Multi-criteria Ranking of Renewable Energy Systems for Cities Located in Windy and Desert Areas

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***Abstract*—Renewable Energy Systems (RES) continue to expand globally in the pursuit of energy sustainability. These systems contain different components and function based on technical, environmental, economic, and political factors. This research began by examining more than 50 relevant studies in the renewable energy field. The study then created a ranking system that combines expert knowledge with practical measurements of technical performance, environmental benefits, and cost effectiveness to find the best energy options for windy desert locations. While no renewable system can excel in every category, this balanced approach identifies the most practical overall solutions. Research in Yazd city, Iran revealed an unexpected result: a basic grid-connected wind turbine system performed better than more complicated setups. This simple system achieved 96.5% renewable energy use, generated profit instead of cost (with a negative Cost of Energy of $−0.2071), and reduced greenhouse gases by approximately 80%. Such findings provide valuable guidance for similar climate regions around the world and challenge standard assumptions about desert energy solutions.**

***Keywords*—renewable energy, multi-criteria ranking, green house gas emissions, Yazd, economic feasibility, photovoltaic energy, wind energy**

I. Introduction

National and international programs heading toward expanding the deployment of renewable energy sources have become widespread. A survey of global energy policy indicates that many countries have officially approved renewable energy goals; one example is Germany's commitment to raise renewables' share to 50 percent of its total energy balance by 2050, which emphasizes the coordinated worldwide action [1]. Furthermore, there is a growing movement towards decreasing the use of fossil fuels and a rearrangement of capital towards low-carbon projects and green finance instruments, reflecting a trend to support renewable solutions [2]. Another study by Lesk *et al.* [3] also emphasize that large-scale investment in renewable capacity and the systematic phase-out of fossil-fuel infrastructures are vital for meeting the long-term decarbonization goals [3]. The main issue associated with fossil-fuel use is the resulting increase in GHG emissions. Climate transition research done by Lesk *et al.* [3] also states that an effective immediate discontinuation of existing fossil-fuel assets is necessary to shrink the cumulative emissions and limit temperature rises in accordance with international targets [3]. To add more, life-cycle assessments by Doerffer *et al.* [4] reveal that the mining and processing stages of fossil-fuel supply chains commonly generate noticeable negative environmental impacts, mainly resource depletion and ecological disturbance [4]. Empirical studies by Ghaderi *et al.* [5] claim that regions with high reliance on fossil fuel energy sources suggestively contribute to environmental burdens [5]. Further, according to Setiawan *et al.* [6], both simulations and observational data confirm that replacing fossil fuels with renewable energy can significantly lower GHG outputs and mitigate climate impacts [6]. Overall, the overwhelming scientific consensus and policy momentum clearly demonstrate that transitioning from fossil fuels to renewable energy sources is environmentally imperative to reduce greenhouse gas emissions and mitigating climate change.

Electricity represents a significant portion of global energy consumption, necessitating sophisticated modeling of its demand patterns and climate sensitivities [7]. Households form one of the largest electricity-consuming sectors primarily through space heating and cooling, lighting, and appliance usage and are often comparable to or exceeding industrial and service sectors [8]. Further, electricity's versatility as a "Power-to-X" (P2X) carrier enables its conversion into mechanical work, thermal energy, and chemical fuels, facilitating integration across mobility, heating, and industrial processes [9]. While electricity consumption itself produces no greenhouse gases, its generation and transmission can cause thermal pollution and transmission losses [10]. In fact, despite low-carbon technology growth, global electricity generation remains predominantly from thermal plants burning fossil fuels due to existing infrastructure and dispatchability advantages [11]. As a result, Renewable Energy Source (RES) are implemented at scale to replace carbon-intensive sources. Effective RES integration requires large-scale energy storage (primarily pumped-hydro) and inverter-based ancillary services to maintain grid stability [10, 12].

The global shift to renewable energy systems is critical, yet their design hinges on careful coordination of generation, storage, and distribution to resolve a core challenge: determining configurations that meet urban electricity demand while maximizing environmental benefits. Solving this problem centers around combining localized climatic, demographic, economic, political, and infrastructural data. These variables drive recent research toward case-specific RES analyses, focusing on how hybrid technologies, advanced storage, and sector-coupling strategies can help realize decarbonization goals with technical and socioeconomic constraints.

II. Literature Review

Recent literature on Renewable Energy Systems (RES) demonstrates significant advancements in the design, implementation, and evaluation of sustainable energy solutions for urban environments. A summary of these studies in presented in Table 1. These case studies collectively highlight the multifaceted approach required to achieve deep decarbonization while maintaining economic viability and technical feasibility.

A prominent theme across these studies is the integration of multiple renewable technologies to create resilient hybrid systems. Mohamed *et al.* [13] proposed a multi-objective optimization model incorporating Photovoltaic (PV), wind, biogas, electric vehicle charging, and storage solutions to minimize both Levelized Cost of Energy (LCOE) and Greenhouse Gas (GHG) emissions. Similarly, Chowdhury *et al.* [14] assessed a hybrid PV/hydro/biogas/diesel microgrid in Bangladesh that achieved an impressive 99.5% renewable share with an LCOE of \$0.182/kWh while reducing CO_2 emissions by more than 100 times compared to conventional systems.

Storage technologies emerge as critical enablers for high renewable penetration. Lukwesa *et al.* [15] developed a linear programming model that demonstrated in Hokkaido that 40% variable renewable energy penetration is achievable without cost increases, while 60–80% penetration requires significant storage investments. The research by Kut *et al.* [16] emphasizes underground hydrogen storage as a solution for large-scale seasonal energy balancing, highlighting its role in integratin.g hydrogen with PV, wind, and Battery Energy Storage Systems (BESS) to meet urban electricity demands.

Several case studies focus on specific urban implementations. Gouveia *et al.* [17] investigated the Positive Energy District model in Lisbon's Alfama district, quantifying potential energy retrofits that could reduce space heating by 84% and cooling demand by 19%, while assessing rooftop/window PV potential of up to 60 GWh/year. Luca *et al.* [18] analyzed the feasibility of converting Altavilla Silentina, a small Italian city, into a zero-greenhouse gas municipality by 2030 through integrated wind turbines, PV panels, biogas cogeneration, thermal solar panels, and heat pumps.

Mostafavi Sani *et al.* [19] embed hydrogen production, storage and use in a tri-objective framework for small Canadian communities, finding that as green-hydrogen technologies mature the need for grid imports disappears while life-cycle impacts fall 63%.

Holzer *et al.* [20] use classroom workshops and an interactive scenario tool to elicit electricity-mix preferences from 164 Swiss pupils; after basic energy-literacy training, their favoured 2035 mix averages 88% renewables—less ambitious than expert or adult views yet markedly greener than most published model scenarios, highlighting the pedagogical value of involving youth in planning.

Regional system design questions dominate Sotnyk *et al.*'s UKRAINE-EXPANSE analysis [21]: cost-optimal pathways that either eliminate hard-coal generation, raise renewable contributions to 30%, or combine both, still satisfy 2035 demand with only a 5–13 % cost premium, relying mainly on expanded wind, pumped-hydro storage and transmission reinforcements while keeping nuclear and gas for firm capacity.

Santos *et al.* [22] demonstrate that Brazil's enormous residential rooftop-PV resource is largely climate-proof: even in a 4 °C warming world technical potential falls by <1% and economic potential by only 0.008%, confirming distributed PV as a resilient mitigation–adaptation option.

Economic feasibility remains a central concern. Narayanan *et al.* [23] investigated 100% renewable systems with battery storage for urban electricity demand in Kortrijk, Belgium, concluding that such systems become economically viable only when RES costs drop to approximately 40% and BESS costs to 7% of current LCOE. Tazay *et al.* [24] evaluated a PV/wind hybrid system at Al Baha University that achieved less than 0.1% load shortage and over 30% CO_2 reduction with a competitive COE of 0.085 \$/kWh.

Multi-criteria decision frameworks are increasingly employed to balance competing objectives. Alexandri *et al.* [25] applied Multi Attribute Utility Theory to Athens' building stock, evaluating GHG reduction, energy savings, heat-island impact, costs, and payback periods. Kabeyi *et al.* [26] proposed a five-dimensional sustainability framework encompassing environmental, economic, social, technical, and institutional/political factors to optimize renewable electricity generation.

The sector coupling approach is gaining recognition as essential for deep decarbonization. Arabzadeh *et al.* [27] proposed Helsinki's decarbonization through renewable electrification, storage, and sector coupling, finding that while a zero-carbon system by 2050 is feasible, it requires integration with the national grid. Li *et al.* [28] investigated optimal design and flexible operation of cross-sector urban energy clusters, demonstrating that multi-sector integration reduces GHG emissions by 4%, grid purchases by 14.3%, and gas use by 72.2%.

These case studies together demonstrate that achieving urban decarbonization through renewable energy systems requires approaches that integrate diverse technologies, optimize across multiple criteria, leverage storage solutions, and couple energy sectors.

Iran is a developing country that has a high amount of energy consumption and it has a low energy efficiency [29]. On the other hand, Iran has a high potential to receive solar illumination and many permanent wind corridors are placed in Iran [30]. Therefore, Yazd city in Iran are chosen as a study area. This city received high amounts of solar irradiation and also has been placed alongside a permanent wind corridor.

Different kinds of RES are investigated and three criteria including GHG emissions, renewable fraction and COE will be calculated for each RES. Then by gathering the opinions of experts, three introduced criteria are ranked and the weight of each criterion is identified. Finally, all investigated RES will be ranked and the most appropriate solution is determined.

This research presents a novel approach to renewable energy system optimization for desert urban environments by developing a straightforward multi-criteria ranking framework that incorporates expert opinion weighting from 30 energy specialists.

Table 1. Recent literature on renewable energy systems

No.	Year	Authors	Summary
1	2024	Kut *et al.* [16]	➢ Provides a comprehensive overview of hydrogen production, storage, safety, and utilization technologies. ➢ Emphasizes technical, economic, and environmental dimensions for carbon-neutral energy systems. ➢ Highlights underground hydrogen storage for large-scale seasonal energy balancing. ➢ Informs multi-criteria Renewable Energy System (RES) designs integrating H_2 with PV, wind, and BESS to meet urban electricity demands and decarbonization targets. ➢ Includes cost, safety, and scalability assessments aligned with COE and GHG-reduction analyses.
2	2024	Nagaj *et al.* [31]	➢ Empirically evaluates decarbonization strategies (energy-efficiency enhancements, renewable-share increases) across 27 EU member states (1990–2022). ➢ Derives statistically significant CO_2 reduction and economic metrics. ➢ Provides quantitative data on decarbonization potential, cost-effectiveness, and policy-context considerations. ➢ Directly informs multi-criteria optimization of urban renewable energy systems.
3	2024	Blom *et al.* [32]	➢ Systematically reviews hybrid energy systems in healthcare facilities, quantifying GHG reductions and cost savings. ➢ Offers empirical data on decarbonization potential and hybrid-RES integration in low- and middle-income contexts.
4	2024	Ekechukwu *et al.* [33]	➢ Systematically reviews technical (storage, grid stability, demand-side management), socio-economic (policy, finance, stakeholder engagement), and environmental (GHG reduction, climate resilience) aspects of renewable integration. ➢ Proposes a multi-criteria framework for designing cost-effective, zero-carbon RES combinations. ➢ Directly applicable to urban electricity supply and decarbonization planning.
5	2021	Gouveia *et al.* [17]	➢ Investigates Positive Energy District (PED) model in Lisbon's Alfama district: ➢ Quantifies energy retrofits (84% space heating, 19% cooling demand reductions). ➢ Assesses rooftop/window PV potential (up to 60 GWh/year). ➢ Estimates total investment (60–81 M€) and proposes financing mechanisms to address energy poverty. ➢ Aligns with urban RES design by combining efficiency, PV, and economic feasibility analysis. ➢ Provides quantitative environmental metrics and a concrete case study for net-zero carbon goals.
6	2024	Cinca *et al.* [34]	➢ Reviews auxiliary services end-of-life hydropower plants can offer in decarbonized electricity systems such as Participation in secondary/tertiary regulation markets, Power Purchase Agreements (PPAs), local energy communities, Renewable energy storage and grid inertia support.
7	2024	Kansara *et al.* [35]	➢ Develops a multi-objective optimization framework for integrated energy systems (PV, wind, solar-thermal, heat pumps, electric boilers, thermal storage). ➢ Goals: Minimize costs and CO_2 emissions. ➢ Compares physics-driven vs. data-driven models. ➢ Achieves 37% computational time savings with high accuracy. ➢ Demonstrates scalable decision-making for renewable/storage sizing under. economic/environmental constraints.
8	2023	Mohamed *et al.* [13]	➢ Proposes a multi-objective optimization model integrating PV, wind, biogas, EV charging, and storage. ➢ Goals: Minimize Levelized Cost of Energy (LCOE) and GHG emissions. ➢ Quantifies cost/emission reductions for RES configurations and BESS integration. ➢ Directly addresses COE metrics, decarbonization potential, and urban multi-criteria RES design.
9	2024	Li *et al.* [36]	➢ Develops a MINLP model to integrate wind, solar, and biomass into industrial steam systems. ➢ Goals: Minimize life-cycle cost (including COE and carbon costs) and total emissions. ➢ Conducts sensitivity analyses on biomass share, carbon price, demand, and emission limits. ➢ Framework applicable to urban RES for balancing demand fulfillment, environmental impact, and economic viability.
10	2023	Chantzis *et al.* [37]	➢ Simulates thermal demand flexibility in a Mediterranean office building using heat pumps and thermal mass. ➢ Quantifies shifts in energy use, costs, and CO_2 emissions under dynamic price/CO_2-intensity signals. ➢ Provides metrics for building-scale decarbonization and economic feasibility to inform urban RES design.
11	2024	Aguilar *et al.* [38]	➢ Reviews electric-bus charging stations in Quito, Buenos Aires, Bogotá, and Santiago. ➢ Focuses on BESS management, charging infrastructure, and renewable grid integration. ➢ Offers insights on cost mitigation, GHG reductions, and policy frameworks.
12	2022	Lukwesa *et al.* [15]	➢ Develops a linear programming model to optimize wind/solar capacities, transmission lines, and storage. ➢ Applied to Hokkaido: ➢ 40% VRE penetration achievable without cost increases. ➢ 40–60% requires transmission upgrades; 60–80% needs storage. ➢ Demonstrates pathway for deep decarbonization via renewable integration, grid upgrades, and storage.
13	2023	Fahim *et al.* [39]	➢ Conducts multi-criteria assessment of ASEAN's renewable transition. ➢ Evaluates technical potential, COE, GHG reductions, and policy scenarios. ➢ Integrates climate, economic, and political factors to guide urban/metropolitan RES design.
14	2023	Li *et al.* [28]	➢ Investigates lithium-ion batteries, hydrogen fuel cells, and PV integration for urban transport decarbonization. ➢ Quantifies GHG reductions, energy security enhancements, and economic co-benefits. ➢ Informs optimal RES configurations for clean mobility in metropolitan systems.
15	2021	Caat *et al.* [40]	➢ Case study in Amsterdam: Integrates rooftop solar, supermarket waste-heat recovery, and aquifer thermal storage. ➢ Quantifies:Thermal supply-demand mismatches and Exergy efficiency gains and CO_2 reductions (aligned with 2030/2050 targets). ➢ Demonstrates multi-component synergies to heat 47 dwellings per greenhouse. ➢ Directly addresses urban RES needs: renewable integration, environmental impact assessment, and city-block scalability.
16	2022	Gao *et al.* [41]	➢ Reviews fifth-generation urban district heating substations integrating solar thermal, water-source, and air-source heat pumps. ➢ The study employs exergy-based thermodynamic modeling and optimization. ➢ It demonstrates how optimal renewable component combinations reduce GHG emissions and improve energy efficiency in existing metropolitan infrastructure.

17	2022	Yoo *et al.* [42]	➢ Evaluates life-cycle GHG emissions of a net-zero biofuel plant for aviation, focusing on deep-decarbonization strategies and jet fuel carbon intensity. ➢ It does not address urban renewable energy system design, multi-criteria optimization of PV/wind/BESS mixes, city-scale case studies, or metropolitan electricity supply economics. ➢ The study fails to meet urban RES planning requirements, infrastructure potential, COE, or GHG reduction metrics in cities.
18	2024	Lameh *et al.* [43]	➢ Presents a mixed-integer linear programming framework co-optimizing renewable generation, hydrogen production/storage, and CO_2 capture/utilization to achieve net-zero emissions. ➢ It quantifies the impact of temporal energy supply-demand variability on system design and operation. ➢ The framework addresses decarbonization potential and multi-criteria optimization but lacks urban-scale focus, detailed COE metrics, demographic/political factors, or metropolitan case studies.
19	2023	Perea-Moreno *et al.* [44]	➢ Provides an editorial overview of energy-saving strategies for sustainable cities, emphasizing renewable integration (solar, wind, hydropower) and storage in urban planning. ➢ It highlights multi-criteria decision analysis incorporating climate, demographics, economics, politics, and infrastructure. ➢ The study prioritizes cost-of-energy metrics, deep decarbonization, 100% renewable potential, and battery storage, directly addressing city-scale RES feasibility.
20	2024	Waite *et al.* [45]	➢ Maps carbon-neutral pathways for Thailand and Bangkok via stakeholder-engaged integrated assessment modeling. ➢ It models power-sector renewables, electrification, efficiency improvements, carbon capture, hydrogen, and negative emissions technologies. ➢ The study integrates climate, demographic, economic, political, and infrastructure variables to inform urban RES portfolio planning.
21	2024	Adanma *et al.* [46]	➢ Conducts a systematic literature review (2018–2024) on economic and environmental impacts of renewable adoption globally. ➢ The multi-criteria approach covers policy effects, energy storage innovations, and integrates economic feasibility, environmental performance, and political/infrastructure factors.
22	2021	Elnozahy *et al.* [47]	➢ Uses Utopia-point optimization (GA/PSO) to size a PV/wind/BESS/diesel system, achieving 0.182 $/kWh COE and 12,076 kg/year GHG emissions. ➢ It quantifies economic-environmental trade-offs, integrates BESS, and benchmarks against HOMER.
23	2022	Grubert *et al.* [48]	➢ Reviews US decarbonization strategies, focusing on renewable-storage-infrastructure integration to phase out fossil fuels. ➢ It synthesizes policy and economic frameworks but lacks urban case studies, detailed multi-criteria analyses, or city-level COE/GHG metrics.
24	2024	Wilmot *et al.* [49]	➢ Provides a satellite-based framework to quantify city-scale CO_2 emissions across 77 cities (~16% of global CO_2). ➢ It enables planners to validate RES impacts, incorporate emission data into decision models, and track decarbonization progress.
25	2022	Souza *et al.* [50]	➢ Develops a multi-criteria model for urban district energy communities powered entirely by renewables. ➢ It optimizes generator/storage sizing for heat, cooling, and power, minimizing COE and CO_2 emissions. ➢ The study demonstrates a viable 100% RES pathway for metropolitan areas.
26	2024	Rossi *et al.* [51]	➢ Quantifies fossil fuel impacts on air quality/health and evaluates solar/wind/hydropower/EV/storage systems. ➢ It analyzes COE trends, efficiency gains, GHG reductions, and environmental-economic trade-offs for urban decarbonization.
27	2024	Nguyen *et al.* [52]	➢ Applies AI/ML to optimize biomass/biofuel supply chains, lowering costs and emissions. ➢ The study focuses on component-level RES optimization but lacks urban-scale integration, multi-criteria analyses, or city case studies.
28	2023	Chen *et al.* [53]	➢ Uses econometric analysis (1990–2020 G7 data) to show renewables and digitalization reduce GHG emissions. ➢ It provides macro-level decarbonization evidence but omits urban RES design, COE metrics, or city case studies.
29	2025	Griffiths *et al.* [54]	➢ Investigates net-zero industry strategies via multi-level roadmaps and international cooperation. ➢ While aligning with multi-criteria RES planning, it lacks urban electricity demand modeling, COE metrics, or city-specific cases.
30	2024	Kim *et al.* [55]	➢ This study evaluates electrolysis-based hydrogen production's GHG and COE metrics for urban RES storage. ➢ Its methodology informs multi-criteria frameworks for integrating renewables with hydrogen storage in cities.
31	2023	Ballerini *et al.* [56]	➢ Simulates a solar-assisted ground-source heat pump in Milan, showing 30% COP improvement and reduced temperature drift. ➢ The study focuses on building-scale decarbonization, not urban electricity supply or multi-criteria RES optimization.
32	2023	Mignogna *et al.* [57]	➢ It reviews biogas/biomethane production, providing LCOE and GHG data for bioenergy integration into RES. ➢ It lacks multi-criteria frameworks, hybrid PV/wind/bioenergy configurations, or urban case studies.
33	2022	Moghaddam *et al.* [58]	➢ This work evaluates AI-driven renewable automation in European smart cities, quantifying GHG reductions and economic impacts.
34	2021	Gil-García *et al.* [59]	➢ Assesses EV integration with PV/wind/biogas/diesel, finding 39% and 82% renewable penetration needed for 2030/2050 targets. ➢ It provides quantitative insights into urban RES combinations for decarbonization.
35	2023	Xu *et al.* [60]	➢ This work proposes a multi-objective framework for the Yangtze River Delta, minimizing costs and emissions across power, industry, buildings, and transport. ➢ It quantifies CO_2 reduction potentials (4.5–22.2 Gt by sector; 7.1–4688.1 Mt by city) and demonstrates cross-sector energy recycling.
36	2024	De Souza *et al.* [61]	➢ It develops an MILP model for a nine-building Italian energy community, reducing CO_2 by 24.3% with cost impacts from –31.9% to +1.9%. ➢ The study evaluates COE, decarbonization, and infrastructure integration, adaptable to metropolitan contexts.

37	2022	Kabeyi *et al.* [26]	➢ This work proposes a five-dimensional sustainability framework (environmental, economic, social, technical, institutional/political) to optimize renewable/low-carbon electricity generation. ➢ It emphasizes advanced energy storage and mixed RES portfolios to minimize costs, emissions, and ensure grid stability. ➢ The framework addresses urban RES design needs, including COE, decarbonization potential, BESS integration, and policy considerations.
38	2023	Li *et al.* [62]	➢ Investigates optimal design and flexible operation of cross-sector urban energy clusters (solar, industrial, residential, commercial loads with natural-gas backup). ➢ Under demand, price, and solar uncertainty, multi-sector integration reduces GHG emissions by 4%, grid purchases by 14.3%, and gas use by 72.2%. ➢ The study highlights resilience and decarbonization potential for urban RES planning.
39	2024	Furlanetto *et al.* [63]	➢ Analyzes carbon capture in a three-node power network, quantifying CO_2 and co-pollutant reductions under technical, economic, and policy scenarios. ➢ While providing emissions and retrofit cost insights, it omits urban RES design, multi-criteria optimization, and city-scale decarbonization case studies.
40	2025	Ali *et al.* [64]	➢ Reviews electrolysis and CO_2 capture advancements for electrofuels, reporting 20% efficiency gains and 30–40% cost reductions. ➢ These metrics support COE and decarbonization analyses in urban RES designs, integrating synthetic fuels with PV, wind, storage, and biogas.
41	2024	Vespasiano *et al.* [65]	➢ Evaluates hydrogen blending in residential gas boilers, quantifying efficiency, GHG, and economic impacts across hydrogen fractions. ➢ It lacks urban RES integration, multi-criteria design (climate, infrastructure, storage), and city-scale zero-carbon electricity case studies.
42	2024	Liu *et al.* [66]	➢ Conducts a life-cycle GHG assessment of CO_2-Plume Geothermal (CPG) systems, providing decarbonization and environmental metrics. ➢ While addressing GHG reduction, it excludes urban integration, COE analysis, multi-criteria frameworks, and metropolitan case studies.
43	2022	Rinawati *et al.* [67]	➢ Systematically reviews hydrogen-based power generation LCA methodologies, offering benchmarks for environmental impact evaluation. ➢ The study guides hydrogen integration (storage/generation) within urban RES portfolios.
44	2024	Bharti *et al.* [68]	➢ This study discusses replacing fossil fuels with solar, wind, hydro, and storage to reduce GHG emissions and modernize grids. ➢ It aligns with decarbonization and BESS integration but lacks urban-scale RES design, COE analysis, or metropolitan case studies.
45	2024	Chowdhury *et al.* [14]	➢ Assesses a hybrid PV/hydro/biogas/diesel microgrid in Bangladesh, achieving 99.5% renewable share, \$0.182/kWh LCOE, and >100 × CO_2 reduction. ➢ Its multi-criteria methodology offers a transferable framework for cost-effective, low-carbon urban RES solutions.
46	2022	Tazay *et al.* [24]	➢ Evaluates a PV/wind hybrid system at Al Baha University, achieving <0.1% load shortage, >30% CO_2 reduction, and 0.085 \$/kWh COE. ➢ The case study directly addresses urban RES configurations, COE metrics, and environmental impact.
47	2022	Alexandri *et al.* [25]	➢ Applies Multi Attribute Utility Theory to Athens' building stock, evaluating GHG reduction, energy savings, heat-island impact, costs, and payback. ➢ It provides a multi-criteria framework for urban decarbonization and carbon neutrality by 2050.
48	2022	Sporleder *et al.* [69]	➢ This work reviews optimization methods for urban district heating systems, integrating renewables to minimize GHG emissions and costs. ➢ The synthesis of economic, decarbonization, and infrastructure factors exemplifies a multi-criteria framework for metropolitan RES.
49	2023	Wang *et al.* [70]	➢ It proposes a dynamic scheduling framework for hydrogen-integrated energy systems, quantifying CO_2 reductions when grid emissions <0.3 kg CO_2/kWh and hydrogen efficiency >75%.
50	2023	Blom *et al.* [71]	➢ Reviews GHG mitigation in healthcare systems, ranking actions by emission reduction, complexity, and cost. ➢ While focused on healthcare, its multi-criteria methodology can inform urban RES portfolio design for cost-effectiveness and environmental impact.
51	2018	Luca *et al.* [18]	➢ Presents an economic and energy feasibility analysis to convert Altavilla Silentina, a small southern Italian city, into a zero greenhouse gas city by 2030. ➢ The proposed system integrates wind turbines, photovoltaic panels, biogas cogeneration, thermal solar panels, and heat pumps to meet electric and thermal demands, including transport electrification. ➢ EnergyPLAN software models the city-wide energy system across daily, weekly, and yearly timeframes, while TRNSYS simulates photovoltaic performance. ➢ Hourly EnergyPLAN outputs identify measures for near-zero carbon status, iteratively updated to assess impacts on the city's energy balance. ➢ An economic analysis evaluates electricity and thermal energy costs to validate feasibility.
52	2019	Narayanan *et al* .[23]	➢ Investigates the cost-effectiveness of 100% Renewable Energy Systems (RES) with battery storage (BESS) for urban electricity demand using a flexible-load methodology. ➢ A case study in Kortrijk, Belgium (75,000 inhabitants) shows RES-BESS systems are uneconomical unless RES costs drop to ~40% (0.044 €/kWh) and BESS costs to 7% (0.038 €/kWh) of current LCOE. ➢ The study concludes sector integration (electricity, heat, transport) is critical for high RES penetration, as standalone electricity solutions are insufficient.
53	2019	Razmjoo *et al.* [72]	➢ Evaluates PV-wind-diesel hybrid systems for energy sustainability in Zabol and Zahak, Iran, using Homer software and meteorological data. ➢ Solar radiation averages 9 h/d (Zabol) and 9.1 h/d (Zahak), with wind speeds of 5.35 m/s and 4.7 m/s, respectively. ➢ Annual PV production reaches 1700 kWh (Zabol) and 1669 kWh (Zahak), while wind turbines generate 9036 kWh and 7263 kWh. ➢ The analysis confirms solar and wind investments in both cities are economically justified.

54	2020	Arabzadeh *et al.* [27]	➢ Proposes Helsinki's decarbonization via renewable electrification, storage, and sector coupling, with a macro-level energy balance model and MILP micro-level optimization. ➢ A zero-carbon system by 2050 is feasible but requires integration with the national grid to address supply-demand mismatches. ➢ With 1.5 GW wind capacity (56% of annual demand), 90% is used locally, while 10% relies on external markets due to temporal limitations. ➢ Decarbonization improves resilience but highlights challenges in peak production adequacy and heating sector dependency on electricity.
55	2025	Sotnyk *et al.* [21]	➢ The UKRAINE-EXPANSE model analyzes decarbonization pathways for Ukraine's electricity sector by 2035. ➢ The study explores scenarios of completely phasing out coal, achieving 30% renewable energy penetration, or a combined approach. ➢ Cost-optimal solutions include expanding wind power, pumped hydro storage, and transmission infrastructure, supported by existing nuclear and gas plants for reliability. ➢ Transitioning to these renewable scenarios entails only modest cost increases (5–13%) compared to maintaining coal-intensive generation. ➢ Highlights achievable pathways to significant emission reductions with manageable economic implications, promoting an energy-secure future for Ukraine.
56	2023	Holzer *et al.* [20]	➢ The study employs classroom workshops involving 164 Swiss high school students, evaluating preferences for future electricity mixes. ➢ Pupils used an interactive energy scenario tool after receiving basic energy literacy training. ➢ Students' preferred 2035 electricity supply comprised an average of 88% renewable energy, less ambitious than expert scenarios but more progressive than conventional predictions. ➢ Results highlight the importance of early stakeholder engagement, particularly youth, in shaping energy policy decisions. ➢ Educational initiatives effectively promote informed and proactive citizen participation in sustainable energy transitions.
57	2021	Santos *et al.* [22]	➢ Investigates climate change impacts on the potential for residential rooftop solar Photovoltaic (PV) installations across Brazil. ➢ Assesses scenarios including a warming of up to 4 °C and its influence on technical and economic viability. ➢ Findings demonstrate a minimal reduction in technical potential (<1%) and negligible economic impact (0.008%) even under severe climate warming scenarios. ➢ Highlights distributed PV systems' resilience, positioning them as robust options for both mitigation and adaptation strategies. ➢ Reinforces the significance of residential solar PV as a stable, climate-resilient renewable energy investment.
58	2025	Sani *et al.* [19]	➢ Proposes a tri-objective energy system optimization framework for small communities in Canada, integrating hydrogen production, storage, and utilization. ➢ Objectives include minimizing life-cycle environmental impacts, costs, and grid dependency. ➢ Results indicate hydrogen-based systems drastically reduce environmental impacts (up to 63%) compared to conventional scenarios. ➢ Grid imports become unnecessary when hydrogen technologies become economically viable and technically mature. ➢ Localized renewable energy solutions significantly enhance environmental sustainability and energy independence for remote communities.

Unlike previous studies focused on temperate regions or single resources, this work specifically examines the complementary potential of both solar and wind in hot desert climates, revealing the surprising superiority of wind energy in this context despite conventional assumptions favoring solar dominance. The study directly challenges established conclusions regarding storage necessity by demonstrating that in grid-connected systems with favorable sell-back rates, storage systems may be economically disadvantageous. By employing a component-agnostic methodology that evaluates system configurations independent of specific technologies, this research provides broadly applicable insights across evolving technology landscapes. The systematic sensitivity analysis across climate variables creates a transferable decision framework for similar regions worldwide, offering clear, actionable configuration rankings that bridge the gap between theoretical optimization models and practical implementation guidance for hot desert urban environments.

III. Materials and Methods

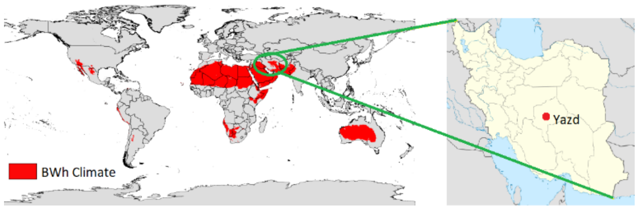
The performance of Renewable Energy Systems (RES) is influenced by a variety of factors. While RES can be deployed in numerous locations worldwide, their high initial costs necessitate the identification of optimal system combinations to maximize efficiency and capacity utilization. In this section, both renewable and non-renewable energy sources are evaluated for a typical residential demand of 1600 GWh per year in a windy, arid region. Subsequently, different RES configurations are assessed, and their performance is analyzed based on technical, economic, and environmental criteria.

The RES examined in this study consist of generic components and are not tied to any specific technology, as the primary objective is to compare and rank system structures. Only two renewable resources, solar irradiance and wind speed, are considered, while other potential sources such as bioenergy, geothermal, and hydropower are excluded due to a lack of reliable data.

A. Study Area

Yazd is a major city in central Iran and ranks as the country's 15th most populous urban center. Notably, its historic district was designated a UNESCO World Heritage Site in 2017, recognizing its cultural and architectural significance. Geographically, Yazd is located at 31°53′50″N latitude and 54°22′4″E longitude [73], as illustrated in Fig. 1.

Yazd exhibits a hot desert climate (BWh according to the Köppen climate classification system) [74], as depicted in Fig. 1. Climatic data indicate that the city experiences precipitation on only 23 days annually, with the remainder of the year characterized by intense sunshine and negligible humidity. Additionally, Yazd benefits from nearly continuous wind flow, with an annual mean speed of 5.2 m/s [75]. The city receives substantial solar irradiation, with annual average and peak ground-level solar radiation measuring approximately 260 W/m² and 1093 W/m², respectively [76]. With a population of approximately 656,474 residents, accounting for 0.7% of Iran's total population, Yazd's annual residential electricity consumption reaches roughly 1600 GWh [77]. Given these climatic and demographic conditions, the region presents a highly suitable environment for the establishment of photovoltaic and wind energy systems to meet local electricity demands.



(a) (b)

Fig. 1. a) Distribution of the regions with the BWh climate (in Koppen Climate Classification) around the world [74]; b) Location of Yazd city in Iran.

B. General Structure of Renewable Energy System

The schematic representation of the investigated Renewable Energy System (RES) is presented in in Fig. 2. Each system component is described in detail in subsequent sections. The system architecture was modeled using HOMER software, a widely recognized simulation tool for renewable energy systems [78]. This software enables comprehensive analysis of multiple scenarios while generating diverse output parameters. All system components incorporated in this study were designed to maintain compatibility with the software's architecture and established simulation standards.

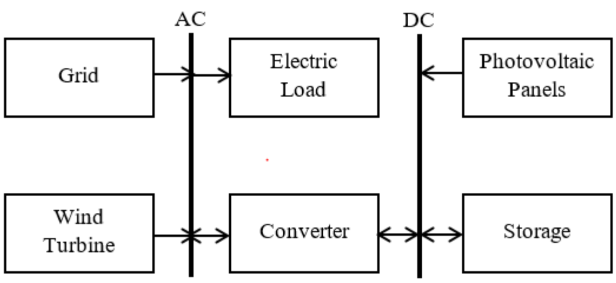


Fig. 2. The diagram of the investigated RES.

1) Electric load

The proposed Renewable Energy System (RES) is designed for residential consumers in the Northern Hemisphere, where peak electricity demand occurs in July. The system supplies Alternating Current (AC) power to meet an average daily residential consumption of 2.340 GWh/day in Yazd, as illustrated in Fig. 3. This load component is directly connected to the AC power distribution network. The monthly consumption profile demonstrates distinct seasonal variations, with maximum demand coinciding with summer cooling requirements.

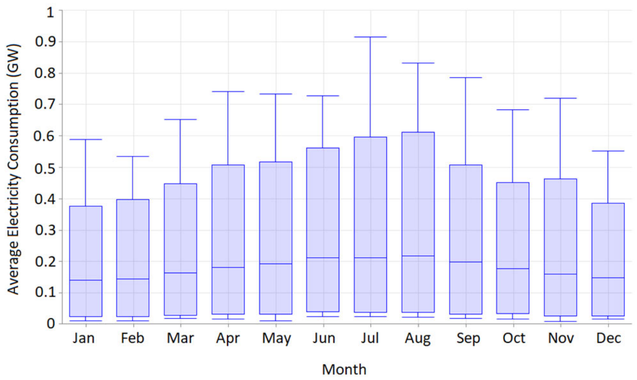


Fig. 3. Monthly profile of residential electricity demand in Yazd city by combining accurate weather data and the standard profile of electricity demand in HOMER.

2) Grid

The grid component serves as an interface with the public power distribution network, supplying Alternating Current (AC) electricity. In Iran, grid electricity is predominantly generated from fossil fuel sources [79], resulting in significant Greenhouse Gas (GHG) emissions, the quantitative values of which are presented in Table 2. These emissions necessitate careful environmental consideration when utilizing grid power.

Table 2. Greenhouse gas emission related to the grid electricity generation [77]

Parameter	Unit	Amount
Carbon Dioxide	g/kWh	164.34
Particulate Material	g/kWh	0.003
Sulfur Dioxide	g/kWh	0.05
Nitrogen Oxides	g/kWh	0.16

* The other parameters were negligible.

To promote renewable energy adoption, the Iranian government has enacted supportive legislation [79], enabling both distributed and centralized renewable energy producers to feed surplus electricity back into the grid. As of 2017, the grid electricity purchase price was 0.192/kWh, while the sell-back price for renewable energy was set at 0.379/kWh [80]. For the purposes of this study, transmission losses in the power distribution network have not been considered in the analysis.

3) Wind Turbine (WT)

A generic wind turbine model was incorporated into the system, with its optimal capacity to be determined through Renewable Energy System (RES) performance optimization. The turbine generates Alternating Current (AC) electricity, enabling direct integration with the AC power distribution network without requiring additional power conversion equipment.

Previous studies have identified 17 m as the optimal hub height for wind turbines in Yazd [81], where ambient temperature variations significantly influence turbine performance. These temperature fluctuations affect air density, which in turn modifies the turbine's power output characteristics [82]. The power curve for the selected wind turbine model is presented in Fig. 4.

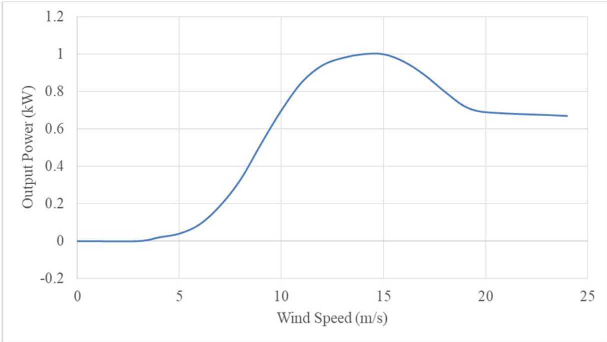


Fig. 4. The output power curve of the considered wind turbine for Yazd city [83, 84].

The capital costs of the assumed generic wind turbine are about 7000 $/kW and the O&M (Operation and Maintenance) cost of this component is equaled to 10 per kW [83, 84].

4) *Photovoltaic Panels (PV)*

A generic flat-plate photovoltaic panel with DC electrical bus was considered in which a horizontal axis tracker adjusts the slope and azimuth monthly. The capital and replacement costs of this component are 2500 $/year/kW [83, 84]. The relevant data of the suggested PV panel is shown in Table 3. This component is connected to a DC power line, thus it is necessary to use an electrical converter to synchronize the output of this component with the AC power line. Similar to the wind turbine, final amount of required capacity for this component is determined for each RES separately.

Table 3. Parameters of the assumed PV panels [85]

Parameter	Unit	Amount
Derating Factor	%	80
Ground Reflectance	%	20
Nominal Operating Cell Temperature (NOCT)	°C	47
Efficiency at Standard Test Conditions (STC)	%	19
Temperature Effect on the Power	%/°C	−0.5
O&M Cost of the PV Panel	$/year/kW	10
O&M Cost of the Tracker	$/year/kW	4.5

5) *Converter*

A typical electricity converter consists of an inverter and a rectifier. The inverter is responsible for synchronizing input and output voltage and the rectifier is converting DC to AC. In this study, a rectifier with the relative capacity amount of 100% and efficiency of 95% was considered. Also, the efficiency of the inverter was assumed to 95% as well. The O&M cost of the suggested converter was considered 20 $/year/kW [86]. This component makes the connection between the DC and the AC power lines.

6) *Storage (Battery)*

Excess generated electricity from the renewable resources can be sold back to the grid or can be stored in a storage system. A storage system consists of rechargeable batteries and controllers which mostly have significant capital and replacement costs (about 70,000 $/year/kW). Also, the O&M cost is about 1.5 $/year/kW [84]. The energy storage system is integrated with the DC power bus and serves two primary functions: (1) supplying electricity during periods of insufficient renewable generation, and (2) storing surplus energy production. The system incorporates an intelligent energy management strategy that enables economic optimization through arbitrage opportunities, when feed-in tariff rates exceed grid electricity prices, stored energy can be profitably dispatched to the grid. Under such conditions, the system automatically switches to grid-supplied power for local demand fulfillment while exporting the stored energy. The assumed parameters of this component is shown in Table 4.

Table 4. Used parameters for the assumed storage system[87]

Parameter	Unit	Amount
Initial State of Charge	%	0
Minimum State of Charge	%	5
Nominal Voltage	V	600
Nominal Capacity	Ah	167
Roundtrip Efficiency	%	90
Maximum Charge Current	A	167
Maximum Discharge Current	A	500

C. *Different Configurations of the Renewable Energy Systems*

Renewable Energy Systems (RES) typically require substantial capital investments [88]. To ensure comparability among different RES configurations, this analysis assumes identical implementation conditions, with a focus on operational and maintenance costs rather than initial capital requirements. This approach is justified by considering that sufficient funding is available for any potential RES combination under evaluation. Furthermore, while various national policies exist to promote RES adoption through financial incentives and support mechanisms [89], these factors have been excluded from the simulation parameters. Such policy-driven variables should instead be analyzed separately to maintain focus on the technical and operational performance metrics of each system configuration.

This study evaluates seven distinct Renewable Energy System (RES) configurations designed to meet the electricity demand of the study area. While each configuration maintains identical RES component types, their respective capacities are optimized to satisfy the load requirements. The analysis assesses three key performance metrics for each system: (1) levelized Cost of Energy (COE), (2) renewable fraction (defined as the percentage of total demand supplied by renewable sources), and (3) Greenhouse Gas (GHG) emissions.

The comparative assessment of these metrics enables the ranking of RES configurations based on their technical, economic, and environmental performance. The findings provide valuable insights for urban areas with similar climatic and energy demand characteristics to the study region.

All RES configurations that are investigated are shown in Table 5.

Table 5. All investigated RES in this study (✓ symbol shows the relevant component is considered in the configuration)

RES	Grid	PV Panels	Wind Turbine	Storage	Converter
RES #1	✓				
RES #2	✓	✓			✓
RES #3	✓	✓		✓	✓
RES #4	✓		✓		
RES #5	✓		✓	✓	
RES #6	✓	✓	✓		✓
RES #7	✓	✓	✓	✓	✓

All introduced RES are implemented and simulated with Homer software. This software has various renewable and non-renewable components and it is possible to model different types of Electricity Energy System (EES) by it. Homer uses a demand-base optimizer by default but it is possible to add economic and environmental criteria to the optimizer as well [90].

This study employs a multi-criteria assessment framework to evaluate and rank the Renewable Energy System (RES) configurations. Three key performance indicators are considered: (1) levelized Cost of Energy (COE), (2) renewable fraction (the percentage of demand met by renewable sources), and (3) Greenhouse Gas (GHG) emissions. A critical aspect of this analysis involves determining the relative weighting of these criteria, as their importance may vary depending on policy priorities and stakeholder perspectives. One method to determine the weight of each criterion is implementing of the opinions of experts [91]. For this purpose, thirty experts are selected and their opinions about the importance of every criteria are gathered. Finally, all the investigated RES are ranked.

D. *Sensitivity Analysis*

A sensitivity analysis was conducted to assess system performance under variable environmental conditions. Three key meteorological parameters were selected for evaluation: (1) Global Horizontal Irradiance (GHI), (2) wind speed, and (3) ambient temperature. Each parameter was varied within ±30% of its baseline value, representing the plausible range of climatic fluctuations in the study region. This analytical approach serves two primary purposes: (1) To quantify the robustness of each RES configuration to environmental variability, (2) to evaluate the potential applicability of the findings to other regions with similar climatic characteristics The ±30% variation range was selected to encompass both typical interannual variability and potential climate change impacts while maintaining physically realistic boundary conditions for the desert climate of Yazd. Chosen values for these parameters are shown in

Table 6.

Table 6 All assumed values for the parameters of sensitivity analysis

Mean Annual Parameters	Unit	Values
Global Horizontal Irradiance	$kWh/m^2/day$	3.57, 5.40, 7.24
Wind Speed	m/s	4.33, 6.56, 8.79
Temperature	℃	10.47, 15.87, 21.26

E. *Used Relations of Investigating System*

In this research, the physical model of a PV panel with single diodes and a series resistance is used to calculate the output power from PV component. Eq. (1) indicates the maximum PV-cell power production [92].

$$P_{max.c}(t) = V_{OC.c}(t).I_{SC.c}(t).FF(t) \tag{1}$$

where $V_{OC.c}(t)$ and $I_{SC.c}(t)$ are the open circuit voltage and the short circuit current, respectively. Eqs. (2) and (3) show the how to calculate the values of $V_{OC.c}(t)$ and $I_{SC.c}(t)$.

$$I_{SC.c}(t) = (I_{SC.c.stc} + K_i\,(T_C\,(t) - 25))\,\frac{G(t)}{1000} \tag{2}$$

$$V_{OC.c}(t) = V_{OC.c.stc} + K_v\,(T_C\,(t) - 25) \tag{3}$$

where K_v, K_i and are the temperature coeficents of voltage and current, respectively. $G(t)$ shows global solar iiradiance at time *t*. $T_C\,(t)$ indicates PV-cell temperature at time *t* and is defined with Eq. (4).

$$T_C(t) = T_a\,(t) + \frac{G(t)(NOCT - 20)}{800} \tag{4}$$

where NOCT shows the nominal operating PV-cell temperature and $T_a\,(t)$ is ambiant temperature at time *t*. The *FF (t)* indicates the fill facor of PV-cell at time *t* and is defined with Eq. (5).

$$FF(t) = (1 - r_s(t))\,.\frac{v_{oc}(t) - \ln(\,v_{oc}(t) + 0.72)}{v_{oc}(t) + 1} \tag{5}$$

where $v_{oc}(t)$ and $r_s(t)$ are the normalized open circuit voltage and series resistance for the PV-cell (see Eqs. (6) and (7)).

$$\mathrm{v_{oc}(t)} = \frac{\mathrm{V_{oc.c}(t)}}{\mathrm{V_t(t)}} \tag{6}$$

$$\mathrm{r_s(t)} = \frac{\mathrm{I_{SC.c}(t)}}{\mathrm{V_{OC.c}(t)}}\,\frac{\mathrm{V_{OC.c.stc}(t)}}{\mathrm{I_{SC.c.stc}(t)}}\,(1 - \frac{\mathrm{FF_{stc}}}{\mathrm{FF_{0\,stc}}}) \tag{7}$$

$$\mathrm{V_t(t)} = \frac{\mathrm{n.K_B.T_{a.k}\,(t)}}{\mathrm{e}} \tag{8}$$

where K_B is boltzmann's constant, *n* is diode idiality factor, and $T_{a.k}\,(t)$ is ambient temperature in Kelvin at time *t*.

It has to say that the available data in HOMER are for the PV-module and not for the PV-cells. Hence,

$$P_{max.c.stc}(t) = \frac{P_{max.m.stc}(t)}{N_{C.M}} \tag{9}$$

$$V_{OC.c.stc}(t) = \frac{V_{OC.m.stc}(t)}{N_{C.M}} \tag{10}$$

$$I_{SC.c.stc}(t) = I_{SC.m.stc}(t) \tag{11}$$

$$P_{av.PV}(t) = N_{S.M}.N_{P.M}N_{C.M}P_{max.C} \tag{12}$$

where $N_{P.M}$ and $N_{S.M}$ indicate the number of PV-modules connected in parallel and series. $N_{C.M}$ shows number of PV-cells in PV-module and $P_{av.PV}(t)$ is the output power of the PV component.

In order to evaluate the wind energy potential, the probability density function for wind velocity *V* is shown by Eq. (13) [93, 94].

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{13}$$

where *V* is the mean wind velocity, *c* is a dimensionless shape parameter and *k* is the scale parameter which has units similar to the speed (m/s). These parameters are obtained from Justs *et al.* [95, 96] as follows:

$$k = 0.83V^{0.5} \tag{14}$$

$$c = \frac{V}{\Gamma(1+k^{-1})} \quad (15)$$

where Γ is the gamma function. The available power of the wind per unit area is calculated by [97, 98]:

$$P_{wind} = \frac{1}{2}\rho V_m^3 \left(\frac{W}{m^2}\right) \quad (16)$$

where V_m is the monthly mean wind speed (m/s) and ρ is the standard air density. Considering an ideal turbine, power output is influenced by pressure and temperature. Therefore, the corrected monthly air density $\bar{\rho}\ (\frac{kg}{m^3})$ is calculated by Eq. (17) [99, 100].

$$\bar{\rho} = \frac{\bar{P}}{R_d \bar{T}} \quad (17)$$

where R_d shows the specific gas constant for air (*J/kgK*), $\bar{T}$ indicates the monthly mean air temperature in degrees Kelvin and $\bar{P}$ is the monthly mean air pressure (N/m^2). Hence the power available in wind at the standard height 10 m, can be obtained from Eq. (18) [101]:

$$P_{10} = \frac{1}{2}\bar{\rho} V_m^3 \left(\frac{W}{m^2}\right) \quad (18)$$

Also, the available mean power per month for a height less than 100 m, above the ground level can be calculated as [102–104]:

$$P_h = 360\, \bar{\rho} V_m^3 (\frac{h}{10})^{3\alpha} \left(\frac{W}{m^2}\right) \quad (19)$$

where α shows the roughness factor.

Battery banks, as the storage system, are commonly used in RES. The power of the battery at charge state is calculated by Eq. (20) [105]:

$$P_{BAT}(t) = P_{BAT}(t-1) \times (1-\sigma) + \left[P_{RES}(t) - \frac{P_{Load}(t)}{\eta_{INV}}\right] \times \eta_{BAT} \quad (20)$$

where $P_{BAT}(t-1)$ shows the charge state at time $t-1$, $P_{BAT}(t)$ expresses the battery state of charge at time t. Also, η_{INV} and η_{BAT} are the inverter and the battery charge efficiency, where are considered 0.95 and 0.9, respectively. $P_{Load}(t)$ is the load demand, σ is the self-discharge rate of the battery and $P_{RES}(t)$ is the power generated by PV and WT components.

IV. Result and Discussion

A specific amount of the electricity demand (AC load) was considered for the all investigated RES. The monthly profile of AC load is shown in Fig. 5.

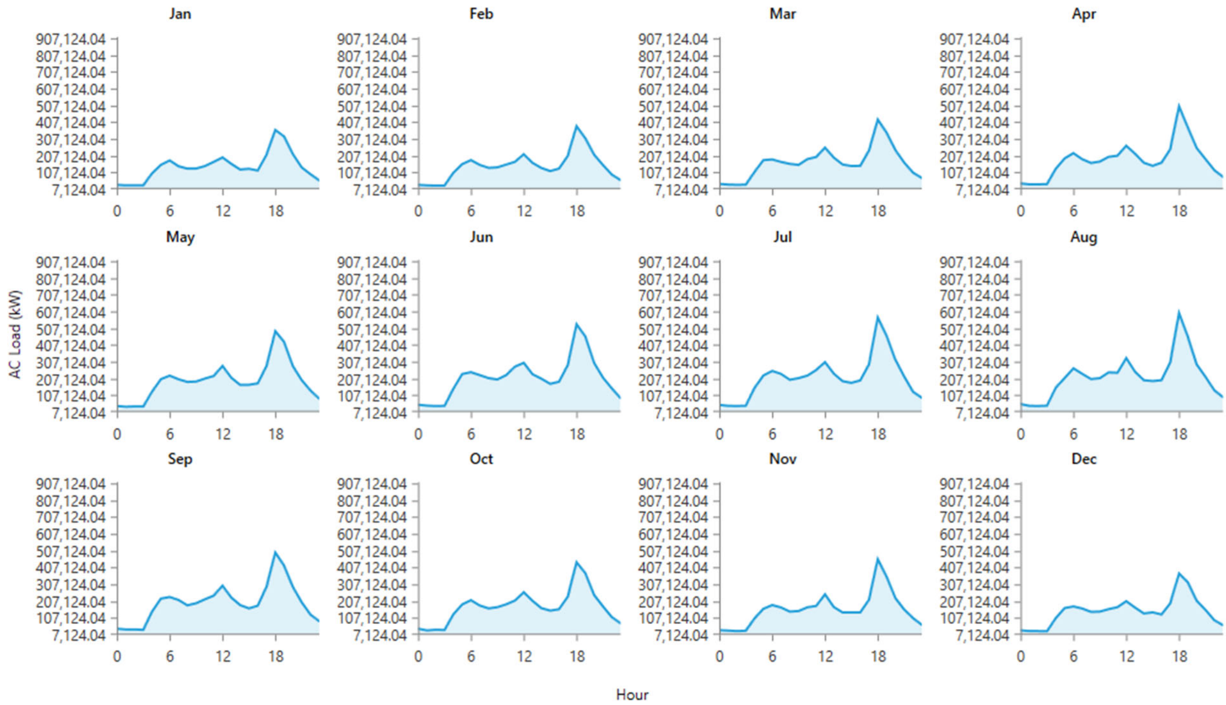


Fig. 5. Monthly profile of AC load in the study area by combining accurate weather data and the standard profile of electricity demand in HOMER.

The maximum load was related to hours between hours 17 and 20 for all months. Also three hours including 6, 12 and 18 showed relative peaks during a day.

One of the advantages of the discussed RES is the reduction of the amount of the electricity purchased of the gird. The result is shown in Fig. 6.

According to Fig. 6, it's clear that using only photovoltaic panels (RES #2) is not reasonable and it makes no (few or negligible) difference compared to RES #1. The least amount of purchased electricity is related to RES #6 with 179.62 GWh/yr which is 4.89 times smaller than RES #1 (only grid). Also, the obtained results showed that when wind turbine was used the amounts of electricity purchased was always less than 175 GWh/yr. Dividing the supplementary of electricity purchased by the total demand specifies the renewable fraction which is reported in Table 7.

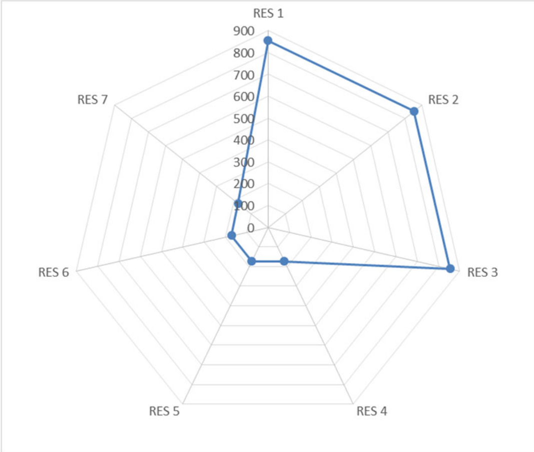


Fig. 6. Purchased electricity of the grid (GWh/yr).

Table 7. Renewable fraction of the investigated RES

RES	Renewable Fraction (%)
RES #1	0.000
RES #2	0.001
RES #3	0.001
RES #4	96.500
RES #5	96.500
RES #6	96.500
RES #7	96.500

Table 7 shows that RES configuration consists of grid and only wind turbine had the highest renewable fraction. It means that wind turbine is a better choice for the study area. It should be noted that the difference between RES #2 and RES #3, RES #4 and RES #5, RES #6 and RES #7 is related to the utilization of storage system. As discussed, excess electricity can be sold back directly to the grid, thus according to

Table 6, utilization of storage system will not make notable difference. This inference agrees with results shown in Fig. 6. Selling back the additional produced electricity to the grid affects the COE. Lower amounts of COE not only economically affect the consumers but also allow for further urban development. The COE of the investigated RES configurations are represented in

Table 8.

Table 8. COE of the investigated RES

RES	Cost of Energy ($)
RES #1	0.1920
RES #2	0.1921
RES #3	0.1926
RES #4	−0.2071
RES #5	−0.2070
RES #6	−0.2071
RES #7	−0.2069

The obtained results show that the minimum amount of COE is related to RES #6 and RES #4 but the differences are insignificant when the wind turbine is used. It means using the wind energy in the study area will bring more economic benefits. More over in this study, GHG emission was evaluated as well. The given results are shown in Fig. 7.

The analysis reveals a direct correlation between grid electricity consumption and GHG emissions, as clearly demonstrated in Fig. 7. Notably, the integration of wind turbines results in a substantial reduction in GHG emissions, consistent with findings from prior studies. The comprehensive evaluation of all investigated Renewable Energy Systems (RES) considered three key criteria: (1) levelized Cost of Energy (COE), (2) renewable fraction, and (3) GHG emissions. Based on this multi-criteria assessment, the systems were systematically ranked, with the comparative results presented in Table 9.

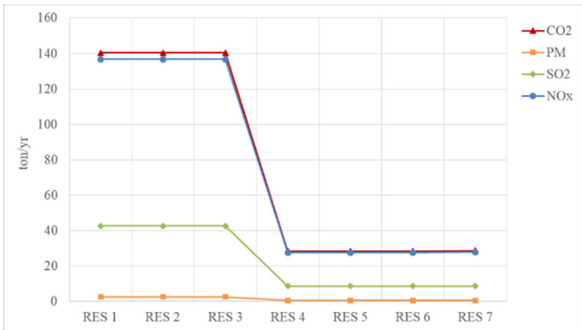


Fig. 7. GHG emissions (ton/yr).

Table 9. Ranking of the investigated RES based on the criteria (The best RES was ranked as 1)

RES	Cost of Energy	Renewable Fraction	GHG Emission
RES #1	4	3	6
RES #2	5	2	5
RES #3	6	2	5
RES #4	1	1	3
RES #5	2	1	2
RES #6	1	1	1
RES #7	3	1	4

In this step, the relative weights of the three evaluation criteria (COE, renewable fraction, and GHG emissions) are employed. An expert-based weighting approach was deployed involving thirty selected energy specialists who provided ordinal rankings of the criteria's importance; the collected rankings were analyzed through discrete probability distributions and normalized to derive quantitative weights between 0 and 1, and thereby transforming qualitative expert judgments into probabilistic weights for systematic RES assessment. Larger values indicate greater importance of the criterion. The results of ranking criteria are shown in Table 10.

Table 10. Ranking of the criteria based on the opinions of the experts

	Cost of Energy	Renewable Fraction	GHG Emission
Weight	0.4	0.2	0.4

As it can be seen from Table 10, based on the opinions of the experts, two criteria including Cost of Energy and GHG Emission is twice as important as the Renewable Fraction. For achieving the final results of ranking the RES, Table 9 and Table 10 were considered as two matrices and multiply to each other. Table 9 is a 3×3 matrix and Table 10 is a 3×1 matrix, thus their multiplication is a 3×1 matrix. In this way, the final result is a new matrix indicating ranking of the investigated RES configuration. The final ranking matrix is shown in Table 11.

Table 11 Final ranking of the investigated RES

RES	Rank
RES #1	6
RES #2	5
RES #3	7
RES #4	2
RES #5	3
RES #6	1
RES #7	4

The results demonstrate that RES Configuration #6, comprising wind turbines, PV panels, and grid connection, emerges as the optimal system based on the evaluation criteria. In contrast, Configuration #3 (grid, PV panels, and storage system) ranks as the least favorable option. A comparative analysis between Configurations #6 and #7 reveals that integrating storage systems is economically disadvantageous when surplus electricity can be exported to the grid at a higher feed-in tariff, as the added costs of storage outweigh potential revenue from arbitrage. This conclusion is similar to results of studies done by Kalathil *et al.* [106] and Fanelli *et al.* [107] for other climates. However, some other researchers have reached another conclusion. According to their results, using electricity storage systems is the best alternative solution and it is not possible to sell back the excess generated electricity [108–110]. Yet, using wind turbine is more effective for cities which are in windy regions. It seems this conclusion is affected by this truth that wind energy can be used even at the night. This conclusion is compatible with the results of studies performed by Al-Dousari *et al.* [111] and Ammari *et al.* [107].

Sensitivity analysis revealed that wind speed exerted the strongest influence on system performance, significantly affecting the Cost of Energy (COE), carbon emissions, and renewable fraction, as demonstrated in Fig. 8 and 9. In contrast, variations in temperature showed negligible impacts. These findings establish wind speed as the dominant environmental parameter for renewable energy systems in the study area and similar regions, with implications for site selection and system design prioritization.

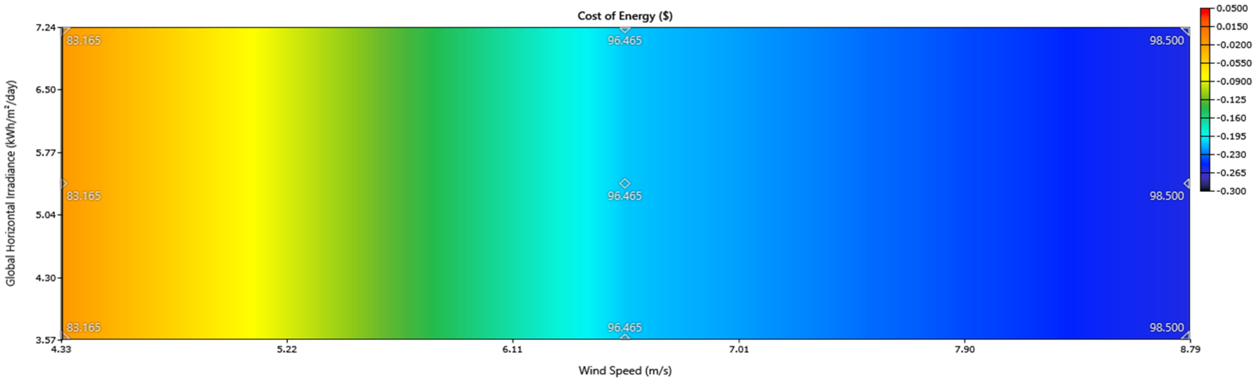


Fig. 8. Sensitivity of Cost of Energy based on the Wind Speed (x-axis) and Global Horizontal Irradiance (y-axis). Inside numbers show Renewable Fraction.

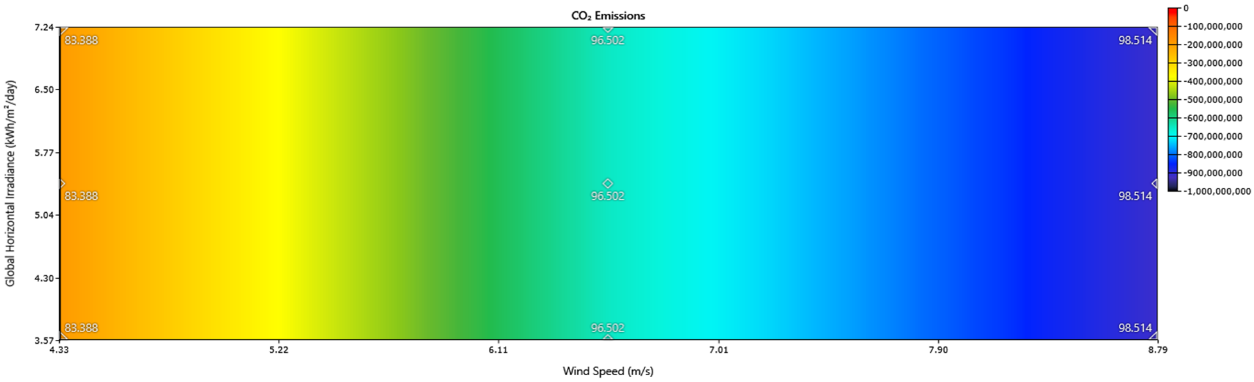


Fig. 9. Sensitivity of CO_2 Emission based on the Wind Speed (x-axis) and Global Horizontal Irradiance (y-axis). Inside numbers show Renewable Fraction.

V. Conclusion

The Global population growth has directly contributed to climate change through increased energy demand, necessitating exploration of sustainable alternatives to fossil fuels. While renewable energy systems offer environmental benefits, their economic viability varies significantly across different regions. The integration of distributed energy production with grid connectivity presents opportunities to improve economic performance through excess electricity sell-back mechanisms. Identifying optimal renewable energy configurations for specific regions requires systematic evaluation across multiple decision-making criteria and comprehensive ranking methodologies.

This study evaluated a hybrid renewable energy system comprising photovoltaic panels, wind turbines, grid connectivity, converters, and storage systems to meet specific electricity demands in a windy desert urban environment. Regional weather, economic, and demographic data were collected for Yazd city in Iran as the study area. All possible configurations were investigated to determine renewable fraction, cost of energy, and greenhouse gas emissions for each structure. Expert opinion from thirty energy specialists was incorporated to establish weighted criteria importance for comprehensive evaluation, followed by systematic ranking of all investigated renewable energy system configurations.

The research contributes significantly to the renewable energy discourse by addressing the unique characteristics of hot desert urban environments with dual high solar and wind resources. The practical matrix-based ranking methodology enhanced by expert input provides a more accessible yet robust alternative to complex optimization models. Findings challenge conventional assumptions about solar dominance in desert regions by demonstrating wind resource superiority in this context. The component-agnostic approach ensures broader applicability across evolving technology landscapes, while the systematic sensitivity analysis creates a transferable framework for regions with similar climatic conditions.

Key findings from this study include:

- Configuration #6 (grid, PV panels, and wind turbines without storage) emerged as the optimal renewable energy system for the study area.
- The optimal system achieved approximately 96.5% renewable fraction with a negative cost of energy at $−0.2071, indicating net economic benefit.
- Greenhouse gas emissions were reduced by approximately 80% compared to grid-only configurations.
- Wind turbines demonstrated significantly higher electricity generation potential than photovoltaic panels in this desert urban environment.
- Grid-connected systems with favorable sell-back rates rendered storage systems economically disadvantageous, contradicting previous studies on storage necessity.
- Wind speed was identified as the dominant environmental parameter for system performance, significantly affecting cost of energy, carbon emissions, and renewable fraction.
- Temperature variations showed negligible impact on overall system performance.

VI. Future Work and Limitations

This study faced several methodological and scope-related limitations that open avenues for future research. First, the analysis employed generic components for renewable energy systems without specifying particular technologies, which limits the practical applicability of the findings. Future work should examine specific technological configurations to provide more targeted recommendations for implementation. Additionally, the exclusion of bio-energy, geothermal, and hydro-power due to data limitations presents an opportunity for subsequent research to incorporate these renewable sources as reliable datasets become available. The analysis did not account for transmission losses in power distribution networks or policy-driven variables such as financial incentives and support mechanisms, both critical factors that future studies should integrate to better reflect real-world conditions. Furthermore, the assumption of identical implementation conditions across different RES configurations, focusing only on operational and maintenance costs rather than initial capital requirements, warrants more comprehensive economic modeling in future work that incorporates the full lifecycle costs and financing considerations.

The findings of this study are also constrained by methodological choices and geographical specificity. The multi-criteria ranking framework's reliance on expert opinions from thirty energy specialists to determine criteria weightings could be supplemented in future research with sensitivity analyses of these weightings or broader stakeholder perspectives. While the study concluded that integrating storage systems is economically disadvantageous in grid-connected systems with favorable sell-back rates, future work should investigate scenarios with varying sell-back rates and off-grid applications to provide a more complete picture. The sensitivity analysis, limited to variations of ±30% in environmental parameters, could be expanded in future studies to consider more extreme scenarios that may arise with climate change. Lastly, as the study focused specifically on Yazd, Iran's hot desert climate, future research should test the framework's transferability by applying it to diverse geographical and climatic contexts, validating whether the multi-criteria approach can consistently identify balanced solutions across varying conditions while maintaining its aim of finding the most appropriate conditions considering all criteria together.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Farshid Mohammadkhani gathered the data, developed the modeling, and carried out the analysis. Ali Khatibi gathered the data, developed the modeling, and carried out the analysis. Hooman Aminzadeh Vahedi conducted the literature review, wrote the literature review section, and prepared the final draft. Fateme Razi Astaraie supervised the entire study. All authors have read and approved the final version of the manuscript.

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