha W.M., Andrew H.C., Shajie A.D., Paulraj J.P.I. Renewable power interface based rural telecom. *International Journal of Power Electronics and Drive System*. 2019.10(2):917-927. https://doi.org/10.11591/ijpeds.v10.i2.pp917-927.
3. Oviroh P.O., Jen Tien-Chien. The energy cost analysis of hybrid systems and diesel generators in powering selected base transceiver station locations in Nigeria. *Energies*. 2018;11(3):687. https://doi.org/10.3390/en11030687.
4. Zebra E.I.C., Windt H.J., Nhumaio G., Faaij A.P.C. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*. 2021;144:111036. https://doi.org/10.1016/j.rser.2021.111036.
5. Semaoui S., Arab A.H., Bacha S., Azoui B. The new strategy of energy management for a photovoltaic system without extra intended for remote-housing. *Solar energy*. 2013;94:71-85. https://doi.org/10.1016/j.solener.2013.04.029.
6. Robitaille M., Agbossou K., Doumbia M.L. Modeling of an islanding protection method for a hybrid renewable distributed generator. In: *Canadian Conference on Electrical and Computer Engineering*. 2005. https://doi.org/10.1109/CCECE.2005.1557259.
7. Sahoo U., Kumar R., Singh S.K., Tripathi A.K. Energy, exergy, economic analysis and optimization of polygeneration hybrid solar-biomass system. *Applied Thermal Engineering*. 2018;145:685-692. https://doi.org/10.1016/j.applthermaleng.2018.09.093.
8. Koohi-Kamali S., Rahim N.A. Coordinated control of smart microgrid during and after islanding operation to prevent under frequency load shedding using energy storage system. *Energy conversion and management*. 2016;127:623-646. https://doi.org/10.1016/j.enconman.2016.09.052.
9. Raveendhra D., Poojitha R., Narasimharaju B.L., Domyshev A., Dreglea A., Dao Minh Hien, et al. Part II: State-of-the-art technologies of solar-powered DC microgrid with hybrid energy storage systems: converter topologies. *Energies*. 2023;16(17):6194. https://doi.org/10.3390/en16176194.
10. Shezan S.A., Ishraque M.F., Muyeen S.M., Arifuzzaman S.M., Paul L.C., Das S.K., et al. Effective dispatch strategies assortment according to the effect of the operation for an islanded hybrid microgrid. *Energy Conversion and Management: X*. 2022;14:100192. https://doi.org/10.1016/j.ecmx.2022.100192.

11. Kuetche C.F.M., Tsuanyo D., Fopah-Lele A. Analysis of hybrid energy systems for telecommunications equipment: a case study in Buea Cameroon. In: *Renewable Energy and digital technologies for the development of Africa: E3S Web of Conferences*. 2022;354:02007. https://doi.org/10.1051/e3sconf/202235402007.
12. Naderipour A., Ramtin A.R., Abdullah A., Marzbali M.H., Nowdeh S.A., Kamyab H. Hybrid energy system optimization with battery storage for remote area application considering loss of energy probability and economic analysis. *Energy*. 2022;239(D):122303. https://doi.org/10.1016/j.energy.2021.122303.
13. Kushwaha P.K., Bhattacharjee C. Integrated techno-economic-enviro-socio design of the hybrid renewable energy system with suitable dispatch strategy for domestic and telecommunication load across India. *Journal of Energy Storage*. 2022;55(A):105340. https://doi.org/10.1016/j.est.2022.105340.
14. Okundamiya M.S., Wara S.T., Obakhena H.I. Optimization and techno-economic analysis of a mixed power system for sustainable operation of cellular sites in 5G era. *International Journal of Hydrogen Energy*. 2022;47(39):17351-17366. https://doi.org/10.1016/j.ijhydene.2022.03.207.
15. Memon S.A., Upadhyay D.S., Patel R.N. Optimal configuration of solar and wind-based hybrid renewable energy system with and without energy storage including environmental and social criteria: a case study. *Journal of Energy Storage*. 2021;44:103446. https://doi.org/10.1016/j.est.2021.103446.
16. Khan F.A., Pal N., Saeed S.H. Optimization and sizing of SPV/wind hybrid renewable energy system: a techno-economic and social perspective. *Energy*. 2021;233:121114. https://doi.org/10.1016/j.energy.2021.121114.
17. Ali F., Ahmar M., Jiang Yuexiang, AlAhmad M. A techno-economic assessment of hybrid energy systems in rural Pakistan. *Energy*. 2021;215(A):119103. https://doi.org/10.1016/j.energy.2020.119103.
18. Das B.K., Alotaibi M.A., Das P., Islam M.S., Das S.K., Hossain M.A. Feasibility and techno-economic analysis of stand-alone and grid-connected PV/wind/diesel/batt hybrid energy system: a case study. *Energy Strategy Reviews*. 2021;37:100673. https://doi.org/10.1016/j.esr.2021.100673.
19. Kumar A., Verma A. Optimal techno-economic sizing of a solar-biomass-battery hybrid system for off-setting dependency on diesel generators for microgrid facilities. *Journal of Energy Storage*. 2021;36:102251. https://doi.org/10.1016/j.est.2021.102251.
20. Amara S., Toumi S., Salah C.B., Saidi A.S. Improvement of techno-economic optimal sizing of a hybrid off-grid micro-grid system. *Energy*. 2021;233:121166. https://doi.org/10.1016/j.energy.2021.121166.
21. Alshammari N., Asumadu J. Optimum unit sizing of hybrid renewable energy system utilizing harmony search, Jaya and particle swarm optimization algorithms. *Sustainable Cities and Society*. 2020;60:102255. https://doi.org/10.1016/j.scs.2020.102255.
22. Diab A.A.Z., Sultan H.M., Kuznetsov O.N. Optimal sizing of hybrid solar/wind/hydroelectric pumped storage energy system in Egypt based on different meta-heuristic techniques. *Environmental Science and Pollution Research*. 2020;27(26):32318-32340. https://doi.org/10.1007/s11356-019-06566-0.
23. Ramesh M., Saini R.P. Dispatch strategies based performance analysis of a hybrid renewable energy system for a remote rural area in India. *Journal of Cleaner Production*. 2020;259:120697. https://doi.org/10.1016/j.jclepro.2020.120697.
24. Li Chong, Zhou Dequn, Wang Hui, Lu Yuzheng, Li Dongdong. Techno-economic performance study of stand-alone wind/diesel/battery hybrid system with different battery technologies in the cold region of China. *Energy*. 2020;192:116702. https://doi.org/10.1016/j.energy.2019.116702.
25. Veilleux G., Potisat T., Pezim D., Ribback C. Techno-economic analysis of microgrid projects for rural electrification: a systematic approach to the redesign of Koh Jik off-grid case study. *Energy for Sustainable Development*. 2020;54:1-13. https://doi.org/10.1016/j.esd.2019.09.007.
26. Aziz A.S., Tajuddin M.F.N., Adzman M.R., Mohammed M.F., Ramli M.A.M. Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: a case study of Iraq. *Energy*. 2020;191:116591. https://doi.org/10.1016/j.energy.2019.116591.
27. Mayer M.J., Szilágyi A., Gróf G. Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm. *Applied Energy*. 2020;269:115058. https://doi.org/10.1016/j.apenergy.2020.115058.
28. Odou O.D.T., Bhandari R., Adamou R. Hybrid off-grid renewable power system for sustainable rural electrification in Benin. *Renewable Energy*. 2020;145:1266-1279. https://doi.org/10.1016/j.renene.2019.06.032.
29. Kumar J., Suryakiran B.V., Verma A., Bhatti T.S. Analysis of techno-economic viability with demand response strategy of a grid-connected microgrid model for enhanced rural electrification in Uttar Pradesh state, India. *Energy*. 2019;178:176-185. https://doi.org/10.1016/j.energy.2019.04.105.
30. Kim Min-Hwi, Kim Deukwon, Heo Jaehyeok, Lee Dong-Won. Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. *Energy*. 2019;187:115916. https://doi.org/10.1016/j.energy.2019.115916.
31. Baseer M., Alqahtani A., Rehman S. Techno-economic design and evaluation of hybrid energy systems for residential communities: case study of Jubail industrial city. *Journal of Cleaner Production*. 2019;237:117806. https://doi.org/10.1016/j.jclepro.2019.117806.
32. Javed M.S., Song Aotian, Ma Tao. Techno-economic assessment of a stand-alone hybrid solar-wind-battery system for a remote island using genetic algorithm. *Energy*. 2019;176:704-717. https://doi.org/10.1016/j.energy.2019.03.131.

33. Sawle Y., Gupta S.C., Bohre A.K. Socio-techno-economic design of hybrid renewable energy system using optimization techniques. *Renewable Energy*. 2018;119:459-472. https://doi.org/10.1016/j.renene.2017.11.058.
34. Ahmad J., Imran M., Khalid A., Iqbal W., Ashraf S.R., Adnan M., et al. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: a case study of Kallar Kahar. *Energy*. 2018;148:208-234. https://doi.org/10.1016/j.energy.2018.01.133.
35. Duman A.C., Güler Ö. Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households. *Sustainable Cities and Society*. 2018;42:107-126. https://doi.org/10.1016/j.scs.2018.06.029.
36. Alharthi, Ya.Z., Siddiki M.K., Chaudhry G.M. Resource assessment and techno-economic analysis of a grid-connected solar PV-wind hybrid system for different locations in Saudi Arabia. *Sustainability.* 2018;10(10):3690. https://doi.org/10.3390/su10103690.
37. Das B.K., Zaman F. Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection. *Energy*. 2019;169:263-276. https://doi.org/10.1016/j.energy.2018.12.014.
38. Kumar A., Singh A.R., Deng Yan, He Xiangning, Kumar Praveen, Bansal R.C. A novel methodological framework for the design of sustainable rural microgrid for developing nations. *Ieee Access*. 2018;6:24925-24951. https://doi.org/10.1109/ACCESS.2018.2832460.
39. Park E. Potentiality of renewable resources: economic feasibility perspectives in South Korea. *Renewable and Sustainable Energy Reviews*. 2017;79:61-70. https://doi.org/10.1016/j.rser.2017.05.043.
40. Yilmaz S., Dincer F. Optimal design of hybrid PV-diesel-battery systems for isolated lands: a case study for Kilis, Turkey. *Renewable and Sustainable Energy Reviews*. 2017;77:344-352. https://doi.org/10.1016/j.rser.2017.04.037.
41. Al-Sharafi A., Sahin A.Z., Ayar T., Yilbas B.S. Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia. *Renewable and Sustainable Energy Reviews*. 2017;69:33-49. https://doi.org/10.1016/j.rser.2016.11.157.
42. Shahzad M.K., Zahid A., Rashid T.U., Rehan M.A., Ali M., Ahmad M. Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. *Renewable Energy*. 2017;106:264-273. https://doi.org/10.1016/j.renene.2017.01.033.
43. Jaiswal A. Lithium-ion battery based renewable energy solution for off-grid electricity: a techno-economic analysis. *Renewable and Sustainable Energy Reviews*. 2017;72:922-934. https://doi.org/10.1016/j.rser.2017.01.049.
44. Azimoh C.L., Klintenberg P., Mbohwa C., Wallin F. Replicability and scalability of mini-grid solution to rural electrification programs in sub-Saharan Africa. *Renewable Energy*. 2017;106:222-231. https://doi.org/10.1016/j.renene.2017.01.017.
45. Das H.S., Tan Chee Wei, Yatim A.H.M., Lau Kwan Yiew. Feasibility analysis of hybrid photovoltaic/battery/fuel cell energy system for an indigenous residence in East Malaysia. *Renewable and Sustainable Energy Reviews*. 2017;76:1332-1347. https://doi.org/10.1016/j.rser.2017.01.174.
46. Vides-Prado A., Camargo E.O., Vides-Prado C., Orozco I.H., Chenlo F., Candelo J.E. Techno-economic feasibility analysis of photovoltaic systems in remote areas for indigenous communities in the Colombian Guajira. *Renewable and Sustainable Energy Reviews*. 2018;82(3):4245-4255. https://doi.org/10.1016/j.rser.2017.05.101.
47. Ajlan A., Tan Chee Wei, Abdilahi A.M. Assessment of environmental and economic perspectives for renewable-based hybrid power system in Yemen. *Renewable and Sustainable Energy Reviews*. 2017;75:559-570. https://doi.org/10.1016/j.rser.2016.11.024.
48. Halabi L.M., Mekhilef S., Olitomiwa L. Performance analysis of hybrid PV/diesel/battery system using HOMER: a case study Sabah, Malaysia. *Energy conversion and management*. 2017;144:322-339. https://doi.org/10.1016/j.enconman.2017.04.070.
49. Qolipour M., Mostafaeipour A., Tousi O.M. Techno-economic feasibility of a photovoltaic-wind power plant construction for electric and hydrogen production: a case study. *Renewable and sustainable energy reviews*. 2017;78(C):113-123. https://doi.org/10.1016/j.rser.2017.04.088.
50. Becerra M., Morán J., Cepeda F., Valenzuela M. Wind energy potential in Chile: assessment of a small scale wind farm for residential clients. *Energy Conversion and Management*. 2017;140:71-90. https://doi.org/10.1016/j.enconman.2017.02.062.
51. Eltamaly A.M., Mohamed M.A., Al-Saud M.S., Alolah A.I. Load management as a smart grid concept for sizing and designing of hybrid renewable energy systems. *Engineering Optimization*. 2017;49(10):1813-1828. https://doi.org/10.1080/0305215X.2016.1261246.
52. Mohamed M.A., Eltamaly A.M., Alolah A.I. Swarm intelligence-based optimization of grid-dependent hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*. 2017;77:515-524. https://doi.org/10.1016/j.rser.2017.04.048.
53. Ansari M.S., Jalil M.F., Bansal R. A review of optimization techniques for hybrid renewable energy systems. *International Journal of Modelling and Simulation*. 2023;43(5):722-735. https://doi.org/10.1080/02286203.2022.2119524.
54. Bansal A.K. Sizing and forecasting techniques in photovoltaic-wind based hybrid renewable energy system: a review. *Journal of Cleaner Production*. 2022;369:133376. https://doi.org/10.1016/j.jclepro.2022.133376.
55. Kumar P., Pal N., Sharma H. Optimization and techno-economic analysis of a solar photo-voltaic/biomass/diesel/battery hybrid off-grid power generation system for rural remote electrification in eastern India. *Energy*. 2022;247:123560. https://doi.org/10.1016/j.energy.2022.123560.

56. Healy M.L., Dahlben L.J., Isaacs J.A. Environmental assessment of single-walled carbon nanotube processes. *Journal of Industrial Ecology*. 2008;12(3):376-393. https://doi.org/10.1111/j.1530-9290.2008.00058.x.
57. Tsoutsos T., Frantzeskaki N., Gekas V. Environmental impacts from the solar energy technologies. *Energy policy*. 2005;33(3):289-296. https://doi.org/10.1016/S0301-4215(03)00241-6.
58. Nazir M.S., Mahdi A.J., Bilal M., Sohail H.M., Ali N., Iqbal H.M.N. Environmental impact and pollution-related challenges of renewable wind energy paradigm – a review. *Science of the Total Environment*. 2019;683:436-444. https://doi.org/10.1016/j.scitotenv.2019.05.274.
59. Nazir M.S., Ali N., Bilal M., Iqbal H. Potential environmental impacts of wind energy development: a global perspective. *Current Opinion in Environmental Science & Health*. 2020;13:85-90. https://doi.org/10.1016/j.coesh.2020.01.002.
60. Fearnside P.M. Environmental and social impacts of hydroelectric dams in Brazilian Amazonia: Implications for the aluminum industry. *World development*. 2016;77:48-65. https://doi.org/10.1016/j.worlddev.2015.08.015.
61. Henning H.-M., Palzer A. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies – Part I: Methodology. Renewable and Sustainable Energy Reviews. 2014;30:1003-1018. https://doi.org/10.1016/J.RSER.2013.09.012.
62. McPherson M., Karney B. A scenario based approach to designing electricity grids with high variable renewable energy penetrations in Ontario, Canada: Development and application of the SILVER model. *Energy.* 2017;138:185-196. https://doi.org/10.1016/j.energy.2017.07.027.
63. Esteban M., Portugal-Pereira J. Post-disaster resilience of a 100% renewable energy system in Japan. *Energy*. 2014;68:756-764. https://doi.org/10.1016/j.energy.2014.02.045.
64. Esen H., Inalli M., Esen M. A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling. *Building and environment*. 2007;42(5):1955-1965. https://doi.org/10.1016/j.buildenv.2006.04.007.
65. Esen M., Yuksel T. Experimental evaluation of using various renewable energy sources for heating a greenhouse. *Energy and Buildings*. 2013;65:340-351. https://doi.org/10.1016/j.enbuild.2013.06.018.
66. Ajan C.W., Ahmed S.S., Ahmad H.B., Taha F., Zin A.A.B.M. On the policy of photovoltaic and diesel generation mix for an off-grid site: East Malaysian perspectives. *Solar Energy*. 2003;74(6):453-467. https://doi.org/10.1016/S0038-092X(03)00228-7.
67. Hosseinalizadeh R., Shakouri G.H., Amalnick M.S., Taghipour P. Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: case study of Iran. *Renewable and Sustainable Energy Reviews.* 2016;54:139-150. https://doi.org/10.1016/j.rser.2015.09.046.
68. Gulagi A., Choudhary P., Bogdanov D., Breyer C. Electricity system based on 100% renewable energy for India and SAARC. *PLoS One.* 2017;12(7):e0180611. https://doi.org/10.1371/journal.pone.0180611.
69. Maleki A., Hafeznia H., Rosen M.A., Pourfayaz F. Optimization of a grid-connected hybrid solar-wind-hydrogen CHP system for residential applications by efficient metaheuristic approaches. *Applied Thermal Engineering*. 2017;123:1263-1277. https://doi.org/10.1016/j.applthermaleng.2017.05.100.
70. Mason I.G., Page S.C., Williamson A.G. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. *Energy policy*. 2010;38(8):3973-3984. https://doi.org/10.1016/j.enpol.2010.03.022.
71. Ridha H.M., Gomes C., Hazim H., Ahmadipour M. Sizing and implementing off-grid stand-alone photovoltaic/battery systems based on multi-objective optimization and techno-economic (MADE) analysis. *Energy*. 2020;207:118163. https://doi.org/10.1016/j.energy.2020.118163.
72. Kaabeche A., Diaf S., Ibtiouen R. Firefly-inspired algorithm for optimal sizing of renewable hybrid system considering reliability criteria. *Solar Energy*. 2017;155:727-738. https://doi.org/10.1016/j.solener.2017.06.070.
73. Guezgouz M., Jurasz J., Bekkouche B., Ma Tao, Javed M.S., Kies A. Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems. *Energy Conversion and Management.* 2019;199:112046. https://doi.org/10.1016/j.enconman.2019.112046.
74. Elliston B., Diesendorf M., MacGill I. Simulations of scenarios with 100% renewable electricity in the Australian National electricity market. *Energy Policy*. 2012;45:606-613. https://doi.org/10.1016/j.enpol.2012.03.011.
75. Østergaard P.A. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. *Applied Energy*. 2015;154:921-933. https://doi.org/10.1016/j.apenergy.2015.05.086.

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Заявленный вклад авторов

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The authors declare no conflict of interests.

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