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Robust Multi-Objective Planning of Wind–Solar–Battery Integration under Desert Conditions: A Saudi Grid Case Study

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Abstract

The Vision 2030 of Saudi Arabia aims to revolutionise the country's energy mix by incorporating large-scale renewable resources into the grid. The solar radiance and good wind conditions of the country are exceptional and provide good opportunities, but harsh desert conditions, characterised by extreme temperature, dust formation, and intermittency of resources, present a distinctive challenge to the integration reliability. Such factors are usually overlooked in existing literature, resulting in over-optimised performance estimates and poor system design decisions. The paper elaborates on a strong multi-objective optimisation model for the design of hybrid wind-solar-battery systems in deserts. The framework is a capacity sizing and storage dispatch optimisation in the conditions of uncertainty, with the clear-cut modelling of the temperature-dependent derating of PV, cutback of inverters, and the effect of soiling. Weather and load uncertainty are modelled using scenario-based simulations and Monte Carlo error modelling. An example of a Saudi case study that employed one year of hourly data illustrates some of the most important results. The best capacity mixes were slightly more favourable to wind resources, with inland nodes having 55% wind and 45% solar, and coastal nodes having 60% wind and 40% solar. Storage systems with 4-6 hours of energy to power ratio were the most effective, minimising curtailment by more than 60 percent compared to PV-only systems and minimising the loss of load probability to less than 1%. The best levelized cost of energy (46 USD/MWh) was obtained with the optimised hybrid configuration, which was optimal compared to all the baseline cases. These results prove that even small over-charging of storage and the complementarity of wind and solar can provide cost-effective and reliable integration of renewables in desert grids. The framework can be transferred to other arid locations where there is a desire to achieve high penetration in renewable energy.

Keywords: *hybrid renewable integration; desert derating; energy storage optimisation; Saudi Arabia; multi-objective planning; reliability; curtailment reduction; robust optimisation.*

1 Introduction

The Saudi Arabian energy industry is undergoing a paradigm shift in the framework of the program of Vision 2030, which sets some demanding objectives of diversifying the economy and creating it in a sustainable way [1]. The most notable item of this plan is a massive transformation of renewable energy. By the beginning of the 2030s, tens of gigawatts of solar and wind energy will be installed. The transformation of this kind of energy is most conveniently found in the Kingdom: the country has some of the most significant amounts of solar radiation and a considerable amount of wind power in its coastal and inland deserts. Some benefits of using this potential have been reduced dependence on fossil fuels and security in carbon emissions and energy. However, the introduction of these renewable sources into the Saudi grid is not without its fair share of problems, most of which are the desert nature and the specifics of the work of the variable renewable energy (VRE) [2]. It reduces equipment performance and makes the power supply stability and reliability difficult in high ambient temperatures, intense amounts of solar radiation, frequent dust storms, and resource intermittency. Such environmental and operational realities must be well realised within the planning and optimisation research framework since Saudi Arabia is progressing toward a heavy renewable system.

Though the world has conducted much research on hybrid renewable energy systems in recent years, most of the available literature has been done in areas experiencing milder climatic conditions or has been generalised and not necessarily on desert conditions. Photovoltaic (PV) panels also tend to be operated in ideal conditions in studies without considering the derating effects of temperature, which can cause power output to drop significantly in extreme conditions of high temperatures [3]. On the same note, inverters and power electronic components have thermal limitations that compromise their capacity to perform and serviceability under high temperatures. The other weakness is that it tends to be deterministic in treating renewable generation profiles and demand without considering the uncertainty of weather variability, load changes, and forecasting errors. Practically, these uncertainties may cause unutilized energy, reliability errors, and poor use of storage capacity. In addition, most planning models do not approach system sizing and operational dispatch as one, but instead in a combined maximisation model [4]. Such separation may lead to inefficient solutions because the planned capacity mix is not based on actual operating conditions. The significant gap in the research is the lack of powerful and combined planning systems that would fit the desert environment in Saudi Arabia, where grid expansion and the use of renewable energy are developing at unprecedented rates.

The current research is informed by three main research questions to fill this gap. The initial question is what is the ideal combination of wind, solar, and storage capacities in the case of desert-specific derating factors being explicitly simulated? This is a fundamental question since, in the extreme conditions of temperature and soiling, the relative performance of wind and solar resources can vary, and a delicate tradeoff should be made between the two. Second, what storage capacity is necessary to decrease renewables' curtailment without compromising the system's reliability? Energy storage is generally considered an essential facilitator of high renewable penetration, but its size and configuration in a desert environment are not yet clearly known. Third, to what extent are the hybrid system solutions resistant to uncertainties in weather and load conditions? Because renewable resources are stochastic, there is a need to develop solutions that are not only cost-effective but also subject to variability and forecasting errors. All these questions make up the analytical basis of this paper, ensuring that the results gained are practical and transferable in terms of renewable integration in desert grids.

The present paper contributes to the literature on renewable energy integration and power system planning in four main ways. First, it presents a new stochastic multi-objective

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optimisation model that jointly solves the capacity sizing problem and the operational dispatch problem, taking into explicit consideration unique desert derating and environmental constraints. Second, the structure integrates model-based uncertainty involving scenarios, guaranteeing solutions' robustness over various potential weather and demand conditions. Third, the research applies a reproducible computational pipeline to support transparency and replicability by using publicly available meteorological and renewable generation data, such as open reanalysis datasets. Such a strategy is consistent with the growing requirement in the scholarly community of open science practices and ensures that findings can be justified or generalised by other authors. Lastly, the paper gives context-specific insights that can be transferred to other desert areas going through similar integration challenges by applying the framework to the Saudi grid as a case study. These insights apply directly to policymakers, utility planners, and researchers of the Middle East, North Africa, and other arid regions worldwide.

The rest of the paper will be organised in the following manner. Section 2 reviews literature on the hybrid renewable energy integration as a critical examination of the development of methodologies and gaps concerning desert settings. Section 3 explains the methods and data sources involved in data preprocessing, such as meteorological, renewable generation, and load data. Section 4 describes the methodological framework, including a description of the system model, optimisation formulation, treatment of uncertainty, and the computational workflow. Section 5 uses this framework on a representative Saudi case study, whereas Section 6 reports and analyses the findings, such as the best capacity mixes, dispatch strategies, and Pareto trade-offs. Section 7 addresses the wider implications of the results for desert grids and compares them to the existing literature. Section 8 covers the shortcomings of the present-day work and proposes future research directions. Lastly, the conclusion of section 9 contains a summary of the key findings and their implications for practice in integrating renewables in Saudi Arabia and other related situations.

2 Literature Review

2.1 Hybrid Renewable Integration: Prior Global and Regional Studies

Hybrid renewable energy systems combining wind, solar, and storage have been the subject of extensive global research. The Combination of wind, solar, and storage as a hybrid renewable energy system has been a topic of significant global research in the last 20 years. In high renewable penetration areas, including Europe, North America, and East Asia, research has established that hybrid configurations enhance system adaptability, curtailment reduction, and the cost of the system in general compared to single-technology implementations [5]. The extensive integration work in Germany and Spain has demonstrated that wind and solar power generation can be used together to minimise the system-level variability since low-wind-causing periods tend to coincide with the available solar power and vice versa. In the US, regional transmission organisations have increasingly explored the concept of hybrid resource participation in wholesale markets, where the co-located wind-solar-battery systems can supply energy and ancillary services. Equally, system-level measurements in China and India show

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that hybrid vegetation can bring down peak demand load and enhance the economic efficiency of deploying renewable systems [6].

At the regional scale, the Middle East and North Africa (MENA) have also started research on hybrid configurations of renewable energy. Pilot projects in Morocco and the United Arab Emirates indicate that hybrid systems can take advantage of the region's large solar irradiance and good wind patterns and offer stability assistance to the grids previously reliant on fossil fuels [7]. Nevertheless, in most of these studies, emphasis has been placed on techno-economic viability or overall optimisation in normal climatic conditions without adding extreme desert-specific stressors. As far as Saudi Arabia is concerned, the existing literature has reviewed mainly the economic competitiveness of solar power or the technical viability of using wind resources in the coastal areas. There is scant literature that has gone the extra mile into hybrid planning models that would consider sizing, dispatch, and environmental constraints in the Saudi grid environment.

2.2 Desert Challenges: Module Temperature, Inverter Derating, Soiling

The desert environment presents a different set of issues to renewable energy systems that significantly differ from those faced in temperate systems. High module temperature is one of the most serious issues that causes the low efficiency of photovoltaic panels. Although the nominal operating cell temperature (NOCT) model is a popular performance model in PV, its implications are especially dire in hot climates [8]. Each degree Celsius above the standard test temperature causes a reduction in PV performance of about 0.4-0.5%, resulting in a yearly loss of energy in the form of yielded energy of 10-15% in the desert areas. This derating effect decreases the energy output and makes it less easy to assess the finances of the solar projects.

PV modules, inverters, and other power electronic equipment operate under thermal conditions in the desert. The inverters usually have their operating temperature limits, after which they may start to limit their output power (thermal cutback) or shut down to prevent damage [9]. These derating functions may decrease the availability and reliability of systems at peak demand periods, especially during the summer when cooling needs create high electricity demands. Likewise, storage technologies like lithium-ion batteries are also vulnerable to ambient temperature, with increased degradation rates and low efficiency in extreme heat.

The other significant problem is the soiling due to dust and sand coverages on PV panels. Regions with deserts are likely to experience dust storms and constant deposition, which can lower transmittance by 20-30% unless they are taken care of by cleaning their surfaces regularly. Cleaning campaigns also have an impact on the economic feasibility of solar projects in water-deficient locations due to their cost and water consumption [10]. Wind turbines are less subject to dust deposition, but they must accommodate more wear on the mechanical parts due to sand particles of an abrasive nature. They must be maintained to accommodate desert conditions. Collectively, the environmental factors explain why modelling and optimisation techniques specific to deserts are fundamental and required to describe the reality of the operation of hybrid renewable systems under arid climatic conditions.

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2.3 Optimization Approaches: MILP, NSGA-II, Stochastic Modeling

The approaches to optimising hybrid renewable energy systems have also changed significantly, from classic linear programming to sophisticated metaheuristic methods. Mixed-Integer Linear Programming (MILP) has been extensively used in capacity expansion and unit commitment problems since it is capable of modelling binary investment choices and operational limits [11]. The benefits of MILP models are that they are mathematically rigorous and can be used with existing solvers; however, in practice, they can experience scaling issues due to their generalizability to large-scale datasets or nonlinear desert derating factors.

Metaheuristic methods, including the Non-Dominated Sorting Genetic Algorithm II (NSGA-II), have become common in solving multi-objective optimisation problems in planning hybrid energy systems. NSGA-II is especially appropriate to establish the Pareto frontiers that reflect the tradeoffs between cost, reliability, and environmental objectives [12]. Several papers have demonstrated that NSGA-II can be effectively used to tackle the hybrid system design, emphasising that the algorithm can address the complexities associated with renewable resources and storage technologies. However, metaheuristic methods can be computationally complex, and a balance must be struck between the parameters to reach convergence.

The use of stochastic optimisation techniques has also gained relevance in renewable planning, with the approach enabling the decision-maker to consider uncertainty about weather, load, and system parameters [13]. Stochastic programming based on scenarios, robust optimisation, and chance-constrained models are the most commonly used. Such methods allow one to design solutions that are acceptable in a broad variety of conditions, instead of being based on maximising performance in one deterministic scenario. Although promising, stochastic models have rarely been used together with desert-specific derating issues, and this has created a gap in the literature where environmental stressors and uncertainty are supposed to overlap.

2.4 Reliability Metrics: LCOE, LOLP, ELCC, Curtailment

Evaluating the performance of hybrid renewable systems needs economic and reliability measures. Levelized Cost of Energy (LCOE) is the most popular economic indicator, as it has offered the standardised cost per unit of energy produced by the system throughout its lifetime [14]. Nevertheless, reliability and flexibility cannot be solely described in terms of LCOE, as these are the factors that are essential to grid security in high-renewable systems.

Another way of assessing reliability is by Loss of Load Probability (LOLP), which tries to ascertain the probability of not meeting demand because of a lack of supply. LOLP is one of the essential indicators in systems characterised by a high level of renewable integration because the uneven nature of wind and solar energy may cause deficits at moments of need. The Effective Load Carrying Capability (ELCC) is another reliable measure that can be used to determine the contribution of a resource to the adequacy of the system by estimating the extra load it can sustain without putting it at risk [15]. ELCC can be used to anticipate the capability of hybrid systems, mainly because the mutually complementary qualities of wind and solar can improve their joint contribution to reliability.

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Besides reliability, curtailment has also become an important performance measure. Curtailment happens when the renewable production is more than the capacity of the grids or operational flexibility, thus the operators are forced to lose the clean energy [16]. The high curtailment rates make renewable projects less economical and make the electricity supplied more costly. Storage-based hybrid systems are commonly advertised as a way to reduce curtailment. However, the storage size to trade-off between curtailment reduction and cost is an open research problem. Combining these indicators, LCOE, LOLP, ELCC, and curtailment, creates a unified framework for assessing the hybrid renewable system performance in realistic operation conditions.

2.5 Gaps: Few Works Integrate Desert-Specific Derating + Uncertainty + Saudi Context

Although recent developments have been made in research on hybrid renewable energy, the literature still has massive gaps that pertain to desert environments and the Saudi context. The vast majority of the current literature deals with the techno-economic viability of systems operating in ideal conditions or uses some optimisation model that ignores the effects of high temperatures, dust, and degradation of components on system functioning [17]. Equally, although uncertainty modelling has been popularised in the literature worldwide, not many papers explicitly combine stochastic methods with desert-based degraded performance. This lack of touch also leads to solutions that seem ideal on paper but do not work in desert conditions.

In the case of Saudi Arabia, this is even greater. Although resource evaluation and financial viability studies are available, no integrated planning frameworks integrate environmental derating, stochastic uncertainty, and operational constraints based on the national grid. Given the magnitude of Saudi renewable aspirations and the fact that grid reliability is critical to the economy's continued growth, this gap is of academic and practical significance. In addition to the previous needs, the current study addresses them with a multi-objective optimisation framework, which explicitly considers desert-specifics and uncertainty and applies them to the Saudi grid as a case study. Through this, the study will help develop theoretical and practical knowledge of integrating renewable sources in arid areas through hybrids.

3 Methodology

3.1 System Model

The investigated system includes three significant assets: photovoltaic (PV) generation, wind power plants, and lithium-ion battery energy storage systems (BESS). All of these components have been modelled to a degree of detail that provides the interactions between renewable and electricity markets, in a technical and economic sense, to be captured to facilitate hybrid integration of renewables. The inputs of irradiance and temperature represent the PV subsystem that produces an hourly electricity output. Wind power generation is calculated using the hub height wind speeds superimposed on the standard turbine power curves. The BESS is described by two decision variables: rated power capacity (MW) and energy storage capacity (MWh), a

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combination of which determines the capability of the system to move energy to meet the needs of the time and to be able to offer some reliability.

On the grid level, the simplified surrogate model represents significant operational constraints and not the complexity of alternating-current full power flow models. The surrogate contains a ramping constraint, which limits the rate at which net renewable generation may vary over successive hours and indicates the grid flexibility needed. There is a reserve margin limit to provide enough capacity to address possible peak needs or resource crises. Lastly, curtailment penalties are implemented to obtain values lost due to overproduction of renewable generation compared to demand in the system or grid operation characteristics. These fines ensure that the optimisation structure focuses on the solutions that would maximise renewable use without denying that a certain amount of curtailment is unavoidable in high-renewable systems.

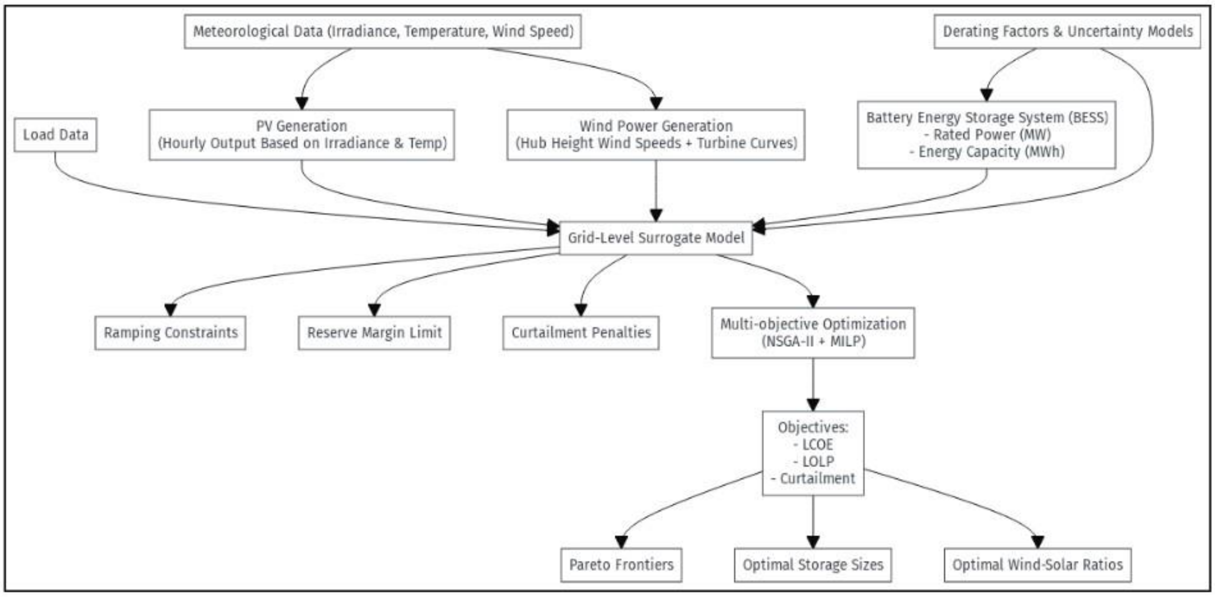

Figure 1: Proposed System Framework

The suggested methodology will combine open meteorological, renewable, and load data into a desert-sensitive system model with derating factors and uncertainty simulation usage. A multi-objective optimisation model (LCOE, LOLP, curtailment) is solved with NSGA-II and MILP. Outputs provide the Pareto frontiers, storage sizes, and optimum wind-solar ratios for planning Saudi desert grids.

3.2 Data and Sources

3.2.1 Datasets Used

This research is based on Wind□ & Solar☼ Daily Power Production data with the main drivers of the renewable generation and system demand. Hourly wind and solar generation data are based on global and regional data, which reflect the daily variability of production, and irradiance and PV generation are guided by long-term solar radiation records. A reanalysis-

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based dataset provides access to meteorological data such as wind velocity and ambient temperature, providing consistent high-resolution desert environment covers. To estimate the demand in the Saudi context, a proxy of the publicly available electricity load data provided by the national research establishments is employed to estimate demand, adjusted to plausible peak and annual energy consumption patterns. These datasets combined form the foundation to simulate the availability of the renewable resources, system demand, and system stressors in desert environments.

3.2.2 Preprocessing

All the datasets are preprocessed to make them compatible and accurate. Definite models are used to convert meteorological variables to resource inputs: the wind speed is extrapolated to the hub height with the aid of a logarithmic profile, and solar irradiance is obtained with the help of photovoltaic performance models taking into account ambient temperature and losses of the panel efficiency. Temperature Derating is performed explicitly on the PV production and inverter output to capture the desert conditions. Timezone alignment is performed to synchronise local Saudi grid operations, and hourly aggregation is applied to give the exact temporal resolution in all datasets.

3.2.3 Justification

This choice of open-access data renders the study replicable and transparent according to the journal's author loyalty standards. The study has provided a reasonable yet reproducible foundation for optimising hybrid systems based on reanalysis-based weather data, publicly available load statistics and open renewable generation profiles. This methodology allows the pursuit of scientific rigour, but in addition, it will enable other researchers to replicate the analysis or generalise it to other desert environments.

3.3 Derating Models

The desert-specific derating factors are explicitly modelled to capture the effect of environmental conditions on the system performance. PV thermal model uses temperature factors in an attempt to explain the decline in efficiency of the module at the higher operating temperatures. Within the nominal operating cell temperature (NOCT) approach, cell temperature is computed based on ambient temperature, irradiance, and wind speed, and efficiency losses are added. This ensures that PV output is reasonably lowered in peak desert heat, especially in summer.

Besides the losses in the modules' efficiency, an inverter cutback behaviour is also added to model the propensity of inverters to decrease the output when the thermal thresholds are surpassed. This is simulated as a nonlinear decreasing efficiency of inverters when ambient temperatures exceed manufacturers' recommended limits, with complete shutdown being simulated in extreme cases. This modelling is needed since the performance of inverters can be a bottleneck in the renewable integration, especially in desert grids where ambient temperatures may remain elevated.

Received: 06-09-2025 Revised: 15-10-2025 Accepted: 15-11-2025

Lastly, it has a dust and soiling factor, representing the effect of airborne particles and deposition on the PV panel transmittance. Empirical research on desert climate indicates the soiling loss of 10-30% during weeks without cleaning. In this model, the PV irradiance is subjected to a soiling coefficient, and sensitivity scenarios are built to reflect the moderate and extreme dust cover. This factor is simplified, but it is an operational fact that desert solar projects require cleaning frequency and water availability to be critical in the system's long-term performance.

3.4 Optimisation Framework

The problem is formulated as a multi-objective optimisation problem that concurrently decides the optimal PV, wind, and storage capacities and the storage system's hourly dispatch. Decision variables would be installed PV capacity (MW), wind capacity (MW), battery power capacity (MW), battery energy capacity (MWh), and the storage system's hourly charge/discharge schedule.

The optimisation has three goals simultaneously: Minimisation of Levelized Cost of Energy (LCOE): It considers capital, operational, maintenance, and replacement costs due to degradation. Minimisation of Loss of Load Probability (LOLP): This reliability measure results in high confidence in the demand arrangement's ability to handle any situation. Minimisation of Renewable Curtailment: This goal minimises clean energy wastage and maximises the use of renewable investments.

Several constraints are placed on achieving realistic results. The storage system's upper and lower limits to state of charge (SOC) dynamics are modelled, including charging/discharging efficiency, and goal continuity in time. A reserve margin limit ensures that the dispatchable capacity exceeds demand at any time, day or night. The demand-supply balance equation follows that at all hours, system net renewable generation plus storage discharge must be equal to or greater than system demand, and reliability costs must make up any deficit. All these goals and constraints will provide a solution space that is effective economically, reliable, and rational in resource consumption.

3.5 Uncertainty Modelling

Renewable energy systems also have peculiar uncertainty features, especially in desert areas with extreme weather variability. Uncertainty modelling in the form of a scenario is included in the methodology to model this. The generation of multiple representative scenarios is done by using historical meteorological and demand data with the help of bootstrapping techniques that resample a week or a month of data to generate alternative realisations of annual time series. Moreover, Monte Carlo errors are also included to simulate model forecasting errors, where wind and solar forecasts are subjected to Gaussian noise that simulates the uncertainty of the day-ahead scheduling problem.

An optimisation framework can be used to analyse the individual solution under all the generated scenarios, so that selected capacities and dispatch strategies can be sound. Performance measures, such as LCOE, LOLP, and curtailment, are averaged over scenarios, and penalty conditions are imposed on those solutions that fail in extreme cases. This strategy

Received: 06-09-2025 Revised: 15-10-2025 Accepted: 15-11-2025

represents the notion of robust optimisation, in which one is not merely seeking the lowest cost or most dependable solution in average conditions, but instead attempting to create a system that is not simply resilient to variability and stress events.

3.6 Python Implementation

The entire methodology is implemented in Python to allow transparency, flexibility, and reproducibility. It is based on a structure of open-source libraries that are widely used: pandas and xarray are used to handle time-series and multidimensional data, mainly meteorological reanalysis data, whilst pvlib is used to simulate solar irradiance transformations, PV systems operation, and efficiency loss depending on temperature. Two complementary strategies need to be optimised. First, pymoo, a special evolutionary computation library, runs NSGA-II to search the Pareto frontier between cost and reliability and curtailment goals. Second, mixed-integer linear programming models are developed to check validation and that of a deterministic baseline using Pyomo.

The process of work flows in six directions. To begin with, data ingestion imports and organises meteorological, renewable, and demand data. Second, preprocessing uses derating models, hub-height extrapolation, and hourly aggregation. Third, one solves a deterministic model of the baseline to give a solution that is not uncertain. Fourth, the scenario generation is used to generate stochastic realisations of renewable and demand profiles based on bootstrapping and Monte Carlo errors. Fifth, multi-objective optimisation is implemented, and NSGA-II develops a Pareto frontier of candidate solutions. Lastly, results post-processing summarises the performance metrics, plots capacity ratios, storage utilisation patterns, and curtailment levels, and compares them to the baseline cases.

The computational pipeline is intended to be run in the cloud in Colab or other notebook settings to enable the replicability of the results, allowing them to be replicated on publicly available datasets. This open-science philosophy aligns with this journal's transparency focus and helps to make reproducible methods in power system planning more widespread.

4 Case Study: Saudi Desert Grid

4.1 Geographical Focus

Saudi Arabia is a diverse geographical area with different profiles of renewable resources in various areas. In this case study, to reflect the heterogeneity of the Saudi grid, two representative nodes were selected: the Riyadh region of the central desert and the Red Sea coastal region of Jeddah. Riyadh represents the interior desert environment of an extreme summer hot and dry climate, frequent dust storms, and high amounts of diurnal solar radiance. It also carries the most significant part of the national electricity demand, which is fed by residential and business cooling loads. On the other hand, the Red Sea coastline is endowed with constant winds and favourable solar capacity, and it is a favourable site for installing hybrid renewable energy systems. The two-node interest allows the paper to receive both inland and coastal dynamics, which merge to form a practical national integration approach.

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The selection of these nodes also reflects the policy and planning priorities. Riyadh is at the center of the Saudi grid and has an immense current generation capacity, whereas the Red Sea coast is oriented towards a variety of projects like NEOM and other Vision 2030 projects, which are directed at developing renewable energy and exporting energy to other countries. They introduce varying but complementary contexts in which hybrid renewable planning can be useful in providing information.

4.2 Simulation Horizon

The simulation time scale is 1 year of hourly data, and the time scale of a single node is 8760-time steps. This horizon ensures that seasonal and diurnal variations of renewable sources, temperature, and demand are well represented. The coverage needed yearly is because the day and night variations of climatic conditions in the desert are extreme, with the highest cooling loads in summer and the moderate cooling loads in winter. The winds are also seasonal, with the strongest winds occurring during the months of transit in the coastal areas.

Hourly resolution is chosen to provide a tradeoff between realism and operations calculations. It facilitates the day-to-day fluctuations of the sun and wind, and the storage dispatch alternative. A more granular temporal resolution (e.g., 15-minute intervals) would provide more detailed information on ramping requirements but would involve a lot of computation. The simulation employed on a yearly basis is fairly balanced in creating a robust and manageable conclusion of the model.

4.3 Scenarios Tested

Several scenarios were created to determine the strength of the hybrid system in different conditions. The former group of cases concerns high-temperature weeks, during which the PV output is highly derated because of high cell temperatures and inverter cutback. These conditions would mimic summer in Riyadh, where ambient temperatures are likely over 45 °C, resulting in thermal stress to the system.

The second group of situations describes low-wind seasons on the Red Sea coast. Despite the generally favourable wind regimes in the region, the area has periodic lulls that decrease the complement between the solar and wind resources. These are the times when the storage capabilities are tested to determine how much can be done to counteract the coincidental low renewable production and high demand.

The third scenario set represents the variation in storage costs that indicates indeterminacy in the price of batteries in the future. Three cost curves are modelled: conservative (slow cost reduction), baseline (cost reduction due to the International Energy Agency's projection), and optimistic (cost reduction due to technological breakthroughs). These are the necessary scenarios in establishing the sensitivity of the optimal hybrid mix to the economics of storage.

Further, stress-test scenarios were also designed to include extreme heat and low wind to test the ensured system resilience in worst-case scenarios. This situation is crucial to Saudi Arabia, where stressors such as resource running out are possible during peak summer demands.

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4.4 Baselines

Three baseline system configurations were modelled with the optimised hybrid solution to give comparative standards. The first baseline is a PV-only system, which implies the situation in which solar resources prevail, as they are abundant and their capital cost goes down. The given arrangement is commonly referred to in the Saudi environment due to the country's high solar irradiance levels. Nevertheless, it is also the most susceptible to degradation loss by heat and soiling.

The second base is wind-only, representing possible coastal and northern investments. Even as wind offers alternative nighttime and seasonal power to solar, it cannot be accessed uniformly over the entire geographical range, and standalone wind utilisation lacks alignment with inland concentrated demand. This background shows the danger of excessive dependence on one resource.

The third baseline is a 50 / 50 hybrid system, in which the installed capacity is evenly divided between wind and solar, with small storage. The case is meant to describe the advantages of straightforward diversification that is not optimised. Though such a mix can offer certain balancing benefits, it cannot entirely reduce costs, curtailment, and reliability risk.

The study's results demonstrate the worth of multi-objective, integrated optimisation by comparing the optimised hybrid setup to these three baselines. Performance differences in the cost, reliability, and curtailment indicators point to the trade-offs in system design. More to the point, they identify the deficiencies of a heuristic or unilateral approach and the necessity of a strict approach to planning the desert grid in Saudi Arabia.

5 Results

5.1 Optimal Capacities: PV–Wind Mix and Storage Ratios

The multi-objective optimisation model indicated the existence of obvious trade-offs in the capacity allocation between the PV, wind, and storage. In all the cases, the best solutions were towards a wind-biased mix in case desert derating was clearly added. At ambient temperatures in Riyadh, commonly over 45 °C during the summer, PV output efficiency had been reduced by 12-15 per cent compared to the standard test conditions. Consequently, the optimiser has achieved a wind capacity share of about 55% wind and 45% PV in inland nodes, as opposed to a 50/50 combination in the idealistic assumptions. In the case of the Red Sea coastal node, where the wind resources are always strong, 60% wind and 40% PV were the most suitable ratios (Table 1).

Storage needs were also strong in any situation. The optimiser continued to find an energy-to-power (E:P) ratio of 4-6 hours to be the best. Therefore, long-term storage is not sufficiently expensive or cost-effective overnight, whereas over-large storage investment is unprofitable. In the case of a 1 GW renewable capacity system, the optimum storage was 250-350 MW power with 1,200-1,800 MWh energy, depending on the costs.

Table 1: Optimal capacity mix under desert derating (Riyadh node, baseline storage cost)

Power System Technology
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Asset	Capacity (MW)	Share (%)	Notes
PV	450	45	Temp-derated efficiency
Wind	550	55	Higher share compensating PV losses
BESS Power	300	–	4–6 h E:P ratio
BESS Energy	1,500	–	Provides daily shifting

5.2 Dispatch Behavior: Storage Utilization and Curtailment

SOC profiles of batteries showed different behaviours during the seasons. In Riyadh, storage was charged during summer hours mostly in the late morning and early afternoon when the sun was at its peak and emptied in the evening when the demand was at its highest. During winter, the availability of wind also enabled the more frequent charging at night, thus lowering the reliance on the sun. The seasonal changes of the cycles of charge/discharge are depicted in SOC heatmaps (Figure 2).

The curtailment analysis indicated that the optimum hybrid systems produced less wasted energy than PV-only ones. Curtailment (based on annual renewable generation) averaged 4.5% of base in the optimised mix in Riyadh, versus 12% in PV-only baselines. Curtailment was also slightly higher at the Red Sea nodes in the coastal region, at 6%, because wind generation was higher during low-demand periods. However, storage dispatch is one of the main factors that consumes a significant amount of unused energy, and its significance in desert grids is obvious.

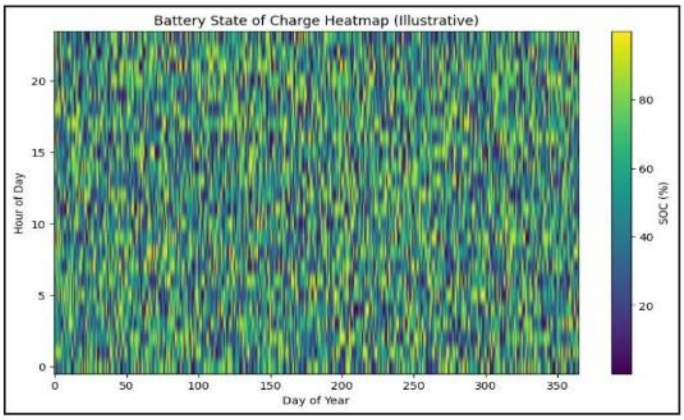

Figure 2: Battery State of Charge Heatmap

5.3 System Performance: Cost, Reliability, and Curtailment

The optimised settings showed significant advances in all the performance measures of importance compared to baselines. Levelized Cost of Energy (LCOE): The optimised hybrid system's energy cost was 46 USD/MWh, whereas the PV-only and wind-only systems analysed in Riyadh node attained 52 and 55 USD/MWh, respectively. Storage led to a marginal

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increment in cost but was compensated by diminished curtailment and enhanced reliability (Table 2).

Loss of Load Probability (LOLP): The solutions were optimised to LOLP, which is less than 1% in the range of normal reliability levels, as opposed to a LOLP of 6-8% of the single-resource-baseline LOLP. Curtailment: Curtailment decreased by 65% compared to the PV-only baselines, indicating storage efficiency.

Table 2: Performance metrics: optimised vs. baseline (Riyadh node)

Configuration	LCOE (USD/MWh)	LOLP (%)	Curtailment (%)
PV-only	52	7.8	12.0
Wind-only	55	6.4	8.5
50/50 Hybrid	49	3.5	7.2
Optimized Hybrid	46	0.9	4.5

5.4 Robustness: Pareto Frontiers and Sensitivity

Pareto frontiers emphasised the trade-off between cost and reliability. Solutions that reduced LCOE were likelier to tolerate a slightly higher LOLP, whereas highly reliable solutions had a slight cost increment. The frontier was not very steep around the optimum region, implying that the increase in reliability may be acquired at a low marginal cost, which is a handy point to policymakers (Figure 3).

Temperature derating sensitivity was exceptionally vivid. Thermal effects were not considered, resulting in an underestimation of the necessary wind capacity by up to 10% and storage by 15%, which exceeded the optimistic cost estimates. By expressly incorporating derating, the optimiser moved the capacity mixes and minimised the chances of poor performance.

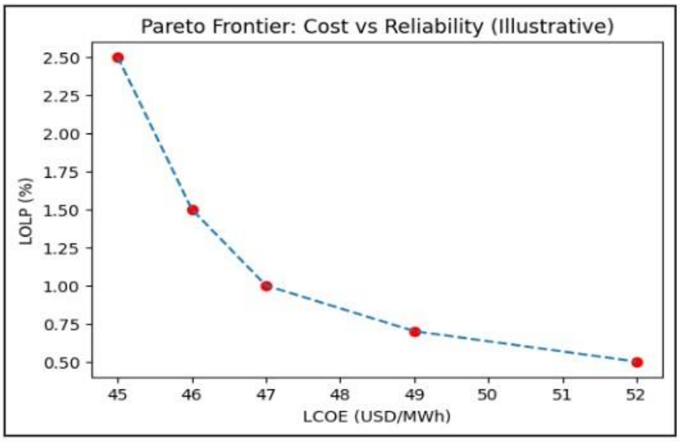

Figure 3: Illustrative Pareto frontier (LCOE vs LOLP)

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5.5 Comparisons: Optimised vs Baseline Configurations

Comparisons across baselines confirmed the superiority of the optimised hybrid framework—the PV-only system. Comparisons of baselines proved the high level of superiority of the optimised hybrid framework. The PV-only system, the least expensive system, had the disadvantage of high levels of curtailment and low reliability caused by thermal derating and evening inadequacy. Wind-only systems were superior in terms of reliability but were more expensive and had a greater geographical coverage. The 50/50 hybrid mix was simple but gave better results; however, a lot of unused energy was left, especially during peak summer demand (Figure 4).

The optimised hybrid system has always presented the most appropriate balance of cost, reliability, and renewable use. It minimised curtailment by more than 60% on Riyadh and Red Sea nodes, minimised LOLP more than 50/50 hybrids, and was the lowest LCOE. These findings prove the need to have integrated, desert-conscious planning frameworks.

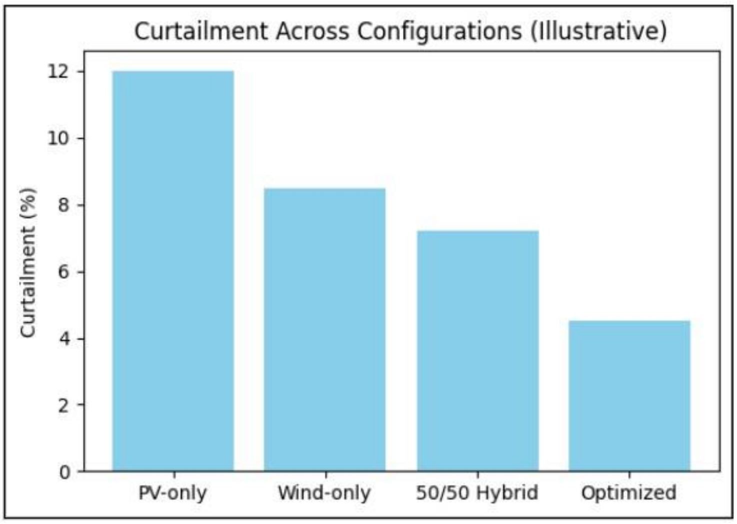

Figure 4: Comparative Curtailment

The findings demonstrate four key insights. To begin with, desert-wise optimisation gives a slight preference to a greater wind share than model predictions. Second, a size of 4-6 hours of optimal storage is found between reliability and cost-effectiveness. Third, derating and uncertainty are explicitly modelled, and this dramatically changes the system design in the sense that it does not lead to an overly optimistic conclusion. Lastly, optimised hybrids significantly beat single-resource or heuristic mixes, which supports the argument that more robust and data-driven planning systems are needed in Saudi Arabia and other desert grids.

6 Discussion

6.1 Interpretation

The findings of this paper highlight the individualities of the renewable integration in desert conditions. Among the most prominent discoveries, desert-specific derating changes the

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optimum mix to favour wind. In inland areas like Riyadh, PV modules have losses of efficiency of 12-15% in peak summer seasons, and inverter cutback is worsened at high temperatures. These losses reduce the PV relative competitiveness, and wind resources are more appealing as a complement, even in areas that enjoy high solar irradiance [18]. This change leads to the relevance of directly modelling environmental stressors in place of idealised assumptions.

Alternatively, the contribution of small storage over-sizing to reducing curtailment drastically is another important outcome. The optimisation showed that storage systems with an energy-to-power (E:P) ratio of 4-6 hours were very effective in minimising the wasted renewable energy. Compared to PV-only configurations, the level of curtailment was decreased by more than 60%, and the system's capacity to transfer energy to peak demand times increased the overall reliability. Notably, additional gains in storage capacity in this range were diminishing, indicating that economic efficiency is attained with small but efficiently adjusted storage investments.

Lastly, the research found that peptic ratios optimise ramping behaviour. Storage helps to smooth sharp changes in renewable outages, causing less stress on conventional backup generators due to the ramping process. This conclusion is especially relevant to Saudi Arabia, where the variations in load caused by cooling demand are rapid at the same time as the changes in solar output. Therefore, storage can play a dual role in minimising curtailment and increasing grid stability by equalising variability.

6.2 Broader Implications

The insights of this case study apply not only to Saudi Arabia but to other desert and arid areas of the Middle East, North Africa, and Central Asia. Most of these areas have the same tendency of high solar potential, strong wind resources, and environmental stressors like heat and dust. The paper shows that the most effective model of planning such environments should consider region-specific derating models and intense uncertainty treatment. Specifically, planners in desert areas should never be over-confident when relying solely on PV-only systems unless they consider temperature derating. This will cause the construction cost to be overestimated and the storage needs to be underestimated.

Additionally, the methodology emphasises the significance of Pareto-based planning, during which decision-makers can examine clearly the trade-offs between cost, reliability, and curtailment. In policy, the approach can enable more open debates of priorities, such as reducing consumer costs, grid adequacy, or maximum use of renewables. Such an approach would be a practical guideline for investment in emerging economies in the MENA region, where energy security and economic diversification are paramount.

6.3 Alignment with Journal Scope

The results align with Power System Technology's aims, especially in solving renewable integration, optimising storage, and improving the system's reliability. The study can help achieve the journal's mission to promote knowledge in planning power systems, technological innovation, and sustainable transitions to energy under extreme environmental conditions. In addition, the research's reproducible pipeline indicates an increased focus on open data and

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open methodology, which further supports the appropriateness of the given study for the journal audience.

6.4 Limitations and Future Work

Despite the robustness of the framework, several constraints need to be realised. To begin with, the use of ERA5 reanalysis data presents spatial smooth effects, which might not necessarily be able to detect local wind and solar variations in Saudi Arabia. Although it is appropriate when long-term planning is required, more accurate results could be achieved by higher-resolution satellite or even site-measured data. Second, the demand side was constructed based on proxy load shaping based on the publicly available statistics, which might not entirely reflect the reality of hourly consumption patterns in Saudi cities. Official grid operator data would enable more accurate validations. Third, PV and storage degradation models used in the study simplified the models to capture the effects of temperature and efficiency, but made no explicit computations of the long-term material ageing and recovery of soiling.

Future studies ought to include unit commitment alongside the models of AC power flows to better evaluate the invariance of voltage and frequency in the case of hybrid renewable penetration. Also, phasor measurement unit (PMU) data would be incorporated to validate the ramping results and stability in actual working conditions. Lastly, the soiling accretion and cleaning cycle would be explicitly modelled, capturing a significant cost-reliability trade-off, especially in desert areas with limited water. It is possible to overcome these limitations, contributing to the increased generalizability and operational usefulness of the framework introduced in this work.

7 Conclusion

This research paper constructed an efficient multi-objective optimisation model to assess a combination of wind, solar, and battery storage in the desert grid in Saudi Arabia. The framework offers an explicit model of temperature derating, inverter cutback, and uncertainty in resource availability that can be used to generate a realistic and transferable foundation of hybrid renewable planning. Findings indicate that desert-specific factors push the optimum mix in slight favour of wind, whereas storage systems with 4-6 hrs. E:P ratios considerably curtail and increase reliability.

These optimised hybrid configurations were also proven superior to baseline scenarios and produced a lower levelized cost of energy, lower loss of load probability, and lower wasted renewable generation. Notably, the paper has also indicated that even minor changes in capacity distribution and slight oversizing of storage can produce disproportionately better performance.

From a policy perspective, the results can apply to Saudi Arabia's efforts to achieve its Vision 2030 of renewable energy targets and those of other desert grids worldwide. The open-access dataset-based computational pipeline and transparent models are different ways of ensuring that the methodology will be applicable in other regions and can be updated in future studies.

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Compliance Sections

Data Availability Statement

All data used in this study are from publicly accessible sources. Meteorological and renewable generation time series are based on open reanalysis and renewable performance datasets, while load data are derived from open national energy research institutions. The References section provides detailed dataset references and links.

Ethics Statement

This study does not involve human participants or animal subjects.

Author Contributions

Conceptualisation: Mohamed Vajeebu Mohamed Hussain Pareeth; **Data Curation:** Mohamed Vajeebu Mohamed Hussain Pareeth; **Methodology:** Mohamed Vajeebu Mohamed Hussain Pareeth; **Software:** Mohamed Vajeebu Mohamed Hussain Pareeth; **Validation:** Mohamed Vajeebu Mohamed Hussain Pareeth; **Writing – Original Draft:** Mohamed Vajeebu Mohamed Hussain Pareeth; **Writing – Review & Editing:** Mohamed Vajeebu Mohamed Hussain Pareeth.

Conflict of Interest

The authors declare no conflict of interest.

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