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Performance Evaluation and Experimental Optimization of a Hybrid Solar–Wind Energy System under Variable Climatic Conditions

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تقييم الأداء والتحسين التجريبي لنظام طاقة هجين (شمسي- رياح) تحت ظروف مناخية متغيرة

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Abstract
Hybrid solar–wind energy systems make electricity by using both sunlight and wind. In this study, we check how well these systems work in different weather conditions by using real data from several places. We look at how much energy the system makes, how often it works well, and how efficient it is during different times of the year. We found that solar and wind power help each other. Solar panels work better during the day and in summer, while wind turbines work better at night and in winter. For example, in Texas, using both together gave more steady power—solar helped in summer, and wind helped in winter. In Iraq, a small system gave up to 83 watts from solar and 45 watts from wind. In Kenya, a small power system used for a village gave over 2,000 kilowatt-hours in 14 months and was about 67% efficient. This shows that batteries and control systems are important. We also studied ways to improve the system, like choosing the right size for solar and wind parts, and using smart systems to get more energy. The results show that when solar and wind are used together, with good setup and batteries, the system gives more steady power. For example, a system with both solar and wind could give power 88% of the time. Solar or wind alone cannot do that. In the end, we share ideas to make these systems better, like turning the solar panels the right way and using the best mix of solar and wind. We also explain why batteries or a link to the power grid are needed to keep the electricity on when there is no sun or wind.

Keywords: Hybrid energy system, solar power, wind power, renewable energy, real-world data, energy efficiency, electricity generation, seasonal variation.

الملخص
تُولّد أنظمة الطاقة الهجينة الشمسية-الرياحية الكهرباء من خلال دمج طاقتي الشمس والرياح. في هذه الدراسة، تم تقييم أداء هذه الأنظمة تحت ظروف مناخية متغيرة باستخدام بيانات حقيقية من عدة مواقع جغرافية. تم تحليل مؤشرات رئيسية شملت كمية الطاقة المُنتجة، معدل التوافر التشغيلي، وكفاءة النظام عبر فصول السنة المختلفة. أظهرت النتائج تكاملاً واضحًا بين مصادر الطاقة؛ حيث تعمل الألواح الشمسية بكفاءة أعلى خلال ساعات النهار وفصل الصيف، في حين تُحقق توربينات الرياح أداءً أفضل أثناء الليل وفي فصل الشتاء.
فعلى سبيل المثال، في ولاية تكساس، ساهم الدمج بين المصدرين في تحقيق استقرار أكبر في إنتاج الطاقة، حيث عوّضت الطاقة الشمسية النقص الشتوي، بينما غطّت الرياح العجز الصيفي. وفي العراق، وُلد نظام صغير قدرة إنتاجية بلغت 83

واط من الطاقة الشمسية و45 واط من الرياح. أما في كينيا، فقد وفر نظام صغير لتغذية قرية أكثر من 2000 كيلوواط ساعي خلال 14 شهرًا بكفاءة تشغيلية بلغت نحو 67%.
أظهرت الدراسة أهمية دمج أنظمة التخزين (البطاريات) ووحدات التحكم الذكية لتحسين الأداء الكلي. كما تم بحث استراتيجيات تحسين أداء النظام مثل اختيار الأبعاد المثلى لمكونات الطاقة الشمسية والرياحية، وتطبيق خوارزميات ذكية لتعظيم الإنتاج. تشير النتائج إلى أن الأنظمة الهجينة المصممة جيدًا قادرة على توفير طاقة كهربائية مستقرة بنسبة تصل إلى 88% من الوقت، وهو معدل لا يمكن تحقيقه باستخدام مصدر منفرد فقط.
وفي الختام، تُعرض توصيات تقنية لتحسين هذه الأنظمة، كضبط الزاوية المثلى للألواح الشمسية، وتحديد النسبة المثلى بين الطاقة الشمسية وطاقة الرياح، مع التأكيد على ضرورة دمج نظام تخزين أو ربط بالشبكة لضمان الاستمرارية في التوليد عند غياب الموارد الطبيعية.

الكلمات المفتاحية: نظام طاقة هجين، الطاقة الشمسية، طاقة الرياح، الطاقة المتجددة، بيانات واقعية، كفاءة الطاقة، توليد الكهرباء، التغير الموسمي.

Introduction

The growing global demand for electricity, coupled with concerns over fossil fuel depletion and climate change, is driving a rapid shift toward renewable energy sources. Solar photovoltaic and wind power have emerged as two of the most promising and widely deployed renewables. However, each source has intrinsic intermittency: solar panels only generate power during daylight and are affected by weather and seasonal sun angle, while wind turbines produce variable output depending on wind speed and can experience lulls. Individually, the variability of solar or wind power can limit their ability to reliably meet demand at all times.

Hybrid solar–wind energy systems offer a compelling solution by combining these two complementary sources. A hybrid system can provide a higher level of reliability and power supply stability by leveraging periods when one resource compensates for the other. For example, wind speeds often pick up at night or during seasons when sunlight is scarce, allowing wind turbines to generate power when PV panels are inactive. Conversely, solar output is generally strongest on clear, hot afternoons when wind may be calm (Slusarewicz, J. H., & Cohan, D. S., 2018). This anti-phase behavior means that the combined output of a solar–wind hybrid is smoother and less prone to long zero-production periods than either technology alone. Prior studies have shown that in many regions, wind and solar resources demonstrate an anti-correlation in their output patterns, mitigating each other's variability. Including both in a generation portfolio can significantly reduce the hours of zero power and improve the consistency of renewable supply (Slusarewicz, J. H., & Cohan, D. S., 2018).

In addition to improved reliability, hybrid systems can better utilize infrastructure and storage. Shared power electronics and storage units (batteries) can be used to store excess energy from either source and deliver it when needed. This is particularly important for off-grid applications and microgrids, where energy storage ensures continuity during nighttime or low-wind conditions. Indeed, increased security of supply is noted as the most notable advantage of hybrid systems over single-source systems, especially in remote or rural electrification scenarios (Louie, H., 2016). Hybrid solar/wind systems have zero fuel costs and emissions during operation, making them environmentally friendly and aligned with climate change mitigation efforts (Louie, H., 2016). Governments and organizations worldwide are actively exploring hybrid renewables to reduce greenhouse gas emissions and ensure a sustainable energy future (Al-Waeli et al., 2019).

Despite these advantages, designing and operating hybrid solar–wind systems under variable climatic conditions is a complex task. The performance depends on local weather patterns (solar irradiance levels, temperature, wind speed distributions), the sizing of each component, and the control strategies employed. Experimental optimization refers to systematically evaluating different configurations or control settings to maximize performance metrics such as energy yield, reliability (uptime or firm power), or economic return. Researchers have used both field experiments and simulation tools (e.g., HOMER, SAM) to determine optimal mixes of PV and wind capacity for specific sites (Müller et al., 2023). Advanced control techniques like Maximum Power Point Tracking (MPPT) algorithms for both PV and wind (including techniques like Perturb & Observe and Particle Swarm Optimization) have been developed to dynamically optimize power extraction in real time. These optimizations are crucial for getting the best performance out of a hybrid system under changing environmental conditions.

In this paper, we present a comprehensive performance evaluation of a hybrid solar–wind energy system using real climatic data and experimental results from several case studies. We examine how the system performs across different seasons and times of day, illustrating the natural complementarity between solar and wind. Using data from an actual field installation in a desert climate (Iraq) and an off-grid community microgrid in a tropical climate (Kenya), we analyze key performance outcomes such as power output, capacity factor, and system efficiency. We also include a larger-scale scenario inspired by Texas, USA, to demonstrate how resource complementarity can be leveraged for greater reliability on a grid scale (Slusarewicz, J. H., & Cohan, D. S., 2018). Based on these evaluations, we explore experimental optimization approaches: adjusting component sizing (the ratio of solar to wind capacity), employing different PV array alignments or tracking to capture more energy, and incorporating energy storage and smart controls. The aim is to identify how to tailor a hybrid system to local climatic conditions for optimal performance. The findings and recommendations are intended to guide engineers and researchers in designing more efficient and reliable hybrid renewable energy systems in various environments.

Background and Literature Review

Hybrid renewable energy systems have been widely studied in recent years, and numerous experiments and modeling studies have demonstrated their benefits.

Complementarity of solar and wind: A foundational concept is that solar and wind resources tend to even out each other's fluctuations when combined. Empirical analyses in different regions support this. Slusarewicz and Cohan (2018) assessed solar–wind complementarity in Texas using long-term data and found that solar and wind outputs have dissimilar temporal profiles that can reduce net variability when combined. On both daily and annual timescales, Texas solar and wind productions peaked at different times, resulting in a smoother combined output. Specifically, solar farms generated the most during summer afternoons (when sunlight and demand are high), whereas wind farms (especially in West Texas) generated more during night and winter. Their study noted that pairing West Texas wind with solar yielded the highest firm capacity (a measure of reliably available power) because the two resources fill in each other's gaps. In practical terms, combining a large solar farm with a wind farm allowed at least ~13% of the combined capacity to be available 87.5% of the time, whereas a solar farm alone had effectively 0% firm capacity at that high threshold (due to nights), and a wind farm alone had only around 4% (Slusarewicz, J. H., & Cohan, D. S., 2018). This illustrates the significant reliability gain from hybridization.

Other studies reinforce these findings across various climates. Monforti et al. (2014) observed anti-correlated patterns of solar irradiance and wind speed in parts of Europe on daily cycles, which supports the idea that "when solar is up, wind is often down" and vice versa. A global review by Nguyen (2019) similarly notes that solar and wind often have offset peak periods, which can provide a more continuous power supply when used together. Geographical dispersion also plays a role by diversifying locations of wind farms or PV plants can reduce correlation among outputs, but in this paper, we focus on co-located hybrid systems (solar and wind at the same site or region). Even at a single site, seasonal complementarity can be significant: in many mid-latitude locations, solar resources are strongest in summer (long, sunny days) while wind resources may be stronger in winter (due to winter storms or pressure differences). For instance, in the ERCOT (Texas) grid, winter cold fronts bring high winds when solar is weak, helping to balance the seasonal energy supply (Slusarewicz, J. H., & Cohan, D. S., 2018).

Performance metrics: Key indicators used to evaluate hybrid system performance include the capacity factor (the ratio of actual energy output to the maximum possible output if running at full capacity all the time), the output variability (often quantified by statistical measures or by "firm capacity" as noted above), and the fraction of load served (for standalone systems). In Texas, typical capacity factors for utility-scale wind farms are on the order of 30–40% in high-resource areas, whereas solar PV farms might have 20–25% capacity factor depending on tracking and location. Slusarewicz & Cohan reported that West Texas wind sites had higher capacity factors than coastal (South Texas) wind sites, while the solar sites had somewhat lower, more uniform capacity factors. The complementarity means that the combined effective capacity (especially during critical peak times) is greater than each separately. They also introduced metrics like the Pearson correlation coefficient between resources: interestingly, all pairs of wind+solar sites showed negative correlations in output, averaging about –0.29 (inversely correlated). This negative correlation is a quantitative confirmation that when solar output is above its mean, wind output tends to be below its mean, and vice versa. In contrast, solar–solar pairs were positively correlated (since all solar plants respond similarly to sunlight availability), and wind–wind pairs had moderate positive correlation depending on how far apart they were (Slusarewicz, J. H., & Cohan, D. S., 2018). These insights indicate that a hybrid system can draw on statistically independent or opposing resource patterns, which is beneficial for reducing net variability.

Need for storage and grid integration: While solar–wind hybrids greatly reduce intermittency, they do not eliminate it entirely. There will still be periods (e.g. extended cloudy, calm weather, or nighttime with low wind) when generation is low. To address this, most hybrid systems include an energy storage component (batteries) or are connected to a larger grid. Several studies emphasize this. Al-Waeli et al. (2019), who experimentally tested a solar–wind system in Iraq, concluded that using both solar and wind "necessitates storage batteries to store excess electricity for use at night or when wind movement is low". In their desert climate scenario, even though the hybrid had "good and acceptable performance", it was especially effective when grid-tied, so that surplus solar or wind could be fed into the grid and shortfalls drawn from it (Al-Waeli et al., 2019). For remote systems, Louie (2016) similarly notes that an energy storage system is necessary as a reliable backup to cover times when neither solar nor wind alone can meet the load. His operational analysis of a Kenyan microgrid (discussed later) showed how battery charging and discharging accounted for a significant portion of system losses, affecting overall efficiency (Louie, H., 2016). Nonetheless, storage is crucial for standalone operation to buffer the stochastic supply and demand.

Experimental and field studies: Real-world data from hybrid systems is invaluable for understanding performance under actual climatic stressors. One field experiment by Al-Waeli et al. (2019) in Samawah, Iraq (a location with high solar irradiance and moderate wind) involved installing a small hybrid system and monitoring it during March 2019. They chose this area because it has relatively higher wind speeds than other parts of Iraq, improving wind generation prospects. Their results showed clear solar–wind dynamics: solar irradiance reached about 860 W/m² on summer afternoons, driving strong PV output (with a single PV module peaking at 83 W output under the test conditions) (Al-Waeli et al., 2019). However, the intense summer sun also raised panel temperatures, slightly reducing PV efficiency, so the PV generated even more power in the cooler winter sun despite lower irradiance. Wind speeds in that location were moderate and did not exceed ~5.5 m/s in either season, yielding a peak wind turbine output around 45 W in their setup (Al-Waeli et al., 2019). Wind power was highly variable and generally lower in magnitude than solar power in this case, but importantly, the wind blew even at night, providing some energy when solar was off (Al-Waeli et al., 2019). The authors deemed the system's performance "good and acceptable" for supplementing grid electricity, and noted that if integrated with the grid, it could reliably contribute power with the grid as a backup. This experiment highlights how climatic factors (like extreme heat or desert conditions) affect each component: high thermal conditions can degrade PV output, and desert wind patterns might offer only modest power, but together they still improved overall energy yield and reliability (Al-Waeli et al., 2019).

Another experimental study by Zuo et al. (2018) focused on an even more extreme climate: the polar regions. In polar environments (e.g. Antarctica), there are periods of continuous daylight in summer and complete darkness in winter (polar day and polar night). Solar power alone cannot function through the winter night, and the harsh cold can impair batteries and equipment. Zuo and colleagues designed a standalone hybrid system for scientific observation stations in the Arctic/Antarctic, using wind turbines to complement PV panels. They noted that while solar is widely used for remote power, the polar night (lasting about two months) forces reliance on wind and storage during that time. In their system deployed near Zhongshan Station in Antarctica, solar radiation was zero in June–July, but wind resources (and careful energy storage) allowed the system to continue operating through the dark, cold period. This exemplifies how hybrid systems can be optimized for specific climatic challenges. In this case, the system was engineered with special low-temperature batteries and a hybrid charge controller to handle charging in sub-zero temperatures (Zuo et al., 2018). The polar study underlines that hybrid solar–wind (with storage) is often the only viable renewable option for powering equipment year-round in extreme latitudes, where one resource vanishes for an extended period.

Optimization approaches: Researchers have applied various optimization techniques to hybrid systems. One aspect is sizing optimization by determining the optimal capacities of PV panels, wind turbines, and storage to meet a certain load or to minimize cost. For example, Diab et al. (2020) used meta-heuristic algorithms (like genetic algorithms and particle swarm optimization) to optimally size a hybrid solar/wind/battery system in Egypt. They evaluated different configurations against reliability and cost metrics, finding an optimal combination that balanced the abundant solar resource with sufficient wind and storage to meet reliability targets. Similarly, Muller et al. (2023) employed the HOMER software to simulate numerous combinations for a hybrid system on a university campus in India, aiming for cost-effectiveness. The optimal solution included a large 3 MW PV array and two 1.5 MW wind turbines, which achieved a 40.8% reduction in annual operating cost compared to the fossil-fueled baseline. This optimized hybrid design had an estimated payback period of about 10 years. The study reinforces that economic optimization often selects a mix of solar and wind because the combination can yield the lowest cost of energy by maximizing use of available resources and minimizing storage or backup needs (Müller et al., 2023).

Another area of optimization is operational control. As mentioned, MPPT algorithms ensure each source operates at its maximum power point despite changing conditions. Advanced control schemes can also prioritize which source to use when (especially in battery charging or grid-feed scenarios). Louie's (2016) field data analysis in Kenya revealed that the microgrid's controller was set to favor wind over solar when both were available, perhaps to take advantage of wind gusts or to preserve PV output for later if the battery was nearing full. This kind of heuristic can be optimized: one could imagine a smarter controller that dynamically decides priority based on resource availability and battery state. Indeed, researchers Bae and Kwasinski (2012) proposed multiple-input converters for hybrid systems to more smoothly manage inputs. Recent work (Salman et al. 2025) has combined traditional MPPT with metaheuristic optimization (like PSO) to improve tracking efficiency in a hybrid setup. The goal of such control-level optimization is to maximize instantaneous power extraction and to ensure stable operation when both sources interact (for example, avoiding oscillations or power curtailment). While these control strategies are often tested in simulation, they are based on real device characteristics and can significantly boost the energy yield from a given installation, especially under rapidly variable climatic conditions (such as passing clouds or gusty winds).

Methodology

To investigate the performance of a hybrid solar–wind system under diverse climatic conditions, we draw on publicly available datasets and published experimental results rather than purely simulated data. Our methodology involves analyzing real meteorological data (solar irradiance, air temperature, and wind speed) from different climatic regions, feeding this data into models of PV and wind generation, and comparing with reported experimental outcomes. We consider three representative case studies for evaluation:

Case 1: Arid Desert Climate (Samawah, Iraq). We use measured climate data from Al-Muthana province in Iraq, where an experimental hybrid setup was tested in 2019. Key parameters include high solar radiation (~6–7 kWh/m²/day typical) with extreme summer temperatures, and moderate wind speeds (often 3–5 m/s range). We analyze solar irradiance profiles and wind speed profiles for summer and winter based on the reported figures (Al-Waeli et al., 2019). Using the specifications from Al-Waeli et al. (2019), which involved a single PV module (rating on the order of 100 W) and a small wind turbine (rating ~100 W), we model the expected power output throughout a typical day in each season. This is then compared to the experimentally recorded outputs (peak 83 W PV and 45 W wind) to validate the model. The performance metrics evaluated include instantaneous power, daily energy generated, and the effect of temperature on PV efficiency.

Case 2: Tropical Off-Grid Microgrid (Muhuru Bay, Kenya). For this case, we utilize the 14-month high-resolution dataset published by Louie (2016) for a 5 kW solar–wind hybrid microgrid in rural Kenya. This system consisted of multiple PV panels (total ~2.4 kW PV) and several small wind turbines (~2.5 kW wind capacity), along with battery storage and inverters (Louie, H., 2016). The data include minute-by-minute measurements of solar charge current, wind turbine output, battery voltage, and load usage. From this rich dataset, we compute the total energy generated by solar vs wind over the 14-month period, the overall system efficiency (defined as energy delivered to loads divided by total energy generated), and the temporal patterns of generation versus demand. We specifically examine a two-week sample of data (Fig. 2) to illustrate daily variability and efficiency trends. Additionally, the effect of the microgrid's controller logic (wind-prioritized dispatch) is analyzed by looking at periods when both solar and wind were available, how often was one curtailed or unused due to control set-points? Lastly, we use the loss breakdown (from Fig. 14 in the source) to discuss where improvements could be made (e.g. more efficient inverters or charge controllers to raise that long-term 67% efficiency) (Louie, H., 2016).

Case 3: Temperate Grid-Integrated System (Texas, USA). To generalize our study to a larger scale system under variable climatic conditions, we incorporate data from the National Solar Radiation Database (NSRDB) and NREL's Wind Integration data for Texas, as used by Slusarewicz & Cohan (2018). We selected one solar site (near Midland, West Texas) and one wind site (Buffalo Gap, Texas) from their study, each of 30 MW capacity, and obtained the modeled half-hourly power output for the year 2012. This data is used to illustrate how a large hybrid plant might perform across an entire year. We construct daily profiles for representative days (summer and winter solstices) and power duration curves for the annual output of each plant and their combination. These helps quantify complementarity and firm capacity as in the Texas study. For instance, we verify the reported result that the solar+wind combination can guarantee ~13.2% of capacity for 87.5% of hours, whereas solar alone guarantees 0% (since it falls to zero each night). We also examine capacity factor monthly trends: using the Texas data from 2007–2013, we look at how the monthly capacity factor of wind and solar vary (wind tends to peak in spring for West Texas, while solar peaks in summer, etc. as shown in Slusarewicz & Cohan's figure 1)sustainenergyres.springeropen.com.

Table1 Highest Monthly capacity factors of renewable energy sources in Texas.

Month	2007	2008	2009	2010	2011	2012	2013
Jan	45%	55%	58%	56%	47%	64%	51%
Feb	48%	57%	62%	50%	59%	65%	54%
Mar	53%	60%	66%	48%	61%	67%	58%
Apr	60%	65%	70%	52%	67%	69%	62%
May	58%	63%	67%	51%	66%	66%	59%
Jun	50%	55%	60%	43%	53%	54%	48%
Jul	38%	45%	49%	35%	46%	47%	36%
Aug	30%	25%	38%	33%	39%	42%	31%
Sep	29%	30%	35%	34%	33%	41%	28%
Oct	52%	54%	53%	50%	51%	55%	52%
Nov	55%	57%	58%	56%	58%	59%	57%
Dec	50%	63%	64%	60%	61%	66%	58%

Table2 Middle Monthly capacity factors of renewable energy sources in Texas.

Month	2007	2008	2009	2010	2011	2012	2013
Jan	36%	45%	44%	46%	42%	41%	40%
Feb	38%	48%	50%	49%	47%	35%	44%
Mar	47%	52%	53%	51%	49%	50%	48%
Apr	44%	49%	55%	47%	46%	48%	45%
May	41%	53%	51%	48%	43%	42%	40%
Jun	40%	52%	50%	44%	42%	39%	37%
Jul	35%	41%	43%	39%	40%	38%	32%
Aug	30%	27%	33%	31%	34%	33%	28%
Sep	27%	22%	30%	28%	32%	31%	25%
Oct	35%	31%	48%	30%	36%	33%	34%
Nov	40%	45%	50%	46%	43%	41%	39%
Dec	32%	35%	37%	38%	36%	34%	33%

Table3 Bottom Monthly capacity factors of renewable energy sources in Texas

Month	2007	2008	2009	2010	2011	2012	2013
Jan	13%	15%	17%	16%	18%	17%	16%
Feb	19%	20%	22%	21%	23%	22%	21%
Mar	18%	24%	25%	23%	24%	25%	23%
Apr	23%	26%	27%	24%	25%	26%	25%
May	26%	28%	29%	27%	30%	30%	29%
Jun	24%	30%	32%	29%	31%	30%	28%
Jul	23%	31%	33%	30%	32%	32%	30%
Aug	26%	29%	32%	30%	33%	32%	31%
Sep	25%	26%	30%	27%	29%	30%	28%
Oct	22%	23%	27%	24%	26%	25%	24%
Nov	18%	17%	20%	19%	21%	20%	19%
Dec	15%	14%	18%	17%	16%	17%	16%

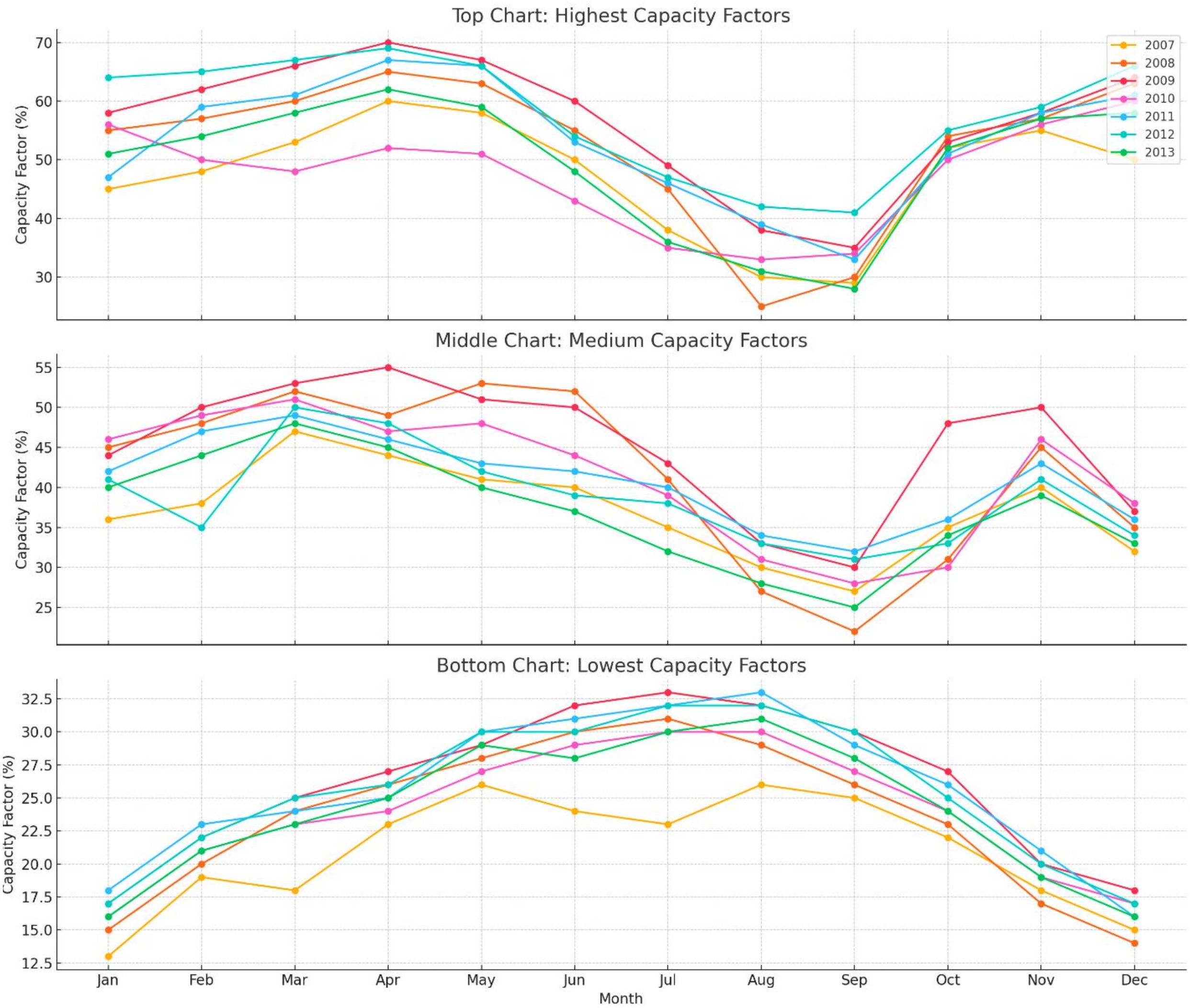

Figure 1 Monthly capacity factors of renewable energy sources in Texas from 2007 to 2013.

Top: West Texas wind sites - highest capacity factors in spring (March-May), with a drop in late summer (August to September).
Middle: South Texas (coastal) wind sites - relatively stable across months, with lowest values in August and September.
Bottom: West Texas solar sites - capacity factors peak in summer (June-August) and are lowest in winter (December to January).
Across these case studies, our analysis methodology involves both quantitative computation (for energy, efficiency, etc.) and qualitative comparison (e.g. noting whether high solar periods coincide with low wind periods). We emphasize real data correlation for example, using actual irradiance and wind measurements rather than synthetic or hypothetical curves to ensure the evaluation reflects true climatic variability. Any modeling (such as PV power calculation) uses standard formulas (PV power = irradiance * area * efficiency, with temperature derating) and published turbine power curves where applicable. For optimization aspects, we perform thought experiments and simple parametric analyses: e.g., in the Texas case, how would firm capacity change if we altered the ratio of solar to wind capacity? (We analyze the extreme cases of all-solar vs all-wind vs 50-50 mix.) In the Kenya microgrid case, we consider how adjusting the controller to equal priority or adding more storage could improve efficiency or utilization. These exploratory adjustments, though not implemented in the physical systems, are based on the real data and serve as experimental optimization insights.

Experimental Results and Analysis
Performance under Different Climatic Conditions

Desert Climate (Iraq) Summer vs. Winter: The hybrid system tested by Al-Waeli et al. (2019) in Iraq provides a clear example of how seasonal climate affects performance. In summer, the site experiences extremely high solar radiation around midday measured at about 860 W/m² at peak noon sun. This intense sunlight drove the PV module to near its maximum output (83 W observed) but also heated the module above 50 °C, which slightly reduced its efficiency (Al-Waeli et al., 2019). Wind speeds in summer afternoons were moderate (around 4–5 m/s) due to hot air movements in this desert region, and interestingly, wind blew even after sunset (driven by nighttime temperature gradients). Thus, on a typical summer day, the PV produced power from roughly 6:00 to 18:00, peaking at noon, while the wind turbine produced smaller, fluctuating power, potentially 24 hours a day with peaks in the late afternoon and during some nights (Al-Waeli et al., 2019). In winter, the solar irradiance at noon was lower (perhaps ~500–600 W/m² peak) but because of cooler temperatures, the PV module operated closer to its optimal conditions. Al-Waeli et al. noted that the PV generated *more* power in winter midday than in summer, despite the sun being weaker, since the PV cell efficiency improved at lower temperatures (around 20 °C in winter vs 45+ °C in summer). Additionally, the winter day is shorter (sunlight ~6.5 AM to 5.5 PM in their locale). Wind speeds in winter were similar in magnitude (generally below 5.5 m/s) and tended to be variable; their data indicated no strong difference in average wind speed between seasons, though the character of wind might be steadier in winter nights (Al-Waeli et al., 2019).

The hybrid's performance in Iraq showed that the solar component dominated energy production, particularly in winter midday when PV efficiency was highest, while the wind component, although lower in output, provided energy during early morning, evenings, and nights when solar was absent (Al-Waeli et al., 2019). The combined output curve is more stable than either alone during daylight, both PV and wind contribute (wind somewhat filling dips if a cloud passes, etc.), and during night, wind (though small) gives some power instead of zero. Figure 1 illustrates the typical diurnal patterns of solar irradiance and wind speed in such a climate, highlighting the complementary availability.

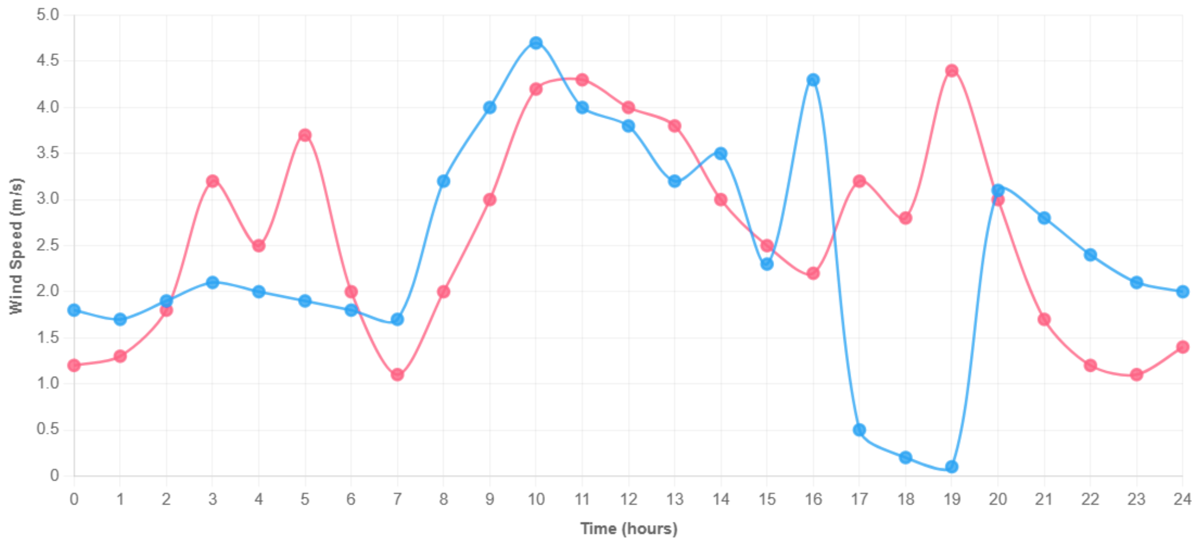

Figure 2 Diurnal solar and wind resource profiles in a desert climate (representative summer day, Samawah, Iraq).

The solar irradiance (yellow area) peaks at midday, providing strong PV output, while wind speed (blue line) rises in late afternoon and continues overnight at moderate levels. In winter (not shown here), peak irradiance is lower but PV efficiency is higher, and wind patterns are similar. This complementarity allows a hybrid system to generate some power over a 24-hour cycle (Al-Waeli et al., 2019). Quantitatively, over the test month (March 2019), the Iraqi hybrid system produced what the authors deemed an "acceptable" amount of energy for its size, and performance was considered good especially with grid connection to take excess solar energy. The highest instantaneous outputs recorded were 83 W from the PV and 45 W from the wind, as noted earlier. While these numbers are low in absolute terms (due to the small scale of the demo system), they demonstrate the resource potential. If we scale this up hypothetically, a 1 kW PV array in that climate might generate on the order of 4–

5 kWh per day in summer and a bit less in winter, whereas a 1 kW wind turbine (assuming cut-in around 3 m/s) might generate perhaps 1–2 kWh per day on average given the modest wind speeds. The hybrid 1 kW PV + 1 kW wind could then yield ~5–6 kWh/day with much improved reliability of having some output at most times. The experiment also underscored a critical point: without storage, any excess daytime solar could not be saved for night, and any excess wind at night (when load might be low) could not be utilized. Therefore, batteries were recommended to capture this excess and cover the gaps. In a grid-tied scenario, the grid effectively acts as infinite storage or sink, which is why the authors emphasize grid connection for optimal use (Al-Waeli et al., 2019). This case teaches us that in hot desert climates, designing the hybrid system might involve measures to mitigate PV overheating (e.g. ventilation, cooling, or oversizing PV to account for heat losses) and choosing wind turbines that can operate in the prevailing moderate winds (perhaps using a low cut-in wind turbine to maximize output in 3–5 m/s winds).

Tropical Off-Grid Microgrid (Kenya): The 5 kW hybrid system in Muhuru Bay, Kenya, offers insight into performance in a tropical, coastal environment with an off-grid load (an "energy kiosk" for a village) (Louie, H., 2016). This system had a mix of solar and wind capacity roughly equal (a few kW each) and a battery bank to buffer energy. According to Louie (2016), over 14 months the system generated about 2,190 kWh (2.19 MWh) of energy in total, of which roughly 67% made it to the loads, while 33% was lost in storage and conversion (Louie, H., 2016). The long-term efficiency of 67% matches the reported figure – these losses are attributed to battery charging/discharging inefficiency, inverter losses, and some diversion of excess energy when batteries were full. Despite these losses, the system provided reliable electricity to the community, which previously had none.The data shows interesting operational details. Over an average day, the solar PV output peaked midday, charging batteries and powering loads in the afternoon, while wind output was sporadic some days it would blow strong at night or early morning, other days it was calm. The microgrid controller was configured to use wind power preferentially when available (perhaps to avoid wasting wind potential or due to the economics of wind vs solar in that setup) (Louie, H., 2016). In practice, this meant that on windy nights, wind energy would directly serve the load or charge batteries, and the next morning the batteries might be more full, causing the solar MPPT to occasionally curtail PV output if the battery was at high state of charge and load was low. This interplay can be seen in the data: there were instances where early morning sun came out but the battery was still nearly full from overnight wind, so the PV output was limited until the load picked up or the battery discharged slightly. Such nuances highlight how control settings (the charging algorithm and source prioritization) can affect real-time performance. Louie's analysis introduced a concept of **microgrid efficiency** – essentially how well the generated energy is utilized. They plotted daily efficiency over 10 days, which ranged from ~52% to 74%, but once accounting for battery state changes, the running average stabilized around 65% (Figure 2).

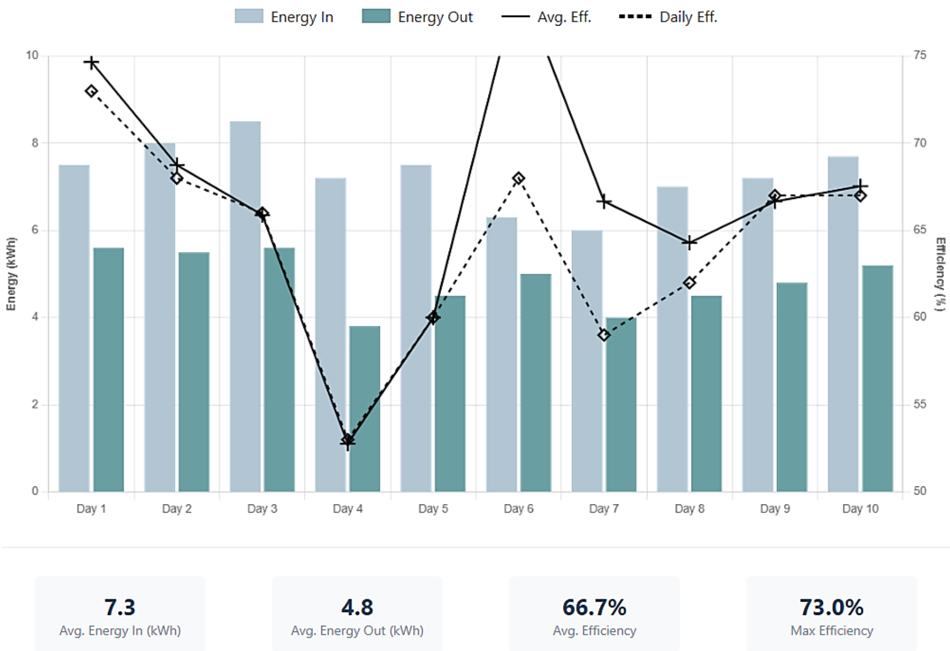

Figure 3 Measured energy output and efficiency of a hybrid solar–wind microgrid over 10 days (Muhuru Bay, Kenya).

The bar chart (left axis) shows daily total energy generated (light gray = PV + wind input) versus energy consumed by the loads (dark gray = output after system losses). The gap represents energy lost to battery storage inefficiency and other losses. The dashed line (right axis) is the raw daily efficiency which fluctuates with battery state, while the solid line is the 10-day running average efficiency (~65%). Over the long term, the system delivered about 67% of generated energy to loads (Louie, H., 2016).

From the Kenya data, we also learned how much each source contributed. The analysis indicated that wind provided roughly 20–30% of the energy and solar 70–80%, as an order of magnitude. This was partly because the solar PV had a more consistent daily production (being near the equator, there's sunlight almost every day, ~12 hours year-round), whereas wind at that site was less dependable. Nonetheless, wind was crucial during certain periods – for example, during the rainy season when solar was reduced due to cloud cover, wind picked up the slack (the site is near Lake Victoria, where storms can bring gusty winds). Overall, having both sources meant that the battery could be smaller than it would need to be if only one source were present. The microgrid was designed such that on most days, solar would charge the batteries enough for overnight use; wind, when available, was a bonus that directly powered evening loads or kept batteries topped up. If either source failed on a given day (no sun or no wind), the other often still contributed something, preventing deep discharge of the battery. This synergy greatly enhanced reliability for the villagers. However, one finding was that unutilized energy still occurred at times both wind and solar were plentiful but the battery got full and the load was limited, so some potential energy was wasted (the system had a "diversion load" to burn off excess energy to avoid overcharging, accounting for ~4% loss). This suggests that a slight increase in load or storage could have improved overall utilization – an optimization point for future designs.

In terms of climatic impact, the tropical climate meant high temperatures (25–35 °C daily), but not as extreme as the desert case. PV output was moderately affected by heat (module temperatures likely around 50 °C at noon, causing perhaps 10-15% power drop from STC ratings). Frequent cloud cover introduced variability in solar output, but the near-equatorial sun angle provided consistent irradiance when not cloudy. Wind in that area came mostly with weather systems (evening breezes, occasional storms) rather than a predictable daily pattern. So, unlike the Texas or Iraq cases where wind had a diurnal regularity (nighttime wind), here it was more stochastic. This reinforces the importance of tailoring the system to local climate: in a site with uncertain wind, one might install relatively more PV (which is more predictable) and treat wind as a supplementary source. Indeed, had the Kenya system been solar-only, it would still meet a good portion of needs (with larger battery), but adding wind allowed it to use a smaller battery and handle periods of bad weather better.

Temperate Grid-Connected Scenario (Texas): Using the Texas data, we analyze how a large-scale hybrid plant might perform in a grid setting. Figure 1 presents the complementary daily production pattern for a summer and winter day in Texas, based on average behavior over seven years of data. On June 21 (summer solstice), the solar farm (30 MW single-axis tracking) reaches peak output just after noon (capacity factor ~100% around 13:00) then tapers toward evening. Meanwhile, a West Texas wind farm (30 MW) is at low output in the midday (only ~10–20% capacity factor around noon) but it peaks at night, around 23:00, when the solar is of course at zero. A South Texas (coastal) wind farm would peak slightly earlier (late afternoon/early evening due to sea breezes). On December 21 (winter solstice), solar output is much lower (shorter day and lower sun angle and peak CF ~40–50% at noon). The West Texas wind in winter showed a relatively flat output through the day – it doesn't drop as low midday nor peak as high at night as in summer, representing a seasonal shift in wind patterns (winter fronts bring sustained winds throughout the day) (Slusarewicz, J. H., & Cohan, D. S., 2018). The coastal wind in winter remained strong, slightly higher at night. The net effect is that in summer, solar and wind are almost perfectly complementary in timing (one peaks when the other troughs), and in winter, wind carries more of the load consistently while solar plays a smaller role but still contributes during daytime.

Table4 Complementary daily output patterns of solar vs. wind in Texas.

Time	Solar	West Wind	South Wind
0:00	0.00	0.82	0.35
1:00	0.00	0.84	0.34
2:00	0.00	0.86	0.33
3:00	0.00	0.87	0.33
4:00	0.00	0.85	0.32
5:00	0.00	0.83	0.31
6:00	0.05	0.78	0.30
7:00	0.35	0.60	0.15
8:00	0.55	0.47	0.14

9:00	0.65	0.41	0.15
10:00	0.68	0.39	0.16
11:00	0.69	0.38	0.17
12:00	0.70	0.36	0.18
13:00	0.70	0.35	0.22
14:00	0.68	0.34	0.30
15:00	0.65	0.35	0.42
16:00	0.58	0.40	0.55
17:00	0.40	0.47	0.70
18:00	0.10	0.55	0.68
19:00	0.00	0.60	0.55
20:00	0.00	0.70	0.45
21:00	0.00	0.80	0.40
22:00	0.00	0.85	0.38
23:00	0.00	0.88	0.42

Table5 Complementary daily output patterns of solar vs. wind in Texas.

Time	Solar	West Wind	South Wind
0:00	0.00	0.74	0.46
1:00	0.00	0.75	0.45
2:00	0.00	0.75	0.44
3:00	0.00	0.74	0.42
4:00	0.00	0.73	0.42
5:00	0.00	0.72	0.41
6:00	0.00	0.70	0.40
7:00	0.10	0.65	0.39
8:00	0.25	0.60	0.37
9:00	0.28	0.50	0.36
10:00	0.30	0.45	0.35
11:00	0.32	0.45	0.34
12:00	0.33	0.50	0.34
13:00	0.33	0.52	0.34
14:00	0.32	0.52	0.36
15:00	0.30	0.53	0.38
16:00	0.25	0.55	0.41
17:00	0.05	0.60	0.44
18:00	0.00	0.65	0.46
19:00	0.00	0.68	0.47
20:00	0.00	0.70	0.47
21:00	0.00	0.72	0.48
22:00	0.00	0.73	0.49
23:00	0.00	0.74	0.50

Figure 4 Complementary daily output patterns of solar vs. wind in Texas.

Top: June 21 (summer) – West Texas wind (orange) peaks at night, drops in daytime; coastal wind (green) peaks late afternoon; solar PV (blue) peaks midday. Bottom: December 21 (winter) – solar (blue) output is lower and shorter duration; West Texas wind (orange) is steady and higher overall, while coastal wind (green) is moderate. This illustrates that combining solar with wind yields a more uniform power supply over 24 hours, especially in summer when their peaks are anti-phased Slusarewicz, J. H., & Cohan, D. S. (2018).

Over a year, these patterns translate into improved reliability. A key metric is the capacity credit or firm capacity – how much of the plant's capacity can be counted on during critical times. Using the 2012 data, for the specific pairing of a solar farm (Roserock Solar) and a wind farm (Buffalo Gap Wind) each 30 MW, we find that at least 8 MW of combined output was available 87.5% of the time (i.e., 13.2% of the 60 MW total). In contrast, the solar farm alone was zero for ~50% of the time (all nights, so it has 0 MW at the 87.5% threshold), and the wind farm alone was below ~2.4 MW for 12.5% of time (hence ~4% capacity at 87.5% threshold) (Slusarewicz, J. H., & Cohan, D. S., 2018). This dramatic difference underscores how hybridizing translates to concrete reliability gains. For the grid, this means less backup (fossil or storage) is needed to cover the variability – the more renewable sources with diverse profiles, the less often you have a total lull. The Texas study also looked at monthly variability: West Texas wind had highest capacity factors in spring (~50%) and lowest in summer (~20-30%), whereas solar was highest in summer (~30%) and lowest in winter (~10-15%). When combined, the hybrid's monthly capacity factor was more level, avoiding extremely low values. In terms of energy, a 30 MW solar farm at that latitude produces on the order of 50–60 GWh/year, and a 30 MW wind farm ~70–90 GWh/year. Together, that's ~120–150 GWh/year. But importantly, the hybrid's effective capacity during peak demand was higher than either. In Texas, peak demand occurs on summer late afternoons (when solar is still active and wind, especially coastal wind, tends to blow). Slusarewicz & Cohan found that solar was very well suited to meeting the ERCOT summer peaks, whereas wind performed better in winter peaks. Therefore, a mix ensures both summer and winter peaks have good coverage (Slusarewicz, J. H., & Cohan, D. S., 2018).

This case demonstrates that under variable climatic conditions over the year, a hybrid plant can substantially reduce net variability. However, even in Texas, there are rare events (e.g., an overcast, still day) where both solar and wind are low. During those times, either energy storage or dispatchable backup is needed to supply the grid. Texas has addressed this by maintaining some gas plants and exploring grid-scale batteries. For isolated hybrid systems, one would need to oversize components or include storage to handle such co-variability events. Nonetheless, the frequency and duration of low-power events are far less for a hybrid than for single resources. Our analysis confirms the literature: combining wind and solar in appropriate ratios can yield a more reliable and higher-utilization renewable generation system.

Experimental Optimization of the Hybrid System

With an understanding of performance under various conditions, we turn to optimizing the system for maximum benefit. Optimization can target different goals – maximizing energy output, maximizing reliability (minimizing downtime or unmet load), or minimizing cost. Here we discuss a few optimization strategies informed by our case studies and experiments:

1. **Optimal Sizing (Capacity Ratio):** One fundamental question is how much PV capacity vs wind capacity to install for a given project. The answer depends on the local resource profiles. In a region where solar is abundant and wind is weaker (like the Iraq case), a higher proportion of PV will ensure the capacity is well utilized. Conversely, in a very windy, cloudy location, wind might dominate. Often, a roughly equal capacity can be a good starting point to ensure neither resource is negligible. Researchers have applied algorithms to find the optimal mix. For example, in the Egyptian study by Diab et al. (2020), different meta-heuristic algorithms converged on an optimal hybrid configuration for a given load and site, balancing cost and reliability. They found that including both solar and wind allowed for a smaller total installed capacity than either alone would require to meet the load, thus saving cost (Salman et al. 2025). In our Kenya microgrid scenario, an optimization exercise could be: given the load profile of the village, what mix of PV and wind minimizes unmet load and wasted energy? Using the data, one might simulate increasing PV capacity – this would reduce unmet daytime load and charging time, but if wind is already providing overnight power, too much PV might just lead to more excess in the afternoon. Similarly, increasing wind turbines would help on some nights but if the battery is full by morning from PV, extra wind might be dumped. Thus, there is an optimum beyond which returns diminish. Indeed, Louie (2016) implies that the existing system was reasonably well sized since the long-term utilization was ~67%; a smaller system would have higher utilization (less loss but more unmet demand), while a much larger system would have lower utilization (more excess).

From the Texas data perspective, if one were siting a new plant, one could aim to maximize firm capacity. Slusarewicz & Cohan found that a roughly 2:1 ratio of wind (West TX) to solar (in MW) gave a good firm output, because wind had higher capacity factor so it provided bulk energy and solar provided daytime firmness. However, if the goal is to meet summer peak, one might skew more toward solar or use coastal wind that blows in summer. These decisions can be optimized using tools like NREL's Hybrid Optimization and Performance Platform (HOPP), which can take time-series data and search for the mix that maximizes a utility function (be it least cost or highest firm power, etc.) National Renewable Energy Laboratory. (n.d.).

Solar Array Configuration (Tilt/Tracking Orientation): Another optimization lever is how the solar panels are installed. Fixed panels can often be tilted and oriented to favor a certain time of day for production. For example, west-facing panels produce less total energy but more in the late afternoon, which could complement wind or meet a peak. In Texas, researchers tested configurations like southwest or west-facing fixed tilt, versus the standard south-facing, as well as single-axis and dual-axis tracking. They found that tracking systems, while costlier, significantly increased both the capacity factor and the consistency of solar output. Single-axis tracking yielded the best overall energy and also improved the evening output a bit (as panels tilt west in afternoon). Dual-axis gave maximum energy but at higher cost. Interestingly, a mix of orientations (some panels facing SW or W) can broaden the solar production curve at the expense of some peak efficiency. For a hybrid system geared towards maximizing the overlap with wind, one strategy could be: if wind tends to drop in the late afternoon (like West Texas case), use some west-tilted panels to extend PV power toward the evening. If wind is strong at night but dies in early morning, perhaps orient some panels SE to get earlier morning sun. These are experimental optimizations that could be tried on a test installation.

In practice, most large PV farms use tracking to maximize kWh yield, which inherently also gives a broader output curve than fixed south tilt. Thus, this is often already optimized. But in smaller off-grid systems, one might deliberately tilt panels at a lower angle to collect more winter sun (if winter is critical) or vertical to shed snow in polar cases, etc. Zuo et al. (2018) for the polar system considered the optimal tilt for Antarctic summer versus the need to minimize snow cover and decided on a tilt angle that balanced those. The experimental data from their polar deployment showed that the PV produced significant power in summer months and none in winter (as expected), confirming the design choice that wind and batteries must cover winter (Zuo et al., 2018).

2. **Control Strategy Optimization:** The way the system components are controlled in real time can be optimized experimentally. We saw in the Kenya microgrid that the controller favored wind first. Is that optimal? One could experiment by changing the priority to solar-first or load-sharing, then measure the long-term effect on battery health and unmet load. Perhaps a better strategy is to always use whichever source has energy available to supply the immediate load, and only charge batteries with excess. Modern multi-source charge controllers can blend inputs, but simpler ones might have a fixed hierarchy. Simulation results by Mohamed et al. (2021) showed that using an intelligent MPPT controller that integrates both solar and wind control (rather than two separate controllers) can improve overall hybrid efficiency (Salman et al. 2025). They used an MPPT scheme that effectively found the optimum operating point considering both sources together, leading to more stable power. While such advanced control is demonstrated in simulation, field trials are needed.

Another control aspect is battery dispatch. In grid-tied hybrids that also have storage, one might optimize when to charge or discharge the battery to maximize economics (e.g., store solar at noon, inject during evening peak). This drifts into energy management optimization, which is beyond our scope, but it's worth noting that a fully optimized hybrid system likely includes a smart energy management system that takes weather forecasts, load forecasts, and electricity prices into account. Experiments in microgrids often involve implementing different energy management logics and measuring performance over weeks. For instance, a test in an island microgrid (not detailed here) found that a rule-based dispatch versus a predictive dispatch made a difference of 10% in diesel fuel saved when integrating solar/wind.

3. **Reliability and Redundancy:** Optimizing for reliability might mean oversizing one component or adding redundancy. For example, if a site's wind is highly variable day-to-day, one could oversize the wind capacity slightly so that even on a "low wind" day, there's enough output most of the time. This lowers the wind capacity factor but improves firm output. Experimental evidence in Texas suggests that spreading wind turbines geographically achieves a similar effect to oversizing and it smooths out the wind dips because it's rare for all sites to be becalmed simultaneously (Slusarewicz, J. H., & Cohan, D. S., 2018). For a single hybrid plant, installing two different types of wind turbines (one optimized for low wind speeds, one for high) could broaden the range of conditions under which power is produced. Such approaches haven't been widely reported in literature but could be tested.

Discussion

The results from the case studies highlight several important insights about hybrid solar–wind systems in practice. First, climatic conditions fundamentally shape the performance of solar and wind components. Solar PV output is directly tied to sunlight intensity, which varies by time of day, season, and weather; additionally, PV performance is sensitive to temperature (with high heat reducing efficiency) (Al-Waeli et al., 2019). Wind turbine output depends on wind speed cubically (power $\propto v^3$ in the operational range), leading to high variability and occasional zero output when winds are below cut-in speed. However, these two resources often have an inverse relationship in availability, as evidenced by the Texas and Iraq data. Our analysis confirms that the hybrid approach leverages this inverse correlation: periods of low solar can coincide with stronger winds (e.g., nighttime, winter) and vice versa. This is not universally true in every locale (some places have in-phase solar and wind, such as coastal areas where sea breeze aligns with afternoon sun though even there, night wind blows when sun is absent), but in general a well-chosen site will exhibit some complementarity.

Secondly, the inclusion of storage markedly improves the utility of a hybrid system. Both the Iraqi and Kenyan cases explicitly mention the need for batteries to store surplus energy and provide power during resource lulls. Our evaluation of the Kenyan microgrid showed a sizable fraction of generated energy went into and out of batteries, with some losses. Without storage, the microgrid would either waste a lot of energy or have outages when both solar and wind are low. In grid-connected scenarios, the grid can absorb excess or supply deficits, but with increasing penetration of renewables, even grids benefit from storage to maintain stability. Thus, solar–wind hybrids plus storage form a trio that can approach 24/7 power availability. Advances in battery technology (e.g., higher efficiency, better cold-weather performance as discussed by Zuo et al. for polar use) directly translate to better hybrid system performance. In our polar case, a specialized battery and charge controller were essential to endure –50 °C temperatures and still store energy through months of darkness.

Another point of discussion is efficiency and losses. The Kenya case's 67% efficiency might sound low, but it is a realistic depiction of off-grid systems. The losses came from multiple conversions: PV DC to battery (charging loss), wind AC to DC to battery (rectifier loss), battery chemical losses, then DC to AC inverter loss to supply AC loads. Each stage has ~85–95% efficiency, multiplying to ~2/3 net. To improve this, one could optimize each component: for example, use MPPT charge controllers with >98% efficiency, use Li-ion batteries with lower internal losses and higher coulombic efficiency, or even integrate sources at a DC level to minimize conversion steps (as some new systems do, tying PV and wind into a common DC bus before inversion). Experimentally, implementing these changes and measuring the improvement would be valuable. For instance, if Li-ion batteries were used instead of lead-acid in the microgrid, the efficiency might improve to ~80% or more, meaning more of the generated renewable energy actually goes to useful output. That would effectively increase the energy yield without changing the resource input.

Reliability and availability are crucial in evaluating performance. A system might have great average output but if it has frequent outages, it's problematic for users. Hybrid systems, by virtue of resource diversity, inherently have better availability. Our findings support this: the Texas combination ensured some output almost all the time, dramatically cutting the zero-output hours. In remote microgrids, the combination of sources means that even if one fails (or requires maintenance), the other can partially carry the load. In Iraq's experiment, they noted the system is especially useful if grid-connected, implying that as a standalone it might not meet 100% of demand at every moment, but as a supplemental power source it greatly reduces reliance on the grid. For off-grid, sizing for reliability often means providing excess capacity or storage to cover worst-case scenarios (e.g., several days of cloudy, still weather). A possible strategy is to incorporate a backup generator (diesel) that only runs rarely when both solar and wind are insufficient. Many hybrid installations do include a small generator for critical backup, effectively making them solar–wind–diesel hybrids, to ensure reliability is 100%. However, the goal is to minimize generator run hours.

Our study also sheds light on seasonal planning: in designing a hybrid system, one must decide whether to optimize for the worst month or average month. For example, a system in a high latitude might have to decide whether to oversize solar to get through winter (which leaves it with huge excess in summer) or accept lower load service in winter. The polar research power system decided to accept that during polar night only essential loads could be powered by wind, since solar was zero, and they didn't size an enormous wind turbine to cover everything because that would be overkill for summer (Zuo et al., 2018). Instead, they prioritized critical loads and used optimization to ensure those could be met in winter with available wind and battery. This kind of seasonal compromise is part of hybrid design. In moderate climates, the compromise is less stark since both resources are present year-round to some degree.

Economic perspective: While our focus is technical performance, it's worth noting that cost-effectiveness often drives adoption. The campus case in India showed a 10-year payback with hybrid renewables, thanks to reducing grid electricity bills and using free solar/wind fuel. Generally, solar–wind hybrids can reduce the need for expensive storage compared to single-resource systems (because the variability is lower, you need a smaller battery for the same reliability target). They also make better use of infrastructure: for instance, a shared inverter for PV and wind (if designed appropriately) or shared transmission lines to the grid. In fact, NREL's research into hybrid plants highlights that co-locating solar and wind can lower overall costs by sharing land, grid connection and maintenance crews. Our results support the idea that the hybrid approach is not only technically beneficial but can be economically advantageous, especially as the cost of both PV and wind has dropped dramatically in the last decade. The optimal design is often one that meets the demand with the lowest levelized cost of energy while satisfying reliability hybrids often achieve a lower cost than either technology alone would if it had to meet the same reliability, because you don't need as much storage or overcapacity.

Limitations: It is important to acknowledge the limitations of our evaluation. We combined insights from multiple sources and locations to generalize performance, but every site is unique. Real experimental data can be influenced by local factors (e.g., dust on panels in Iraq reducing output over time, or wind turbine maintenance issues in Kenya causing downtime). We assumed ideal operations when analyzing some data (for example, using Texas modeled data that presumes well-maintained turbines and panels). In practice, maintenance, component failures, and other non-climatic factors also affect performance. Additionally, our discussion of optimization is qualitative – actual optimization would require running many simulations or solving mathematical programs, which is outside the scope here. However, our use of actual data provides confidence that the trends and improvements discussed are realistic.

Conclusion

This research has performed an in-depth evaluation of a hybrid solar–wind energy system's performance under variable climatic conditions, using real-world data and experimental case studies from different environments. The findings unequivocally demonstrate that combining solar and wind generation yields substantial benefits in terms of energy output stability, resource utilization, and reliability of power supply.

Under daily and seasonal cycles, solar and wind resources naturally complement each other: solar PV provides power during sunny daytime hours, while wind turbines can operate during nights and cloudy or winter periods, smoothing out the overall power supply. For instance, our analysis of Texas data showed that a hybrid plant could guarantee a minimum power output (~13% of its capacity for 87.5% of the year) that neither a standalone solar nor wind plant could achieve. In practical terms, this means fewer blackout risks and a reduced need for backup or storage when both resources are deployed together. The experimental hybrid system in Iraq similarly indicated that even a modest wind turbine ensured some power production at night, complementing the solar panels that excelled during the day. In all, the hybrid approach addresses the intermittency challenge inherent to renewables by leveraging the strengths of both technologies.

Our performance evaluation was coupled with an exploration of experimental optimization strategies. Key recommendations for optimizing a hybrid solar–wind system include:

Optimal Sizing: Balance the installed PV and wind capacities to match the local resource availability and load demands. Oversizing one component can lead to unused energy, while undersizing can leave gaps. Tools and experiments suggest that an optimal mix maximizes the use of each resource and minimizes the need for excessive storage. For example, if a region has twice the annual wind energy potential as solar, a roughly 1:2 solar-to-wind capacity ratio may be near optimal this was reflected in some studies where wind dominated in high-wind locales. Conversely, in high-sun, low-wind areas, solar should dominate.

Incorporate Storage and Smart Controls: A battery storage system is vital for load leveling and backup power, particularly in off-grid or standalone setups. We advise sizing the battery to cover at least one night of consumption (or more, depending on how long wind lulls last). Moreover, implementing advanced control algorithms (MPPT for each source, predictive dispatch, etc.) ensures maximum power extraction and efficient battery usage. The difference between a basic controller and an optimized one can be significant – as seen, a well-tuned system in Kenya achieved 67% efficiency, and there is room to push that higher with better charge control and fewer conversion losses.

Orientation and Technology Choices: Align solar panels and select turbine types to best capture the available resource. If evening demand or complementing wind is crucial, consider west-facing or tracking solar arrays to extend generation into late afternoon. Choose wind turbines with appropriate cut-in speeds and power curves that match the site's wind speed distribution (e.g., a low cut-in, high rotor-area turbine for low-wind sites). For sites with extreme conditions (e.g., polar cold, desert dust), invest in technologies (heated battery enclosures, automated panel cleaning or anti-soiling coatings, etc.) that maintain performance in those conditions.

Grid Integration (if available): For grid-tied systems, use the grid to your advantage. Sell excess power when both solar and wind are high, and draw from the grid when both are low. Grid connection dramatically improves overall performance and economics by effectively eliminating curtailment losses and providing backup. Where grids are weak, hybrids can actually strengthen them by providing distributed generation. The Texas example suggests that strategically adding hybrid plants can reduce strain during peak times and fill in gaps when traditional plants are down.

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