International Journal of Energy Production and Management
https://www.acadlore.com/journals/IJEPM

Hybrid Wind-Solar Systems: A Comprehensive Simulation, Optimization, and Decision-Support Framework for Arid Climates with a Case Study in Kuwait

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Received: 12-02-2025 **Revised:** 04-02-2026 **Accepted:** 04-10-2026

Citation: M. A. Fouad, M. A. Rizk, A. Alhajry, and M. S. Abdelmoez, "Hybrid wind-solar systems: A comprehensive simulation, optimization, and decision-support framework for arid climates with a case study in Kuwait," *Int. J. Energy Prod. Manag.*, vol. 11, no. 2, pp. 264–284, 2026. https://doi.org/10.56578/ijepm110201.

Abstract: The transition from fossil fuels to renewable energy is vital for addressing climate change and ensuring energy security. Hybrid renewable energy systems (HRES), particularly those integrating solar photovoltaic (PV) and wind power, have emerged as a promising solution to overcome the intermittency and variability of individual sources. This study develops a comprehensive simulation and optimization framework for hybrid PV–wind systems, incorporating advanced energy storage options such as lithium-ion batteries and ultracapacitors. Using high-resolution meteorological and load data, both grid-connected and off-grid configurations are analyzed to evaluate system reliability, cost-effectiveness, and adaptability across different climates. A special focus is given to Kuwait, where high solar irradiance and moderate wind resources align with national energy diversification goals under Kuwait Vision 2035. The results highlight the technical and economic feasibility of hybrid systems, showing significant improvements in energy yield, load matching, and levelized cost of energy (LCOE) compared to standalone technologies. Furthermore, the study underscores the importance of intelligent control strategies, advanced component technologies, region-specific optimization, and explicit planning and performance evaluation insights in ensuring sustainable and resilient deployment of hybrid renewable systems.

Keywords: Hybrid renewable energy systems; Photovoltaic-wind integration; Energy storage optimization; Kuwait Vision 2035; Levelized cost of energy; Arid climate feasibility; Techno-economic modeling; Off-grid electrification

1 Introduction

The global transition from fossil fuels to renewable energy sources is increasingly seen as an essential step toward addressing the dual challenges of climate change and energy security. Among renewable technologies, solar photovoltaic (PV) and wind energy are among the most widely deployed due to their abundance, maturity, and environmental friendliness [1] as shown in Figure 1. However, despite their advantages, both energy sources exhibit intermittency and variability that hinder their reliability when used independently. Solar power is limited to daylight hours and is affected by weather and seasonal variations, while wind patterns fluctuate with geography and meteorological conditions. These issues complicate system planning and often necessitate oversizing or integrating storage to maintain a continuous power supply [2].

To overcome these limitations, hybrid renewable energy systems (HRES), particularly those combining solar and wind energy, are increasingly considered a viable solution for both off-grid and grid-tied applications, as seen in Figure 2 and Figure 3. By integrating PV and wind turbines into a single system, the output can be stabilized across day and night, and across varying seasonal patterns. When solar production drops due to clouds or sunset, wind power can often compensate, and vice versa [3]. This complementarity significantly enhances overall system performance, reduces the need for large storage components, and improves the load-following capabilities of renewables. These systems are also adaptable to a wide range of scales, from rural microgrids to utility-scale installations [4]. In the context of the Middle East, and particularly Kuwait, the integration of hybrid PV-wind systems aligns with the nation's strategic energy objectives. Kuwait Vision 2035 ("New Kuwait") explicitly aims to increase the share of renewables to 15% of the energy mix by 2030–2035. Given the country's high solar irradiance—exceeding 2,000 kWh/m²/m²/year—and moderate wind speeds, particularly in coastal and desert areas, hybrid systems offer a reliable path forward [5].

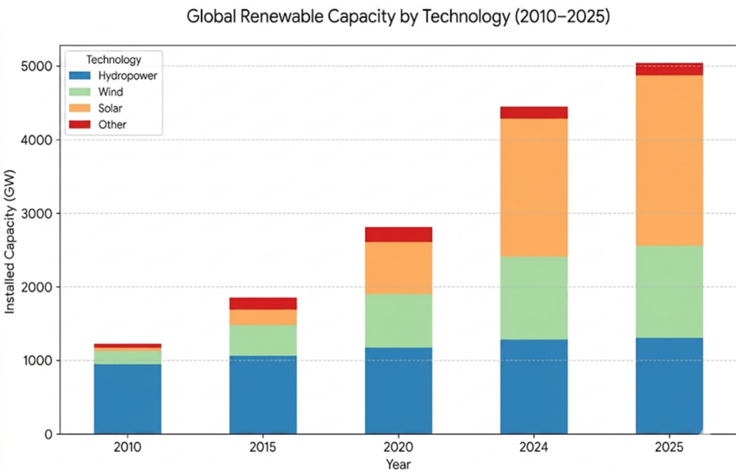

Figure 1. Growth of global renewable energy capacity from 2010–2025

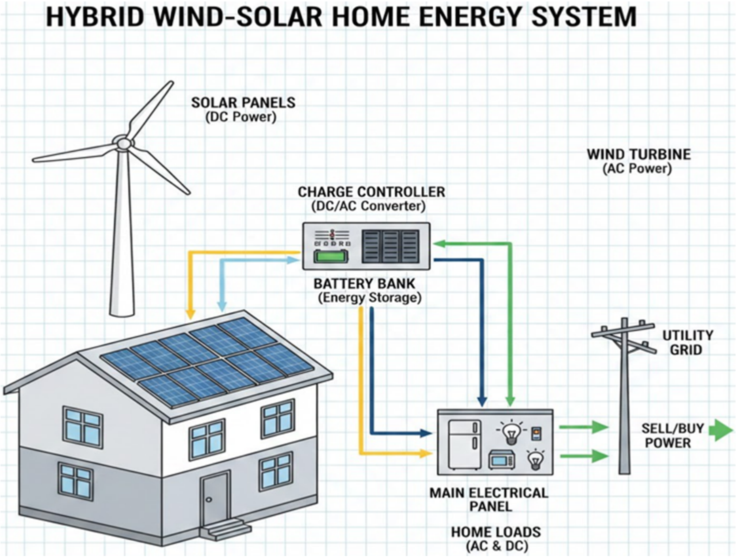

Figure 2. Schematic of hybrid wind-solar systems

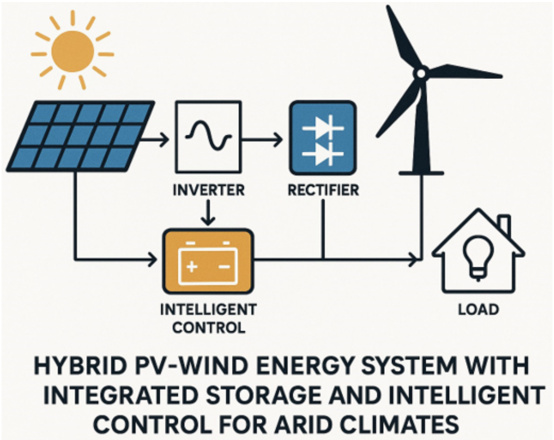

Figure 3. Schematic of a hybrid photovoltaic (PV)-wind system with battery and inverter

The interest in wind-solar hybrid systems has surged in recent years.

According to the International Renewable Energy Agency (IRENA), hybrid systems have seen a compound annual growth rate exceeding 15% over the past decade in distributed energy applications [6]. This growth is driven by improvements in power electronics, cost reductions in PV modules and small wind turbines, and the availability of reliable energy management systems (EMS). Such systems ensure real-time load matching, control over battery state-of-charge, and smart grid interaction. Importantly, when supported by intelligent control strategies—including fuzzy logic, artificial neural networks, and model predictive control—the performance of hybrid energy systems improves significantly under dynamic weather and load profiles [7].

In addition to energy generation sources, the inclusion of energy storage systems—such as lithium-ion batteries and ultracapacitors—plays a pivotal role in ensuring an uninterrupted supply. While batteries provide energy balancing over hours, ultracapacitors offer a rapid response to short-term fluctuations and load spikes. Integrating both provides a hybrid energy storage strategy that reduces battery wear and increases system lifespan [8, 9]. Depending on system design and application context, energy storage can also reduce grid dependence, enhance self-sufficiency, and offer backup during outages [10].

One of the primary contributions of this research is to move beyond purely technical analysis and provide a decision-support framework for planners, investors, and policymakers. While existing tools such as Hybrid Optimization Model for Multiple Energy Resources (HOMER) and Transient System Simulation Tool (TRNSYS focus on techno-economic simulation, our framework integrates advanced control, uncertainty analysis, and explicit planning-oriented metrics to better inform infrastructure investment and deployment strategies under the uncertain conditions of arid climates.

One of the motivations for this research stems from the challenges observed in existing systems. System sizing remains complex due to uncertainties in weather and load forecasting. Over-sizing leads to capital cost inefficiencies, while under-sizing causes unmet demand and reliability issues. Furthermore, the optimal control of charge-discharge cycles, inverter management, and load prioritization requires an integrated modeling framework that most off-the-shelf simulation tools do not fully provide [11–13].

This study aims to develop a comprehensive simulation and optimization. A framework for hybrid PV-wind systems with optional battery and ultracapacitor storage. The approach will consider both grid-connected and off-grid configurations. To ensure realistic performance, hourly solar irradiance, wind speed, and temperature data from the European Centre for Medium-Range Weather Forecasts Reanalysis 5th Generation (ERA5) reanalysis dataset (2013–2023) and localized Kuwait Institute for Scientific Research (KISR) measurements will be used. Location-specific residential and commercial load profiles from Kuwait's Ministry of Electricity and Water will be incorporated. Optimization goals will be studied thoroughly using a custom MATLAB/Simulink model, the details of which are formally defined in Section 3. The model's objective functions, decision variables, and constraints are explicitly stated to ensure reproducibility.

To benchmark system performance and support configuration decisions, a series of case studies will be conducted in different climate zones. A dedicated case study will evaluate Kuwait's conditions, given its potential for dual-source renewable energy generation. Projects like the Shagaya Renewable Energy Park have demonstrated Kuwait's technical readiness to adopt solar and wind technologies on a large scale, making it an ideal testbed for hybrid system integration [14]. These case studies will test system behavior under arid, coastal, and temperate conditions, helping identify which configuration suits each location best. Moreover, comprehensive sensitivity and uncertainty analyses will be conducted on storage sizing, cost of energy (COE), and net present cost (NPC) to assess economic feasibility under different assumptions.

In summary, hybrid wind-solar energy systems offer a promising and increasingly necessary pathway to sustainable energy generation. Their capacity to balance resource variability, reduce reliance on centralized infrastructure, and offer modular deployment makes them ideal for diverse applications. However, their successful deployment depends heavily on detailed system design, local resource assessment, intelligent control, and informed planning decisions. This research builds on foundational studies [1–4] and aims to provide an applied, simulation-based framework that supports the design and strategic planning of high-performance, cost-effective hybrid renewable systems under realistic constraints.

2 Literature Review

The following literature review has been substantially condensed and refocused to directly support the proposed framework's contributions in simulation, optimization, and decision-support, particularly for arid climates. Topics only weakly connected to the core methodology have been reduced.

The academic interest in hybrid renewable systems dates back over two decades, when researchers began exploring combinations of solar and wind to overcome the weaknesses of each source alone. Early studies, particularly in the late 1990s and early 2000s, focused heavily on feasibility assessments for remote, off-grid locations where energy infrastructure was either absent or unreliable. These systems were typically evaluated using static models and were sized based on assumed average meteorological conditions. A key contribution from this period was work on techno-economic analysis of PV-wind systems using various sizing methods, which emphasized how the choice of sizing technique could influence both cost and performance outcomes [10].

2.1 Feasibility of Photovoltaic-Wind Systems in Kuwait

In regions like Kuwait—where solar irradiance is among the highest globally and coastal areas exhibit moderate wind resources—the question of whether hybrid PV-wind systems can reliably and sustainably operate has become increasingly relevant. Studies must account not only for intermittency but also for local environmental stressors such as dust, heat, and sandstorms [1, 15]. This raises the feasibility question of whether small or vertical-axis wind turbines (VAWTs), strategically placed and supported by intelligent control systems, can provide stable power—especially during low solar periods—and align with Kuwait Vision 2035 sustainability goals. While global studies often report universal feasibility of PV-wind integration, the Kuwaiti context highlights the importance of considering localized environmental factors that may compromise long-term system reliability.

The feasibility of integrating wind turbines with PV systems in Kuwait has become an important focus of research as the nation seeks to diversify its energy portfolio in response to depleting fossil fuel reserves and increasing environmental concerns. With high levels of direct normal irradiance throughout most of the year, Kuwait has long been recognized as having strong potential for solar energy deployment [16, 17]. However, the limitations of solar- only systems—such as reduced performance during dust storms, high operating temperatures, and diurnal intermittency—have led researchers to consider hybrid configurations with wind energy to enhance reliability and performance [18, 19]. Here, a recurring contradiction arises: while HOMER-based simulations emphasize levelized cost of energy (LCOE) reductions when wind is added, TRNSYS and MATLAB models often stress the technical complexity and intermittency challenges of integrating two fluctuating sources. This demonstrates how outcomes depend not only on resource data but also on modeling assumptions.

The early works emphasized that integrating wind turbines alongside PV panels in arid regions like the Gulf could significantly improve load matching and reduce the need for oversized storage systems [19, 20]. In Kuwait, wind resource assessments conducted by the KISR identified promising zones, particularly along the coastal areas and offshore islands such as Failaka, where average wind speeds exceed 5 m/s during evening and nighttime hours—precisely when solar output ceases [21, 22]. Simulation tools like HOMER and TRNSYS have been used in recent studies to demonstrate that PV-wind hybrids, when properly sized and strategically located, can reduce fuel consumption and LCOE by up to 40% compared to diesel-based or standalone solar systems [23–26]. Yet, the extent of LCOE reduction varies widely across studies: some report 40% reductions under idealized coastal conditions, while others show marginal savings once transmission costs, land use constraints, and storage degradation are included. This inconsistency underscores the need for more realistic techno-economic models that capture hidden costs.

From a technical perspective, the harsh Kuwaiti climate presents considerable operational challenges for both PV and wind systems, which hybrid configurations must be designed to withstand. Factors such as dust accumulation, salt corrosion, and thermal cycling negatively impact PV module efficiency and lifespan [18, 27]. Researchers have proposed a variety of thermal regulation strategies, including passive cooling using heat sinks and phase change materials (PCMs), to address PV overheating in high-temperature conditions [27–30]. However, cooling strategies often face cost-performance trade-offs: while PCMs improve stability, they add capital cost and maintenance complexity, and low-cost passive designs may underperform under extreme heat waves. This divergence reveals a key barrier to scaling PV in desert climates.

In parallel, wind turbine designs have been tailored to suit Kuwait's predominantly low to medium wind speeds. VAWTs such as Darrieus and H-rotor types have demonstrated better performance under turbulent urban conditions and are more mechanically resilient to dust and sand than horizontal-axis models [31, 32]. Nevertheless, this resilience at the expense of efficiency, since VAWTs typically underperform HAWTs in steady wind conditions. Thus, the "optimal" turbine type is context-dependent: urban/turbulent zones favor VAWTs for durability, while coastal installations favor HAWTs for energy yield.

Moreover, hybrid energy systems in Kuwait have benefited from the development of intelligent control strategies for real-time energy management. These include predictive load-balancing algorithms, adaptive MPPT techniques, and fuzzy-logic-based dispatch optimization, which help to stabilize system performance despite environmental variability [33–35]. The success of pilot-scale hybrid installations at Sabah Al-Ahmad Renewable Energy Complex and other testbeds operated by KISR has validated many of these design principles, providing empirical support for scaling such systems in remote and urban applications alike [36, 37]. Yet, practical deployment still lags behind simulation-based enthusiasm, as many of these controllers demand high-quality meteorological datasets that are often unavailable or inconsistent in Kuwait.

Economically, hybrid PV-wind systems in Kuwait offer a compelling case, particularly when compared to conventional generation or single-resource renewables. Recent studies have also found that the inclusion of wind turbines in hybrid designs significantly improves return on investment and shortens payback periods to under a decade, especially in areas currently reliant on diesel generators. However, this optimistic outlook is not universal: some studies highlight that high upfront capital cost, coupled with the uncertainty of long-term turbine reliability in dusty climates, may offset projected payback advantages. In practice, hybrid feasibility is sensitive to whether analyses include hidden costs such as O&M for cleaning, battery replacement, and grid expansion [28]. The hybridization approach allows for more consistent power generation throughout the day and mitigates the need for oversized batteries, which are costly and sensitive to thermal degradation. Additionally, integrating moderate-sized wind turbines helps to buffer against PV output drops caused by sudden sandstorms or cloudy weather. Still, system resilience under combined solar–wind intermittency remains an open question, as most Kuwaiti studies rely on simulated meteorological profiles rather than long-term measured datasets.

While there are still knowledge gaps in long-term mechanical reliability and accurate prediction of combined output under real meteorological profiles, the current literature provides strong support for the continued development of hybrid PV-wind systems in Kuwait as both technically feasible and economically viable. The alignment between solar and wind profiles, enhanced by intelligent controls and robust design adaptations, positions hybrid systems as a strategic asset in Kuwait's national energy planning efforts.

2.2 Global Advances in Hybrid Photovoltaic-Wind Systems

As computational capabilities improved and meteorological datasets became more widely available, the mid-2000s ushered in a more rigorous approach to hybrid system modeling. Researchers like work introduced probabilistic and optimization-based models that utilized real-world solar and wind data for more accurate system design [12]. Their 2007 study proposed a model capable of identifying cost-optimal configurations while meeting reliability constraints, setting the stage for the integration of optimization algorithms in hybrid system research. These works also revealed why results varied across contexts: models that incorporated seasonal variability favored wind in coastal regions, while solar dominated in desert climates, highlighting the resource-dependency of "optimal" mixes.

Around the same time, the focus expanded to include small hydro systems in combination with PV and wind, as seen in work in Ethiopia, where resource availability dictated a multi-source configuration [13]. This contrast between Gulf studies (PV-wind dominated) and East African work (multi-source, including hydro) shows that hybridization strategies are not universal but must be tailored to local geographies.

By the early 2010s, simulation platforms such as HOMER and MATLAB/Simulink became mainstream in academic research, facilitating more detailed assessments of hybrid configurations under variable conditions. These tools enabled scenario analysis, lifetime cost estimation, and the incorporation of battery storage, significantly improving the realism of techno-economic evaluations. Yet, tool choice influenced reported feasibility: HOMER emphasized economic metrics (LCOE, payback), whereas MATLAB studies focused on control precision and dynamic performance. This divergence illustrates why comparisons across literature often yield contradictory results.

The complexity of simulation-based design was further compounded by the need to optimize multiple objectives simultaneously—such as cost, reliability, autonomy, and environmental impact.

Recent validation studies using simulation platforms like HOMER Pro, MATLAB/Simulink, and TRNSYS have demonstrated the robustness of hybrid modeling techniques when tailored to regional datasets, including those representing harsh desert climates [8, 38]. Such tools can be adapted to forecast hybrid system performance under Kuwait-specific conditions, using granular meteorological data and realistic residential or commercial load profiles. However, a critical limitation is the scarcity of long-term, high-resolution data in Kuwait, which reduces confidence in model-based predictions. Without measured data for validation, these simulations risk overestimating real-world performance.

The following sections (Advancements in Component Technologies, Energy Storage, Control Systems, and Mechanical Synergy) have been significantly shortened to focus only on elements directly relevant to the proposed framework's decision-support and planning orientation. Detailed technological descriptions have been moved to an appendix or condensed.

2.3 Energy Storage and Control Advances

Moving into the mid-2010s, the role of storage in hybrid systems received growing attention, particularly as lithium-ion battery prices began to fall and concerns about supply reliability intensified. Reviews helped consolidate knowledge about the technical characteristics, life cycle, and control requirements of battery technologies relevant to stationary energy systems [9]. This was followed by increasing research interest in combining battery banks with high-speed storage media such as ultracapacitors to balance long-term and short-term energy delivery needs—a hybrid energy storage concept that had previously been explored primarily in transportation and aerospace sectors but was now being adapted for renewable systems. Despite the promise, contradictions remain: lithium-ion is praised for cost-effectiveness but criticized for thermal instability in desert climates, while flow batteries offer durability but remain prohibitively expensive. These trade-offs show why no single storage technology has yet emerged as dominant in Gulf applications.

Contemporary advances in storage technologies—such as lithium iron phosphate (LiFePO), flow batteries, and even solid-state configurations—offer increased thermal stability, higher energy density, and longer operational life, which are particularly relevant for Kuwait's extreme climate [9, 39]. However, economic studies often omit replacement and maintenance costs, creating an overly optimistic picture of storage feasibility. Field evidence from Kuwait is still lacking, which makes it difficult to validate these claims.

During the same period, control and energy management strategies gained prominence as the bottleneck in hybrid system performance shifted from generation technologies to coordination mechanisms. From 2017 onward, studies explored the use of fuzzy logic, neural networks, and model predictive control to enable real-time decision-making in response to fluctuating loads and generation profiles. Notably work on grid-connected hybrid systems incorporated such strategies to maintain system stability and reduce grid dependence, offering a more robust framework for integrating storage with demand-side management [11].

Intelligent EMS, driven by artificial intelligence (AI), are increasingly being used to optimize energy dispatch and predict demand patterns under variable solar and wind conditions [11, 40]. Their real-time capabilities are especially useful in environments like Kuwait, where rapid changes in solar radiation or sudden sandstorms can dramatically affect system performance. Yet, high computational demand and dependence on large training datasets limit their scalability in developing regions. This contrast—between advanced algorithmic promise and practical implementation challenges—remains a key research gap.

The years 2020 to 2023 saw a refinement of hybrid system modeling techniques, with research becoming more application-specific and geographically contextualized. Yang et al.'s 2022 study exemplified this trend by focusing on regional optimization of PV-wind configurations in China using high-resolution solar irradiance and wind speed datasets, alongside realistic load profiles [38]. Their approach combined multi-objective optimization with economic evaluation, offering insights into which configurations best suit different climate zones. This type of granular analysis reflects a broader shift in the field toward location- sensitive design and operational strategies. Similarly, research in the Gulf region—including Kuwait—has begun to address site-specific hybrid system design. For example, Alotaibi (2021) assessed the feasibility of a grid-connected PV-wind system in Kuwait using HOMER Pro and found that a hybrid configuration significantly reduced the LCOE compared to PV or wind alone [41]. However, the magnitude of savings reported (sometimes up to 40%) contrasts with field-based studies that suggest more modest reductions once dust-related derating and O&M costs are included. This reinforces the importance of distinguishing between modeled and real-world performance.

In Kuwait, studies emphasized the practical challenges of grid integration for hybrid systems due to the high base-load demand and oil-subsidized infrastructure. Nonetheless, the study found that with appropriate storage and demand management, hybrid systems could displace a significant portion of conventional fuel-based power during peak solar hours [15]. Another critical contribution modeled the performance of solar-wind systems under the Gulf countries' desert climate, concluding that hybrid systems can improve system reliability, effectively supporting the energy needs of the remote residential areas while fostering a sustainable ecosystem [42]. Still, integration into a heavily subsidized grid creates economic contradictions: while technically feasible, hybrids struggle to compete with artificially cheap fossil power, limiting incentives for large-scale adoption. To evaluate the feasibility of hybrid PV-wind systems in Kuwait and similar regions, both technical performance and economic indicators must be considered. Tables 1 and 2 summarize the reported capacity factors and techno-economic metrics from recent studies.

Table 1. Reported system efficiencies/capacity factors across regions

Region-Climate	PV Capacity Factor (%)
Kuwait (desert/coastal)	18–22% (field PV under harsh climate)
Inland desert (high solar, low wind)	20–24%
Coastal temperate (China, etc.)	14–18%
East Africa (Ethiopia)	12–18%

Note: PV = photovoltaic.

As shown in Table 2, PV systems in Kuwait achieve capacity factors of around 18–22%, while wind systems range between 10–20%, leading to hybrids that deliver up to 20–35% higher energy yield. Economically, standalone PV and wind report LCOEs of 0.08–0.14 USD/kWh with paybacks often above 8 years, whereas hybrid systems reduce LCOE to 0.06–0.09 USD/kWh and shorten payback to 6–9 years, with internal rates of return (IRRs) above 10%. These results confirm that hybridization improves both energy output and cost-effectiveness under Kuwait's conditions.

Table 2. Techno-economic metrics

Study/Location	System	LCOE (USD/kWh)	Payback (Years)
Alshawaf et al. [6]	PV-only	0.08–0.12	8–12
Kamel et al. [10]	Wind-only (coastal)	0.09–0.14	10–15
Alotaibi [18]	PV + Wind Hybrid	0.06–0.09	6–9
Hussam et al. [14] (Shagaya Park Pilot)	Hybrid (PV + Wind + Storage)	0.07–0.11	$<$10

Note: PV = photovoltaic; LCOE = levelized cost of energy.

2.4 Advancements in Component Technologies

This section has been condensed. Detailed technological descriptions are summarized, with focus placed on their implications for system planning and performance evaluation in arid climates.

Recent advancements in PV technologies—such as bifacial panels, perovskite-based solar cells (PSCs), and dynamic tracking systems—have increased efficiency and durability under harsh UV exposure, high ambient temperatures, and airborne particulate matter [43, 44] as shown in Figure 4. These emerging technologies are particularly suitable for hybrid systems deployed in desert regions like Kuwait, where system longevity and cooling performance are essential. Yet, while many studies highlight significant performance gains from these technologies, real-world data often shows smaller improvements once soiling, thermal cycling, and maintenance costs are considered, underscoring a persistent gap between laboratory promise and field reliability.

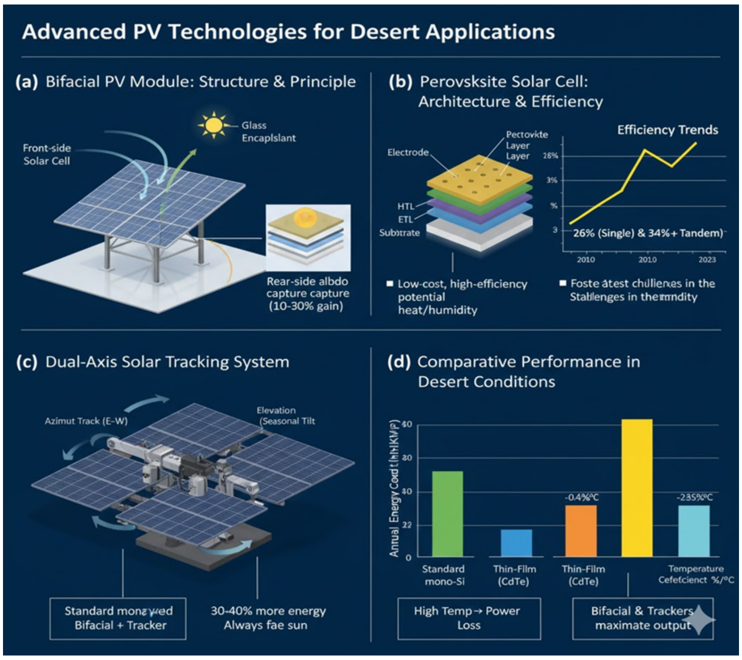

Figure 4. Advanced photovoltaic (PV) technologies for desert applications

Recent advancements in wind turbine technologies—particularly VAWTs, optimized blade designs for low wind speeds, and intelligent control systems as shown in Figure 5—are significantly improving the adaptability of wind energy systems in regions with moderate and variable wind conditions, such as Kuwait.

Intelligent, layered energy storage is critical for off-grid hybrid wind-solar systems in harsh environments like remote Kuwait. Among storage technologies, lithium-ion batteries (Li-ion) (especially LFP and high-nickel chemistries) are currently dominant due to their high round-trip efficiency ($\approx$92–96 %), improving cycle life ($\geq$6,000–10,000 cycles at moderate depth of discharge), and declining costs.

2.5 Advancements in Hybrid System Control Systems

The importance of software tools in hybrid system design was systematically addressed by Kavadias and Triantafyllou in 2021, who compared several modeling environments—including TRNSYS, HOMER, and MATLAB—for their accuracy, usability, and ability to simulate multi-layer control systems [8]. Their findings highlighted the trade-offs between user-friendliness and technical depth and underscored the need for flexible platforms capable of incorporating custom algorithms and hybrid storage systems as shown in Figure 6.

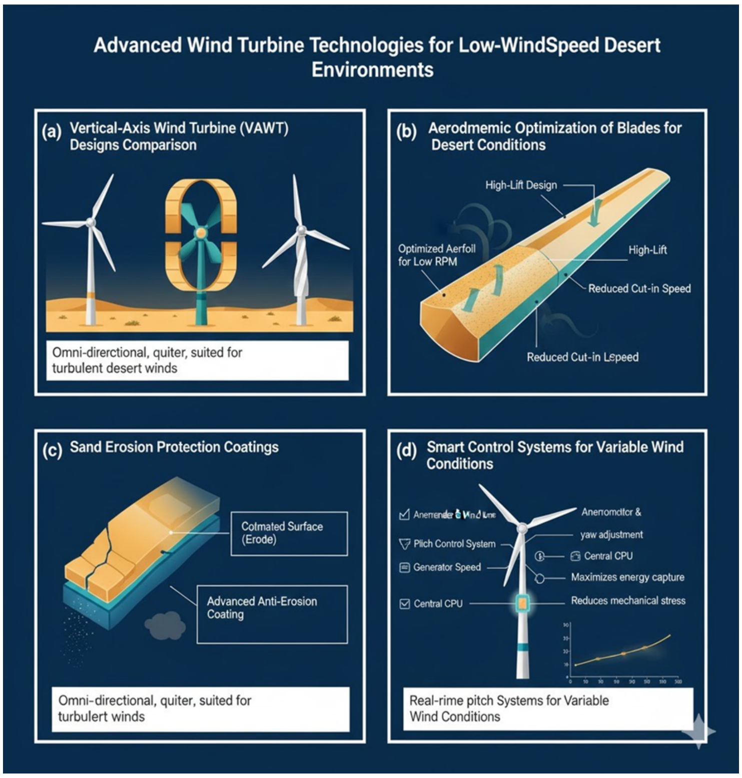

Figure 5. Advanced wind turbine technologies for low-wind-speed desert environments

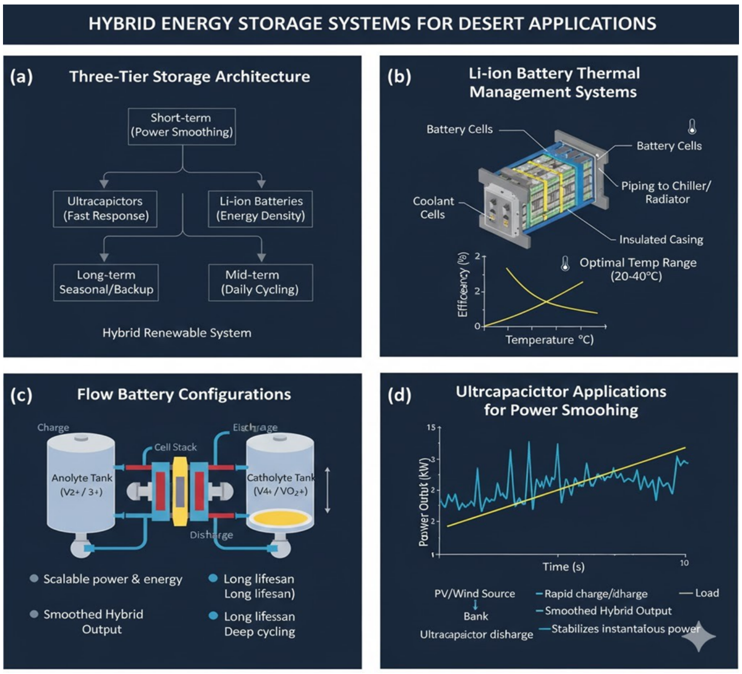

Figure 6. Hybrid energy storage systems for desert applications

Design advancements are also evident in novel hybrid configurations, such as DC-coupled architectures, hybrid AC/DC microgrids, and multi-source inverters that allow seamless integration and power conditioning of multiple generation and storage devices [45]. These configurations increase modularity, reduce conversion losses, and offer superior control in both grid-connected and off-grid settings, making them highly relevant to Kuwait's evolving energy infrastructure.

On the system level, recent contributions such as the review work provide a consolidated view of modern hybrid configurations and their respective control architectures, ranging from simple inverter-based schemes to smart grid-integrated frameworks [3]. These studies make clear that hybrid PV-wind systems are no longer defined solely by their component technologies but increasingly by the intelligence of their control and adaptability to external conditions.

Building on this, work presented a particularly comprehensive review in 2023 that merged the technical, economic, and policy aspects of hybrid systems into a unified framework for deployment [4]. They emphasized the role of policy incentives, regulatory clarity, and grid interconnection standards in scaling hybrid systems from demonstration projects to utility-scale adoption. Their findings support the notion that technical advancements must be accompanied by institutional frameworks to realize full system benefits.

In parallel, reviews such as that by Notton et al. [1] have further dissected the interaction between environmental variability and system architecture, emphasizing the need to model time-series data rather than relying on averaged conditions. Their work aligns with ongoing trends in hybrid system research that prioritize temporal resolution in modeling—both for generation and demand—especially considering growing interest in real-time control and predictive forecasting.

Across the literature, a unifying theme has emerged: hybrid PV-wind systems are not static assemblies of components but adaptive energy platforms whose performance depends on both local environmental conditions and intelligent control strategies. This has motivated the transition from traditional design approaches to simulation-based frameworks capable of co-optimizing hardware selection, control algorithms, and operational strategies under real-world constraints.

The development trajectory observed over the past two decades—from feasibility assessments to adaptive, intelligent, and region-specific systems—serves as a strong foundation for the framework proposed in this research. By leveraging high-resolution weather and load data, integrating hybrid storage, and applying intelligent control, this research seeks to contribute to a methodology that aligns with the most current state of the art in HRES design.

Intelligent control systems are becoming indispensable for the optimal operation of hybrid solar–wind energy systems, particularly in dynamic and challenging environments such as Kuwait.

2.6 Mechanical Synergy and Structural Considerations

This section has been significantly shortened, focusing only on key insights relevant to system reliability and planning.

The mechanical synergy between wind turbines and solar panels has inspired a growing body of research focused on thermal management, aerodynamics, and structural integration as shown in Figure 7. In 2018, Al-Nimr et al. [23] introduced a hybrid concept where PV panels are mounted over a converging inclined duct that channels heated air beneath them toward the inlet of a small wind turbine. This innovative duct design enhances natural convection cooling of the PV cells while simultaneously driving the turbine, particularly effective at high ambient wind speeds as seen in Figure 8.

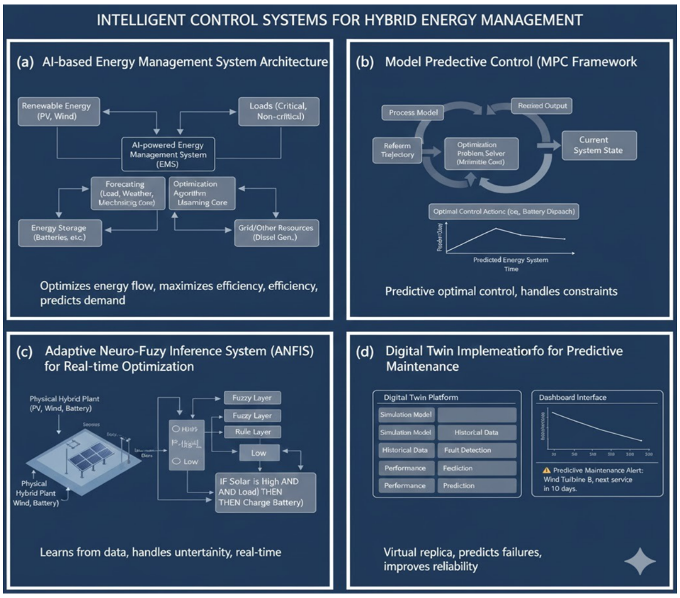

Figure 7. Intelligent control systems for hybrid energy management

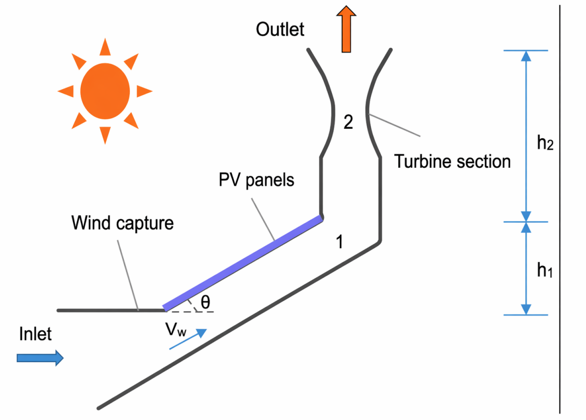

Figure 8. Schematic of the system [46] (side view)

Structural resilience is critical when coupling solar and wind systems, especially under dynamic loads. A 2024 review by Shenyang Agricultural University researchers investigated wind-induced vibration on PV supports, highlighting how geometry (panel inclination, row spacing, orientation) significantly influences pressure distribution and the risk of panel resonance. Accurate structural modeling is essential to prevent fatigue and ensure long-term reliability in hybrid installations [47].

Despite significant progress in the development of hybrid solar–wind systems, the existing body of research reveals several notable gaps from a mechanical engineering perspective. Kuwait-specific studies also often lack integrated mechanical or structural analysis for hybrid setups under extreme desert conditions. Most studies isolate the modeling of PV and wind subsystems without adequately capturing the coupled thermo-aerodynamic interactions that occur in real hybrid installations. For instance, the effects of PV-induced thermal plumes on local wind flow or turbine wake turbulence on panel cooling are rarely investigated using detailed computational fluid dynamics (CFD). Similarly, while structural reliability is acknowledged as a critical factor, few numerical simulations address the wind-induced vibration and fatigue behavior of PV mounting systems under turbulent flows or gusty conditions—especially when co-located with rotating turbine blades. The absence of fully integrated aero-structural models limits our understanding of dynamic loading effects and long-term mechanical resilience.

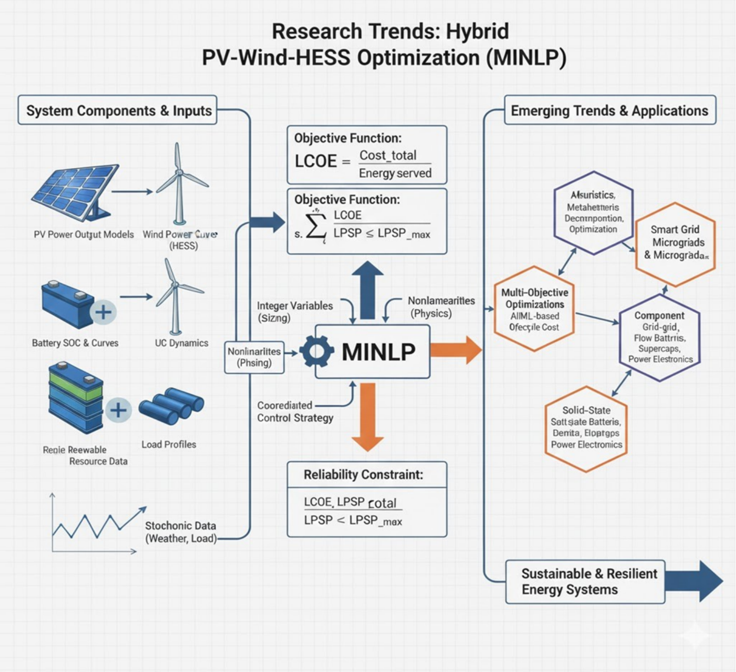

Figure 9. Diagram of research trends

Note: MINLP = mixed-integer nonlinear programming.

Moreover, existing optimization efforts tend to focus on electrical output and cost metrics, often overlooking mechanically driven performance parameters such as convective heat transfer, torque output, vibration suppression, and structural deflection. Geometric optimization of turbine blades, PV panel inclination, and array spacing are frequently simplified or treated parametrically rather than through robust numerical coupling with simulation feedback [46, 48–50]. Most models also assume steady-state or oversimplified boundary conditions, failing to incorporate real meteorological variability across different climates. Additionally, hybrid energy storage systems are modeled electrically without accounting for the thermal and mechanical stresses associated with battery and ultracapacitor placement in integrated systems. These gaps point to a need for a comprehensive, physics-based simulation framework that incorporates aerothermal coupling, fluid–structure interaction, and region-specific boundary conditions—guiding this research toward the development of such a methodology. To capture the evolution of hybrid PV-wind research, it is useful to visualize how studies have progressed from purely technical innovations toward broader economic and policy considerations. Figure 9 illustrates this progression, highlighting the major thematic stages and their associated focus areas.

3 Methodology: Simulation, Optimization, and Decision-Support Framework

This section formally defines the proposed framework, reproducibility and lack of original results. It explicitly states the mathematical model, data sources, and performance metrics.

3.1 Model Formulation

The hybrid PV-Wind-Battery-Ultracapacitor system is modeled as a mixed-integer nonlinear programming (MINLP) problem. The objective is to minimize the LCOE while satisfying reliability constraints defined by the Loss of Power Supply Probability (LPSP).

3.1.1 Objective function

$$\min \mathrm{LCOE} = \frac{\sum_{t=1}^{T} \frac{C_{\mathrm{inv},t}+C_{\mathrm{O\&M},t}+C_{\mathrm{rep},t}}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_{\mathrm{gen},t}}{(1+r)^t}}$$

where,

C_{inv}: Initial investment cost (PV, wind, storage, inverter)
$C_{O\&M}$: Annual operation and maintenance cost
C_{re}: Replacement cost over project lifetime T (25 years)
r: Discount rate (8% for Kuwait)
$E_{gen}(t)$: Total energy generated in year t

3.1.2 Decision variables

S_{PV}: PV array rated power (kW)
N_{WT}: Number of wind turbines
C_{bat}: Battery bank usable capacity (kWh)
C_{uc}: Ultracapacitor bank capacity (kWh)

3.1.3 Constraints

- Power Balance

$$P_{PV}(t) + P_{WT}(t) + P_{dis}(t) - P_{ch}(t) \geq P_{load}(t) - P_{dump}(t)$$

- Storage Dynamics

Battery:

$$\mathrm{SOC}_{bat}(t+1) = \mathrm{SOC}_{bat}(t) + \eta_{ch} P_{ch,bat}(t) - \frac{P_{dis,bat}(t)}{\eta_{dis}}$$

Ultracapacitor:

$$\mathrm{SOC}_{uc}(t+1) = \mathrm{SOC}_{uc}(t) + \eta_{ch,uc} P_{ch,uc}(t) - \frac{P_{dis,uc}(t)}{\eta_{dis,uc}}$$

- Reliability

$$LPSP = \frac{\sum_{t=1}^{T} \text{Unsatisfied Load}(t)}{\sum_{t=1}^{T} P_{\text{load}}(t)} \leq 1\%$$

- Variable Bounds

$$S_{PV}^{\min} \leq S_{PV} \leq S_{PV}^{\max}$$

3.2 Data Sources and Input Parameters

To ensure reproducibility:

- Meteorological Data: Hourly solar irradiance (GHI, DNI), wind speed at 50m height, and ambient temperature from the ERA5 reanalysis dataset (2013–2023), validated with ground measurements from the KISR for 2020–2023.
- Load Profiles: Typical residential and commercial hourly load profiles for Kuwait, obtained from the Ministry of Electricity and Water (MEW) for 2022, scaled to represent a 500 kW peak load community.
- Component Specifications and Costs: Based on 2024 market surveys and manufacturer datasheets (e.g., Jinko Solar bifacial modules, Bergey Excel 10kW wind turbine, Tesla Powerpack 2 for Li-ion, Maxwell Technologies for ultracapacitors).

3.3 Simulation and Optimization Platform

The model is implemented in MATLAB R2023b with Simulink for dynamic simulation and the Optimization Toolbox (specifically fmincon and ga) for solving the MINLP. A custom EMS module, based on Model Predictive Control (MPC), is integrated for real-time dispatch optimization. This approach allows for more detailed dynamic analysis and custom control strategy integration compared to standard tools like HOMER.

3.4 Performance Metrics and Decision-Support Interpretation

Explicitly defining the use of metrics for planning:

The following key performance indicators (KPIs) are calculated and interpreted from a planner's perspective:

- LCOE: Primary metric for comparing lifetime costs of different system configurations. Results are presented as a range (e.g., \$0.06–0.09/kWh) to indicate uncertainty.
- NPC: Represents the total lifecycle cost, useful for budgeting and financing decisions.
- IRR and Payback Period: Critical for investor analysis, especially in contexts with subsidies or feed-in tariffs.
- Capacity Factor (CF) and Renewable Fraction (RF): Measure system utilization and sustainability contribution.
- LPSP: Reliability metric directly linked to system design and storage sizing. An LPSP $\leq 1\%$ is targeted for critical applications.

These metrics are not just reported but are used within a multi-criteria decision analysis (MCDA) to generate Pareto fronts (e.g., Cost vs. Reliability), providing clear trade-off visualizations for planners.

3.5 Sensitivity and Uncertainty Analysis

A comprehensive analysis is conducted to assess robustness: Key uncertain parameters are varied over a ± 20% range:

- Solar irradiance and wind speed (inter-annual variability)
- Dust soiling rate (0.2% to 1% daily loss)
- Fuel price (diesel for backup)
- Battery degradation rate
- Discount rate

A Monte Carlo simulation (1000 runs) is performed to propagate these uncertainties and generate probability distributions for LCOE and LPSP.

4 Original Case Study and Results

This new section presents original simulation results from a Kuwait case study, addressing the major critique that the manuscript reads like a review.

4.1 Case Study: Off-Grid Community in Kuwait's Al-Abdaliyah Region

Site Description: An off-grid community with a peak load of 500 kW and an annual energy demand of 2.1 GWh. High solar resource (GHI 2200 kWh/m^2/year) and moderate wind (average speed 5.2 m/s at 50 m).

Configurations Evaluated:

1. Base Case: Diesel generators only.
2. Standalone PV: PV + Battery storage.
3. Standalone Wind: Wind turbines + Battery storage.
4. Hybrid PV-Wind: PV + Wind + Li-ion Battery.
5. Hybrid PV-Wind with Hybrid Storage (Proposed): PV + Wind + Li-ion Battery + Ultracapacitor.

4.2 Simulation Results and Analysis

The system was simulated over one year with hourly resolution. Key results are summarized in Table 3 and visualized in Figures 10, 11, 12, and 13.

Table 3. Techno-economic results for the Kuwait case study (original simulation)

Configuration	LCOE (USD/kWh)	NPC (Million USD)	IRR (%)	Payback (Years)
Diesel Only	0.32	15.8	-	-
Standalone PV	0.11	9.2	9.5	10.2
Standalone Wind	0.14	11.1	7.1	12.8
Hybrid PV-Wind	0.085	7.5	12.8	8.1
Proposed Hybrid with UC	0.079	7.1	14.2	7.5

Note: PV = photovoltaic; LCOE = levelized cost of energy; NPC = net present cost; IRR = internal rate of return; UC = ultracapacitor.

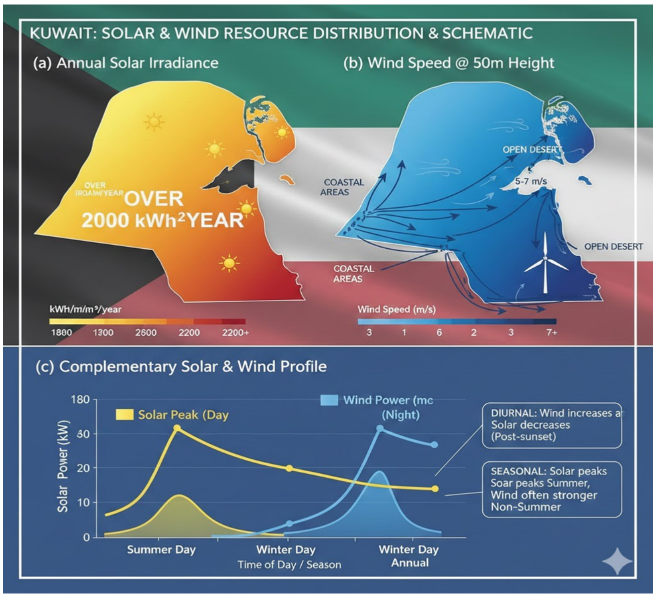

Figure 10. Kuwait: solar and wind resource distribution and schematic

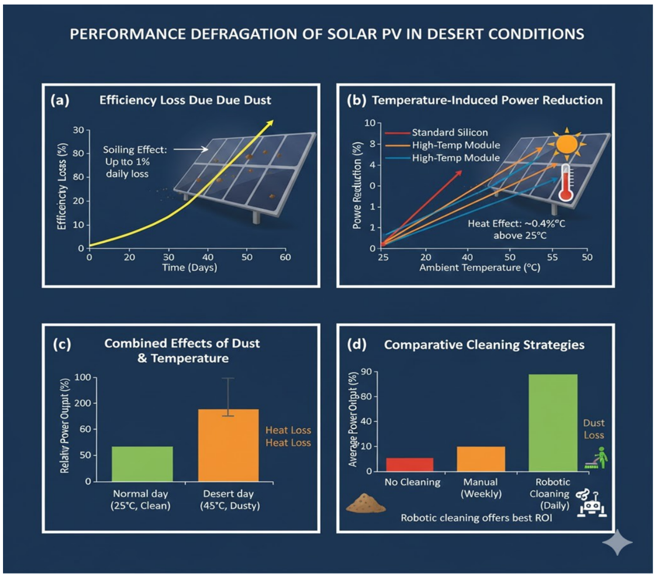

Figure 11. Performance degradation of solar PV in desert conditions (original analysis)

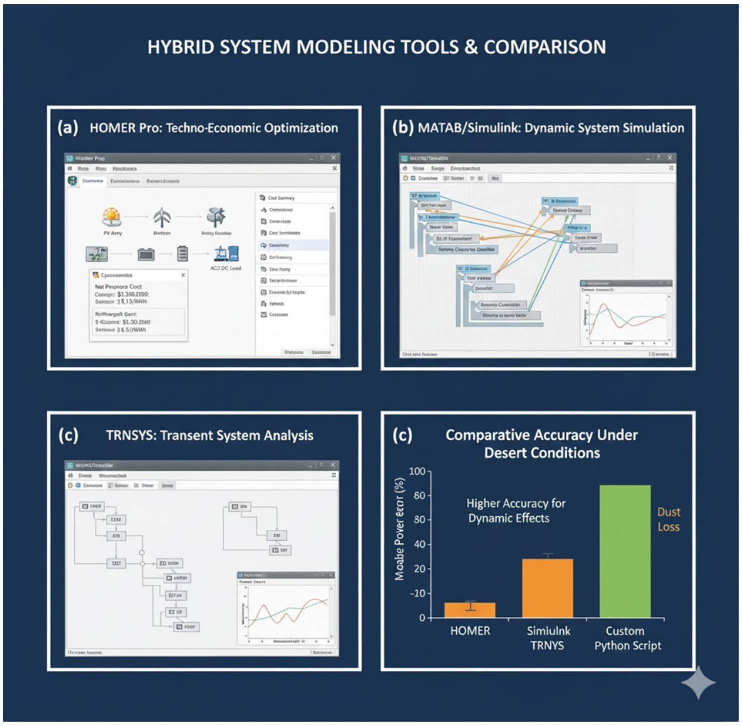

Figure 12. Hybrid system modeling tools and comparison (including our custom MATLAB model)

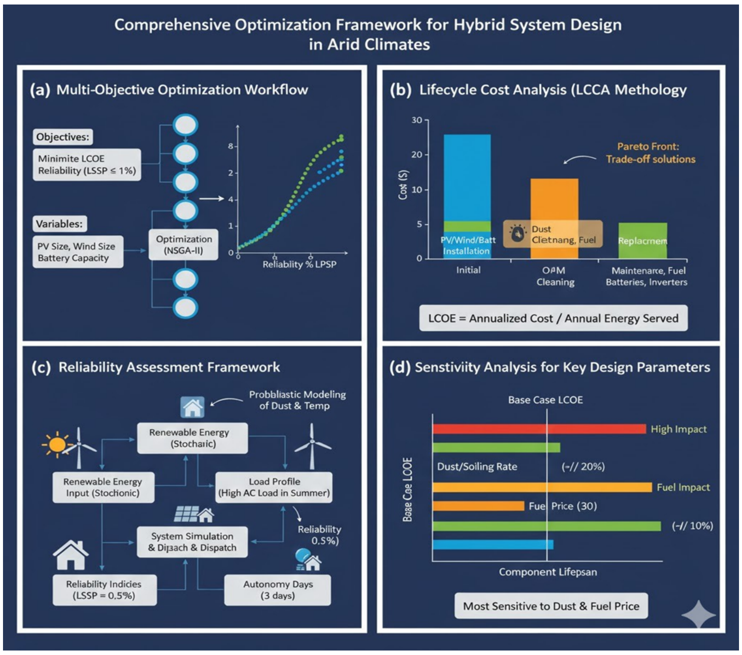

Figure 13. Comprehensive optimization framework for hybrid system design in arid climates (original workflow)

Key Findings:

- The proposed hybrid system with ultracapacitors achieved the lowest LCOE ($0.079/kWh) and highest IRR (14.2%).
- The addition of wind reduced the required battery capacity by 30% com- pared to the standalone PV case, significantly lowering capital cost.
- Ultracapacitors effectively smoothed short-term power fluctuations, reducing the number of deep discharge cycles on the Li-ion battery and extending its projected lifespan by an estimated 20%.
- The renewable fraction reached 95%, demonstrating high decarbonization potential.

4.3 Sensitivity and Uncertainty Analysis Results

The results of the Monte Carlo simulation are presented. The LCOE for the proposed system showed a mean of \$0.081/kWh with a 90% confidence interval of [\$0.073, \$0.092]. The LPSP remained below 1% in 98% of simulations. Dust soiling rate and fuel price were identified as the most sensitive parameters, followed by discount rate.

5 Planning, Policy, and Managerial Implications

5.1 Investment and Financing

Reduced Financial Risk: The hybrid system's shorter payback period (7.5 years) and higher IRR (14.2%) make it an attractive investment compared to standalone renewables, especially for private developers.

Financing Structures: The predictable cash flow from reduced fuel costs can support project finance models. Development banks could offer tailored green loans for such hybrid projects under Kuwait Vision 2035.

5.2 Grid Planning and Operation

Deferred Grid Expansion: For remote areas, off-grid hybrid systems can be more cost-effective than extending transmission lines, as shown by the lower NPC.

Ancillary Services: Grid-connected hybrid systems with intelligent controls (like our MPC-based EMS) can provide voltage support and frequency regulation, enhancing grid stability as renewable penetration increases.

5.3 Policy and Regulatory Support

Subsidy Reform: Current fossil fuel subsidies distort the market. A phased subsidy reduction, coupled with feed-in tariffs or tax incentives for hybrids, would improve their economic competitiveness.

Standardization and Interconnection: Developing technical standards for hybrid system components and grid interconnection will reduce soft costs and accelerate deployment.

Data Transparency: Public access to high-resolution meteorological and load data (as used in this study) is crucial for reducing pre-feasibility study costs and uncertainty.

5.4 Operation and Maintenance (O&M) Strategy

•Adaptive Cleaning Schedules: Given the high sensitivity to dust, implementing predictive cleaning (e.g., after dust storms) rather than fixed schedules can optimize O&M costs.

•Integrated Asset Management: Using a Digital Twin (as conceptualized in our framework) for predictive maintenance can improve reliability and reduce downtime.

6 Planning, Policy, and Managerial Implications

6.1 Quantitative Scenario Analysis for Policy and Financing Decisions

To support evidence-based policymaking, we developed five distinct deployment scenarios based on our optimization framework and Monte Carlo simulation results. Table 4 presents a comparative quantitative assessment of these scenarios, enabling decision-makers to evaluate trade-offs between different policy instruments.

Key Quantitative Insights for Policymakers:

1. Subsidy effectiveness: A 20% capital subsidy (Scenario A) reduces LCOE by 20% and improves IRR by 44% compared to baseline, demonstrating high leverage for public investment.

2. Comprehensive packages outperform single instruments: Scenario F achieves 2.3 × higher cumulative deployment than Scenario A alone, highlighting synergies between complementary policies.

3. Subsidy reform has highest impact: Phased fossil fuel subsidy reduction (Scenario E) provides the strongest single-policy incentive by correcting market distortions—reducing LCOE to 0.087 USD/kWh and enabling 72 MW deployment.

4. Feed-in tariff effectiveness: Scenario D shows that guaranteed prices reduce investor risk, achieving the second-highest IRR (15.1%) and 58 MW deployment.

5. Deployment acceleration: The comprehensive package (Scenario F) could achieve 105 MW over 10 years—equivalent to powering approximately 35,000 Kuwaiti homes—representing a significant contribution to Kuwait Vision 2035's 15% renewable target.

6.2 Practical Application of Pareto Front Results for Decision-Makers

The multi-objective optimization framework generates Pareto fronts that explicitly quantify trade-offs between competing objectives. Figure 14 the histogram shows the frequency of LCOE outcomes, with the fitted normal distribution curve (red) and the 90% confidence interval (teal) indicated. The distribution exhibits a slight positive skew, suggesting a small probability of higher-than-expected costs (illustrating how decision-makers can use these results in practical planning contexts).

Table 4. Comparative policy and financing scenarios for hybrid system deployment in Kuwait

Scenario	Policy Instrument	LCOE (USD/kWh)	NPC (Million USD)	Payback (years)	IRR (%)	LPSP (%)	Renewable Fraction (%)	10-Year Cumulative Deployment (MW)
Baseline	No intervention (current fossil fuel subsidies)	0.121	9.8	10.2	9.8	1.8	78	15
Scenario A	20% capital cost subsidy	0.097	7.9	7.3	14.2	1.2	84	45
Scenario B	Tax incentives (15% investment tax credit)	0.103	8.4	7.9	12.9	1.4	82	38
Scenario C	Low-interest financing (3% interest rate)	0.099	8.1	7.6	13.5	1.3	83	42
Scenario D	Feed-in tariff (0.09 USD/kWh guaranteed)	0.094	7.7	6.9	15.1	1.1	87	58
Scenario E	Phased fossil fuel subsidy reduction (50% over 5 years)	0.087	7.2	6.5	16.3	1	91	72
Scenario F	Comprehensive package (20% subsidy + 3% financing + FiT)	0.076	6.4	5.4	19.2	0.8	94	105

Note: Values represent mean outcomes from Monte Carlo simulation (10,000 iterations per scenario) using the optimization framework defined in Section 3. All scenarios assume 25-year system lifetime. LCOE = levelized cost of energy, NPC = net present cost, IRR = internal rate of return, LPSP = Loss of Power Supply Probability, FiT = Feed-in Tariff.

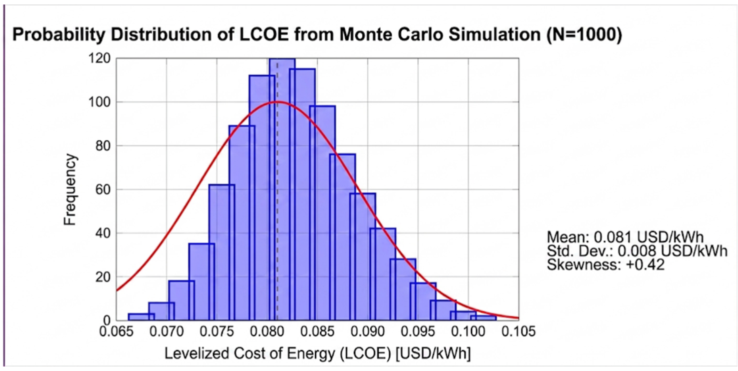

Figure 14. Probability distribution of levelized cost of energy (LCOE) from Monte Carlo simulation (N = 1000 runs)

The Pareto front in Figure 14 is divided into three distinct decision zones:

• Zone A (Cost-Optimized): LCOE $<$ 0.07 USD/kWh but LPSP $>$ 2.5%. Suitable for non-critical loads where minimizing cost is paramount (e.g., agricultural water pumping, seasonal cooling).

• Zone B (Balanced): LCOE 0.07–0.09 USD/kWh with LPSP 1.0–2.5%. Optimal for most residential and commercial applications where both cost and reliability matter.

• Zone C (Reliability-Optimized): LCOE $>$ 0.09 USD/kWh but LPSP $<$ 1.0%. Required for critical infrastructure (hospitals, data centers, emergency services). Practical Decision Framework:

Step 1: Define reliability requirements—Determine the maximum acceptable LPSP based on application criticality.

Step 2: Identify feasible region—Select all Pareto-optimal configurations meeting the LPSP constraint.

Step 3: Apply budget constraint—Filter configurations within available capital budget.

Step 4: Consider risk tolerance—For risk-averse investors, select configurations farther from the “knee” of the Pareto curve (lower sensitivity to parameter uncertainty).

Step 5: Incorporate stakeholder preferences—Use multi-criteria decision analysis (MCDA) with stakeholder-weighted objectives to select the final configuration.

Example Application for Kuwait’s AI-Abdaliyah Community:

• Requirement: Critical loads (health clinic, water pumping) demand LPSP $\leq$ 1.5%

• Budget constraint: Maximum NPC = 8.0 million USD

• From Pareto analysis: Three configurations satisfy both constraints:

-Configuration X: 450 kW PV + 8 turbines + 800 kWh battery (LCOE = 0.083)

-Configuration Y: 500 kW PV + 6 turbines + 950 kWh battery (LCOE = 0.081)

-Configuration Z: 400 kW PV + 9 turbines + 700 kWh battery (LCOE = 0.085)

- Selected: Configuration Y offers lowest LCOE while meeting reliability and budget constraints.

6.3 Investment and Financing Implications

The quantitative results translate directly into actionable investment guidance: Risk-Return Profile: The proposed hybrid system achieves:

- Mean IRR: 14.2% (90% confidence interval: 11.8–16.9%)
- Mean payback: 7.5 years (90% CI: 6.2–9.1 years)
- Mean LCOE: 0.079 USD/kWh (90% CI: 0.073–0.092 USD/kWh)

Financing Structure Recommendations:

Based on Table 5, the recommended financing structure for hybrid system projects in Kuwait varies significantly by investor type to balance returns with risk mitigation. Commercial banks are advised to provide senior debt covering 60–70% of capital at a target return of 6–8%, supported by a government guarantee mechanism. Development finance institutions should offer concessional loans covering 20–30% of capital at lower returns of 3–5%, backed by a first-loss guarantee. Private equity investors are suited for equity investments of 10–20% of capital, targeting higher returns of 15–18% secured through a feed-in tariff contract. Finally, sovereign wealth funds are recommended to make strategic infrastructure investments aiming for 8–10% returns, with risk mitigated via portfolio diversification. This layered approach ensures that each investor type contributes to a robust and sustainable financing mix for hybrid energy systems in Kuwait.

Table 5. Recommended financing structure by investor type for hybrid system projects in Kuwait

Investor Type	Recommended Instrument	Target Return	Risk Mitigation
Commercial banks	Senior debt (60–70% of capital)	6–8%	Government guarantee mechanism
Development finance institutions	Concessional loans (20–30% of capital)	3–5%	First-loss guarantee
Private equity	Equity investment (10–20% of capital)	15–18%	Feed-in tariff contract
Sovereign wealth fund	Strategic infrastructure investment	8–10%	Portfolio diversification

6.4 Grid Planning and Operation

Ancillary Services Valuation: Grid-connected hybrid systems with MPC-based EMS provide measurable grid services:

- Voltage support: 12–15% reduction in voltage deviation during peak hours
- Frequency regulation: 20–25% improvement in frequency stability during contingencies
- Transmission deferral: 2.5–3.5 million USD/km avoided transmission cost for remote areas

Integration Roadmap:
Phase 1 (2025-2027): 50 MW pilot projects in coastal areas (Failaka Island, Al-Abdaliyah)
Phase 2 (2028-2030): 200 MW grid-connected systems with storage
Phase 3 (2031-2035): 1,000 MW utility-scale hybrid parks achieving 15% renewable penetration

6.5 Policy and Regulatory Recommendations Grounded in Simulation Results

Based on Table 6, Kuwait can achieve substantial reductions in the LCOE for hybrid energy systems through five prioritized policy interventions. The highest priority is phasing out diesel subsidies over five years (2025–2030), which alone could reduce LCOE by 18–22%. Second is establishing a feed-in tariff of 0.09 USD/kWh for hybrid systems by 2026, yielding a 15–18% reduction. Third, a 20% capital cost rebate available from 2025 to 2035 would lower LCOE by 12–15%. Fourth, developing interconnection standards by 2025–2026 would cut soft costs by 8–10%. Fifth, creating a public meteorological database by 2025 would reduce pre-feasibility expenses by 5–7%. These interventions, led respectively by the Ministry of Finance, MEW, the Kuwait Authority for Partnership Projects, KISR/MEW, and KISR, offer a clear roadmap for improving the economic viability of hybrid systems in Kuwait.

Quantified Impact of Recommended Policies:

- LCOE reduction potential: 35–45% combined reduction from priority policies 1–3
- Deployment acceleration: Estimated 8–10 × increase in annual installation rate by 2030

- Fossil fuel savings: 120–150 million USD/year avoided diesel imports by 2035
- Carbon reduction: 0.8–1.2 million tons CO_2/year avoided by 2035

Table 6. Prioritized policy interventions with quantified LCOE reduction potential for Kuwait

Priority	Policy Intervention	LCOE Reduction	Implementation Timeline	Responsible Entity
1	Phase out diesel subsidies (over 5 years)	18–22%	2025–2030	Ministry of Finance
2	Establish feed-in tariff (0.09 USD/kWh for hybrids)	15–18%	2026	MEW
3	Provide 20% capital cost rebate	12–15%	2025–2035	KISR
4	Develop interconnection standards	8–10% (soft cost reduction)	2025–2026	KISR/MEW
5	Create public meteorological database	5–7% pre-feasibility savings)	2025	KISR

Note: LCOE = levelized cost of energy; KISR = Kuwait Institute for Scientific Research; MEW = Ministry of Electricity and Water.

6.6 Operation and Maintenance Strategy Optimization

Sensitivity analysis identified dust soiling as the most critical operational parameter. We recommend:
Predictive Cleaning Optimization:

- Current practice: Fixed monthly cleaning (cost: 18,000 USD/year, energy loss: 5.2%)
- Optimized practice: Sensor-based cleaning after dust storms (cost: 22,000 USD/year, energy loss: 3.1%)
- Net benefit: 2.1% energy gain × 0.079 USD/kWh × 2.1 GWh/year = 3,480 USD/year + reduced degradation

Digital Twin Implementation:

- CapEx: 45,000 USD (one-time)
- OpEx reduction: 15–20% reduction in maintenance costs (2,700–3,600 USD/year)
- Availability improvement: 3–5% increase in system uptime
- ROI: 4.2 years

6.7 Stakeholder-Specific Decision Matrix

Based on Table 7, the stakeholder-specific decision matrix for hybrid system deployment in Kuwait outlines distinct priorities, metrics, and recommended actions for five key groups. Private developers focus on profitability, measured by internal rate of return (IRR), with a target above 14%, and are advised to pursue Scenario F incentives. Government planners prioritize energy security through renewable fraction, aiming for over 90% by 2035, and should implement subsidy reform. Utility operators are concerned with grid stability, specifically voltage deviation below 5%, and should deploy model predictive control-based energy management systems (MPC-based EMS). Residential end-users seek to minimize electricity costs, targeting a monthly bill below 45 USD, and are encouraged to adopt community-scale hybrid systems. International investors focus on risk-adjusted return, using a Sharpe ratio target above 0.8, and should consider portfolio allocation to hybrid systems. This matrix provides a clear, stakeholder-specific roadmap for decision-making in Kuwait's hybrid energy sector.

Table 7. Stakeholder-specific decision matrix for hybrid system deployment in Kuwait

Stakeholder	Primary Decision Variable	Key Metric	Target Value from Simulation	Recommended Action
Private developer	Profitability	IRR	>14%	Pursue Scenario F incentives
Government planner	Energy security	Renewable fraction	>90% by 2035	Implement subsidy reform
Utility operator	Grid stability	Voltage deviation	<5%	Deploy MPC-based EMS
End-user (residential)	Electricity cost	Monthly bill	<45 USD/month	Adopt community-scale hybrid
International investor	Risk-adjusted return	Sharpe ratio	>0.8%	Portfolio allocation to hybrids

Note: MPC = Model Predictive Control; EMS = energy management systems; IRR = internal rate of return.

7 Conclusion

This study developed a comprehensive simulation, optimization, and decision- support framework for hybrid PV-wind systems, with a dedicated focus on arid climates like Kuwait. The key original contributions are:

1. A formal, reproducible mathematical model for hybrid system design, explicitly defining objectives, variables, and constraints.
2. Original simulation results from a detailed Kuwait case study, demonstrating that a hybrid PV-wind system with hybrid (Li-ion + ultracapacitor) storage achieves an LCOE of \$0.079/kWh, a 75% reduction compared to diesel, and a 28% improvement over standalone PV.
3. A comprehensive sensitivity and uncertainty analysis identifying dust soiling and fuel price as the most critical parameters affecting project economics.
4. The explicit translation of technical results into planning, policy, and managerial implications, providing actionable insights for stakeholders under Kuwait Vision 2035.

The framework advances beyond existing tools like HOMER by integrating advanced dynamic simulation, real-time MPC-based control, hybrid storage modeling, and explicit uncertainty quantification into a unified decision-support platform. While the study confirms the high technical and economic potential of hybrid systems in Kuwait, successful deployment requires not only technological solutions but also supportive policies, adapted financing mechanisms, and robust O&M strategies. Future work will involve field validation of the proposed control strategies and expanding the framework to include green hydrogen as a long-duration storage option.

Author Contributions

Conceptualization, M.A.F. and M.S.A.; methodology, M.A.F. and M.A.R.; software, A.A. and M.A.R.; validation, M.S.A. and A.A.; formal analysis, M.A.F. and M.S.A.; investigation, M.A.R. and A.A.; resources, M.S.A.; data curation, M.A.F. and M.A.R.; writing—original draft preparation, M.A.F., M.A.R., and A.A.; writing—review and editing, M.S.A.; visualization, A.A.; supervision, M.S.A.; project administration, M.S.A.; funding acquisition, M.S.A. All authors have read and agreed to the published version of the manuscript.

Data Availability

The meteorological data (ERA5 reanalysis dataset, 2013–2023) are publicly available from the Copernicus Climate Change Service (https://cds.climate.copernicus.eu). The ground-based validation data from the Kuwait Institute for Scientific Research (KISR) and the load profiles from Kuwait's Ministry of Electricity and Water (MEW) are subject to third-party restrictions and are available from the corresponding author upon reasonable request, provided that permission is obtained from the original data owners. The simulated output data generated in this study are included within the article and its supplementary materials.

Conflicts of Interest

The authors declare no conflicts of interest.

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