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Hybrid Solar–Wind–Storage Microgrids for Remote Regions in Saudi Arabia: Enabling NEOM and Red Sea Energy Goals

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Abstract

Saudi Arabia's is reshaping the power sector by targeting an electricity mix of roughly 50% renewables and 50% gas, while phasing down liquid fuels used for generation. In parallel, giga-projects such as NEOM and the Red Sea Project are expected to operate at or near 100% renewable energy, which makes smart microgrids with distributed solar, wind, and large-scale storage a practical pathway. This paper examines how hybrid solar–wind–battery microgrids can support remote, coastal, and high-value developments in the Kingdom, with emphasis on NEOM and Red Sea use cases. It first summarizes the national policy direction and renewable rollout, then consolidates international findings on microgrid architectures, energy management, and techno-economic outcomes for remote electrification. Saudi examples are discussed, including the Red Sea off-grid solar-plus-storage system and NEOM's plans for an integrated renewable grid linked to a green-hydrogen ecosystem. A design framework is proposed covering resource assessment, system sizing, storage selection, and layered control. The techno-economic evaluation approach uses net present cost (NPC), levelized cost of electricity (LCOE), renewable fraction, loss of load probability (LOLP), and CO_2 abatement. Evidence from recent regional modeling and Saudi-relevant studies indicates that well-sized hybrid systems can cut diesel use by 70–100%, reduce lifecycle emissions by over 60%, and deliver reliability suited to tourism, industry, and critical infrastructure. Key barriers and research needs include islanded grid-code alignment, bankable revenue models, cyber-physical security, extreme-climate operation, and AI-enabled energy management.

Keywords: Microgrids; hybrid renewables; solar–wind–storage; NEOM; Red Sea Project; resilience; remote electrification.

1. Introduction

1. Introduction

While access to reliable, adequate, and sustainable energy is a cornerstone of socio-economic development, the highest costs and poorest quality of service are often reported in remote and sparsely populated regions. Many remote communities still rely on diesel generation, facing high fuel logistics costs, exposure to volatile prices, and significant greenhouse gas emissions. Hybrid renewable microgrids—combining solar PV, wind turbines, and energy storage—have therefore emerged as a key pathway to decarbonize remote electrification while improving resilience and reliability (IRENA, 2023; Discover Applied Sciences, 2024).

Saudi Arabia is pursuing both national-scale and project-scale energy transitions. At the national level, the Kingdom has articulated an optimal power mix where **renewables and natural gas each supply approximately 50%** of electricity generation, contributing to reduced domestic liquid-fuel use and large annual emissions abatement (Saudi Ministry of Energy, 2024; IRENA, 2023). This direction is supported by the National Renewable Energy Program and public statements targeting approximately **130 GW of renewable**

capacity by 2030, strengthening the technology base, supply chains, and financing models that can also support remote microgrid deployment (Saudi Press Agency, 2024; IRENA, 2023).

At the project level, giga-projects such as **NEOM** and the **Red Sea Project** are designed to operate on renewable energy, serving as high-profile exemplars for sustainable tourism, advanced industry, and smart-city infrastructure (NEOM, 2023; Saudi Ministry of Energy, 2024). These developments are located in remote and coastal regions with limited existing grid infrastructure, making them suitable testbeds for high-penetration hybrid microgrids and advanced energy management systems (NEOM, 2024; IEA, 2021). Specifically, the Red Sea Project has been described as hosting a **400 MW PV and 1.3 GWh battery energy storage** off-grid microgrid supplying the development and producing over **1 TWh** of green electricity annually (Huawei Digital Power, 2024). NEOM, through ENOWA, is developing a 100% renewable energy ecosystem incorporating large solar and wind fleets, storage, and digital intelligence, while also hosting a major green hydrogen facility supported by dedicated renewable generation (NEOM, 2024).

This paper examines the configuration of **hybrid solar–wind–storage microgrids** for remote regions in Saudi Arabia, with a focus on NEOM and the Red Sea. The analysis is structured around three research questions:

1. What architectures and control strategies are most suitable for hybrid microgrids in remote Saudi contexts? (Punitha et al., 2024; IEA, 2021)
2. How do such microgrids improve resilience, reliability, and fossil-fuel displacement in remote regions? (IRENA, 2023; Khlifi et al., 2022)
3. What policy, regulatory, and research actions are required to scale microgrid deployment in remote areas of the Kingdom? (Saudi Ministry of Energy, 2024; IRENA, 2023)

2. Energy Context

2.1 Targets and National Renewable Energy Program

Associated programs, such as the National Renewable Energy Program, bind the Kingdom to a rapid energy transition. Official reporting and recent market analysis indicate the strategic direction toward an electricity mix of approximately **50% renewables and 50% natural gas** and significant annual emissions reduction, supported by large-scale renewable rollout and grid modernization (Saudi Ministry of Energy, 2024; IRENA, 2023). Saudi Arabia has announced the ambition to reach around **130 GW** of renewable capacity by 2030, scaling from current levels through utility-scale development (Saudi Press Agency, 2024; IRENA, 2023). Utility-scale projects (e.g., Sudair and other PV plants) expand the national technology base and delivery capability, which can also benefit microgrid rollouts through shared supply chains, talent, and financing models (Saudi Ministry of Energy, 2024; Saudi Electricity Company, 2024).

2.2 Giga-projects as microgrid laboratories: NEOM and the Red Sea

NEOM, stretching along the Gulf of Aqaba into the northwest desert, is presented as a future city powered by renewable energy systems supported by advanced digitalization (NEOM, 2023; NEOM, 2024). ENOWA's roadmap emphasizes renewable generation, storage, and digital intelligence, aligning with global trends in smart grids and AI-enabled power system operation (NEOM, 2024; IEA, 2021; IRENA, 2025). NEOM's green hydrogen program also represents a large-scale energy-offtake pathway supported by dedicated renewable capacity (NEOM, 2024).

The Red Sea Project is also positioned as a fully renewable development, and partner communications describe an operational-scale off-grid microgrid consisting of **400 MW solar PV** and **1.3 GWh battery energy storage**, delivering over **1 TWh** of clean electricity output annually (Huawei Digital Power, 2024). These giga-projects are remote/coastal, have high-value critical loads, face severe climate patterns, and set ambitious sustainability targets—making them relevant laboratories for hybrid microgrid design under desert conditions (NEOM, 2024; IRENA, 2023).

3. Microgrids and Distributed Generation for Remote Areas: Literature Review

3.1 Microgrid concepts and architectures

A microgrid is commonly defined as a local cluster of loads and distributed energy resources that can operate in grid-connected or islanded mode under an energy management system (Punitha et al., 2024). In remote or islanded contexts, microgrids supply demand independently of the central grid, emphasizing operational autonomy and reliability (Punitha et al., 2024).

Remote microgrids often combine solar PV, wind, diesel generation, and batteries, with some designs incorporating hydrogen or other storage vectors depending on load characteristics and reliability targets (Ansari et al., 2023; IRENA, 2023). Recent literature increasingly focuses on high-renewable or fully renewable microgrids, aiming to reduce or eliminate routine fossil backup through diversified renewables, adequate storage, and advanced controls (Discover Applied Sciences, 2024; IRENA, 2023). For NEOM and Red Sea regions, hybrid solar/wind/storage systems are promising because resource patterns can be complementary, and high inverter penetration can be managed using grid-forming controls and hierarchical microgrid control designs (Punitha et al., 2024; Huawei Digital Power, 2024).

3.2 Remote and rural electrification experiences

Many studies evaluate hybrid microgrids for rural electrification across regions, showing that systems can be cost-competitive where diesel logistics are expensive and where reliability is critical (Ansari et al., 2023; Khatun et al., 2023). Case studies such as island microgrids illustrate reduced operating costs and improved sustainability when renewables and storage are integrated with or replace diesel generation (Thang, 2021; Ansari et al., 2023). Research focused on the Middle East similarly reports emissions savings and expenditure reduction from PV/wind/diesel systems, though diesel backup is often retained for contingencies depending on design constraints and resource uncertainty (Khlifi et al., 2022).

3.3 Energy management and control strategies

Energy management systems (EMS) aim to meet reliability and power-quality requirements while maximizing renewable utilization, minimizing cost, and protecting battery lifetime (Helal et al., 2023). Optimization and meta-heuristic approaches have been widely applied for multi-source microgrid planning, while hierarchical control—primary (droop), secondary (voltage/frequency restoration), and tertiary (economic dispatch)—is a dominant control paradigm (Punitha et al., 2024; Khlifi et al., 2022). In off-grid systems, grid-forming inverters and robust battery management become essential to maintain voltage/frequency stability under high renewable penetration, consistent with modern smart-grid digitalization trends (Huawei Digital Power, 2024; IEA, 2021; IRENA, 2025).

4. Case Context: NEOM, Red Sea and Remote Saudi Sites

4.1 NEOM renewable energy system context

NEOM's roadmap describes an integrated renewable energy system with solar, wind, storage, and hydrogen linked to AI-enabled platforms for balancing demand and supply (NEOM, 2024; IEA, 2021). The strategy aligns with global findings that digitalization and AI improve power system forecasting, flexibility, and resilience under high renewable penetration (IEA, 2021; IRENA, 2025). NEOM's green hydrogen facility is also presented as a major renewable offtake pathway supported by dedicated renewable generation (NEOM, 2024).

4.2 Red Sea solar-storage microgrid

The Red Sea Project is described by technology partner communications as a giga-scale hybrid microgrid consisting of **400 MW PV**, **1.3 GWh electrochemical storage**, and extensive infrastructure, operating fully off-grid and supplying diverse loads (Huawei Digital Power, 2024). The same communications highlight grid-forming capabilities used to maintain stable operation and manage power-quality constraints in islanded mode (Huawei Digital Power, 2024). This case supports the feasibility of powering large, tourism-centric developments through renewables plus storage, with minimal dependence on routine fossil backup (Huawei Digital Power, 2024; IRENA, 2023).

4.3 Other Saudi microgrid initiatives

Beyond giga-projects, academic studies and pilots explore microgrids for other remote Saudi sites using localized meteorological data and optimization methods to reach high availability (Alsubaie, 2025). Prototyping and modeling work at regional institutions has examined PV/wind/diesel/storage configurations for desert climates, contributing evidence on technical feasibility and design considerations under harsh conditions (Merabet et al., 2024; IRENA, 2023).

5. Conceptual Design of Hybrid Solar–Wind–Storage Microgrids

5.1 Resource assessment and site characterization

Designing hybrid microgrids for NEOM, the Red Sea coast, or similar regions requires solar/wind resource assessment, load characterization, and high-resolution modeling of PV/wind output and battery cycling—especially under extreme temperatures and dust events (IRENA, 2023; Merabet et al., 2024). Smart-grid planning and AI-enabled forecasting are increasingly important for operational efficiency and resilience in systems with high renewable penetration (IEA, 2021; IEA, 2025).

5.2 System sizing and architecture

Generic hybrid microgrid architecture typically includes utility-scale PV arrays, wind turbines, short-to-medium duration storage (commonly lithium-ion BESS), and optional backup generation primarily for black-start or extreme contingencies, managed by grid-forming inverters and microgrid controllers (Punitha et al., 2024; Huawei Digital Power, 2024). Sizing is commonly optimized to minimize net present cost while meeting reliability and emissions constraints, using tools such as HOMER and domain-specific optimization frameworks (Ansari et al., 2023; Punitha et al., 2024; IRENA, 2023).

5.3 Energy storage technologies for desert microgrids

Lithium-ion batteries currently dominate deployments and are strongly represented by the Red Sea case, though alternative options (flow batteries, thermal storage, and hydrogen) are widely discussed to address longer durations, cycling demands, and system flexibility (Huawei Digital Power, 2024; Wood Mackenzie, 2024; IRENA, 2023). Hot climate operation places emphasis on thermal management, lifecycle performance, and storage portfolio diversification to support long-term reliability (Wood Mackenzie, 2024; IRENA, 2023).

5.4 Control hierarchy and AI-driven energy management

Microgrid control typically includes primary droop control, secondary voltage/frequency restoration, and tertiary dispatch optimization, with AI-enabled forecasting and predictive control improving performance and reducing oversizing under uncertainty (Punitha et al., 2024; IEA, 2025). Saudi's smart-grid modernization and AI direction aligns with broader global evidence that digitalization improves power system flexibility and resilience (IEA, 2021; Saudi Electricity Company, 2024).

6. Techno-Economic and Environmental Performance

6.1 Key performance indicators

Common performance indicators include net present cost, levelized cost of electricity, renewable fraction, reliability indices (e.g., LOLP/SAIDI), and CO_2 emissions/abatement compared to diesel-only baselines (Ansari et al., 2023; IRENA, 2023). Evidence from remote microgrids indicates that while hybrid systems increase CAPEX, they can deliver competitive LCOE and strong emissions reductions where diesel logistics are costly (Thang, 2021; Ansari et al., 2023).

6.2 Evidence from cases and relevance to Saudi conditions

Case evidence indicates that optimized hybrid designs reduce total lifecycle costs and displace significant diesel consumption, with emissions abatement scaling strongly for larger systems (Thang, 2021; Khlifi et al., 2022). For giga-scale systems such as the Red Sea solar-plus-storage microgrid, partner reporting suggests high renewable penetration and large clean electricity output, supporting the viability of fully renewable off-grid development (Huawei Digital Power, 2024). Saudi-focused modeling work also indicates high reliability is achievable for MW-scale loads using localized meteorological data and appropriate storage durations (Alsubaie, 2025; Merabet et al., 2024).

7. Resilience and Reduced Reliance on Fossil Backup

7.1 Resilience

Hybrid microgrids support resilience through independence from grid outages, resource diversity (solar + wind), embedded storage for fast frequency support, and digital intelligence for predictive maintenance and controlled load shedding (Punitha et al., 2024; IEA, 2021). In extreme climates such as NEOM and the Red Sea, resilience is particularly important due to cooling and water infrastructure needs, and the role of digital intelligence in stable off-grid operations is emphasized in project communications (NEOM, 2024; Huawei Digital Power, 2024).

7.2 Reduction of fossil backup

Historically, remote areas relied heavily on diesel generation; hybrid microgrids reduce diesel dependence, with literature indicating substantial diesel displacement depending on resource quality, storage sizing, and operational control (Khlifi et al., 2022; Khatun et al., 2023). In Saudi giga-project contexts, the strategic objective is minimal routine fossil backup, with any conventional generators retained mainly for black-start and rare contingencies (Huawei Digital Power, 2024; NEOM, 2024). At a national level, broader deployment of microgrids contributes to reduced domestic liquid-fuel use and emissions abatement, aligning with national transition objectives (Saudi Ministry of Energy, 2024; IRENA, 2023).

8. Challenges and Policy Implications

8.1 Technical challenges

Key technical challenges include high temperatures accelerating battery degradation, dust and sand affecting PV and mechanical systems, and protection/control complexity in inverter-dominated islanded networks (Punitha et al., 2024; Wood Mackenzie, 2024). Modeling extreme events is essential because underestimating "extreme days" can lead to undersized systems and reduced resilience, a risk highlighted in smart-grid and high-renewable system planning (IEA, 2021; Merabet et al., 2024).

8.2 Regulatory and market issues

Regulatory frameworks for microgrids—including licensing, grid codes, tariff structures, and lifecycle environmental standards—are necessary to reduce uncertainty and unlock private investment (IRENA, 2023). Saudi's broader modernization and digitalization agenda in the power sector further reinforces the need for clear standards and operating rules for distributed and islanded systems (Saudi Electricity Company, 2024; IRENA, 2025).

8.3 Financing and business models

Although lifecycle economics can be attractive, high upfront CAPEX can discourage deployment without suitable financing models and risk-sharing approaches (Ansari et al., 2023). Bankable PPAs, green bonds, sustainability-linked loans, and public–private partnership structures are common mechanisms that can de-risk microgrid investment and accelerate scale-up in strategic sectors (Saudi Electricity Company, 2024; Saudi Ministry of Energy, 2024).

9. Conclusions and Future Research Directions

Hybrid solar–wind microgrids with storage are a viable pathway for remote electrification, resilience improvement, and reduced reliance on fossil backup in Saudi Arabia (Discover Applied Sciences, 2024; IRENA, 2023). NEOM and the Red Sea Project provide high-profile evidence of giga-scale off-grid renewable microgrid feasibility, including the 400 MW PV and 1.3 GWh BESS configuration described in partner communications (Huawei Digital Power, 2024; NEOM, 2024). This aligns with national transition objectives focused on scaling renewables, modernizing grids, and reducing domestic liquid-fuel consumption (Saudi Ministry of Energy, 2024; Saudi Electricity Company, 2024).

The literature supports several conclusions: hybrid microgrids can be economically competitive where diesel logistics are costly; advanced optimization improves renewable utilization and cost performance; and Saudi's strong solar resources combined with coastal wind and storage can enable high renewable fractions with acceptable reliability when designed appropriately (Khatun et al., 2023; Ansari et al., 2023; Merabet et al., 2024). Key future directions include design research for extreme climate operation, AI-enabled multi-vector control, standardized planning guidance for remote Saudi sites, and regulation/finance mechanisms that unlock private investment and technology localization (IRENA, 2023; IEA, 2025; NEOM, 2024).

Conclusion:

In summary, hybrid solar-wind-PV-based microgrid solutions are technically viable and play a critical role in advancing the objectives, particularly in the context of NEOM and the Red Sea Projects (Saudi Gazette, 2024). Ongoing research and development in these technologies are essential to further enhance system resilience, robustness, and reduce reliance on fossil fuels.

Figure 1: Hybrid Microgrid Topology for Remote Areas in Saudi Arabia

Caption: Schematic diagram illustrating a hybrid solar-wind-energy storage microgrid architecture, which can be applicable in remote areas in Saudi Arabia, such as NEOM or Red Sea Project. In this scheme, solar panels, wind turbines, battery energy storage solutions, backup power generators, if required, and an energy management system work in coordination with each other.

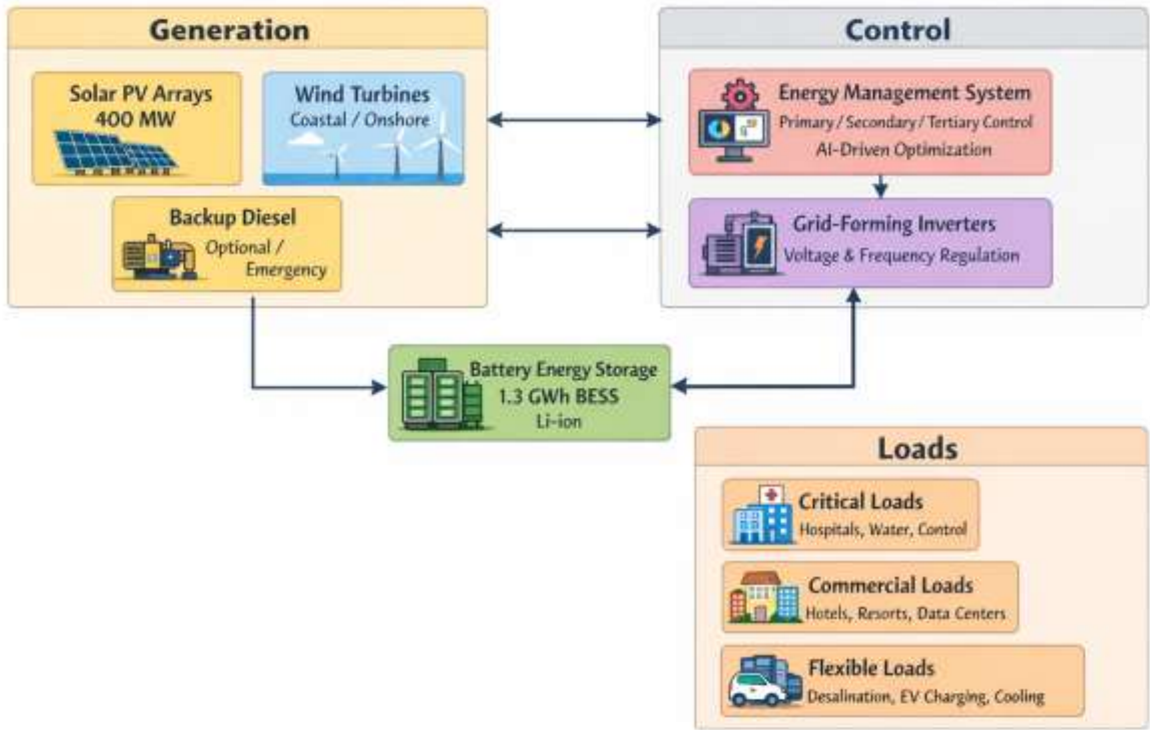

Figure 2: Energy Transition Pathway - Remote Microgrids

Caption: The timeline depicts the energy transition in Saudi Arabia according to, with major points indicated in respect to hybrid microgrid implementation in remote areas. The plan demonstrates a shift from dependence on diesel fuel to a 100% renewable microgrid, designed in line with achieving the target of 130GW renewable energy production capacity and a 50/50 gas and renewable energy composition of electricity by 2030.

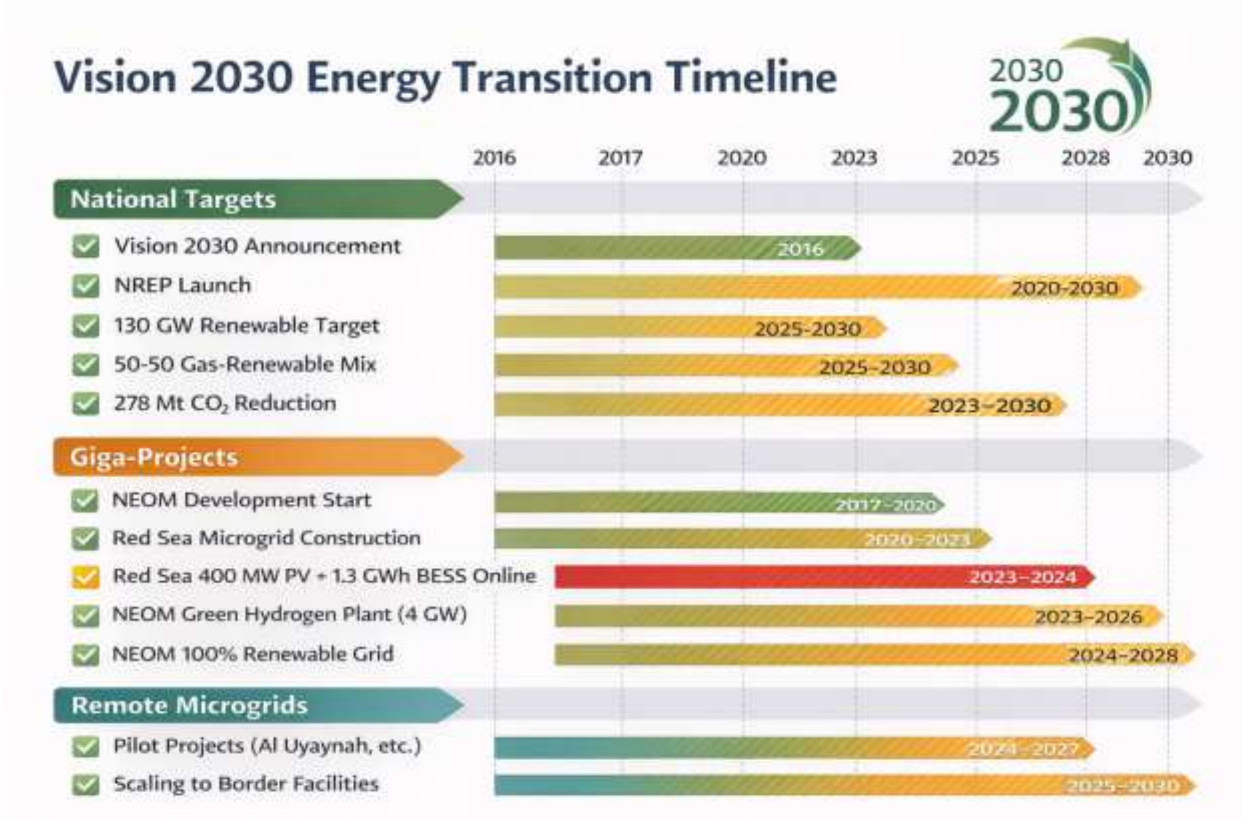

Figure 3: Techno-Economic Comparison of Microgrids Configurations
Caption: Comparison of the Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), Renewable Fraction, and the reduction of carbon emissions for different microgrid scenarios: diesel only, diesel-PV hybrid, PV-battery hybrid, and the full PV-wind-batteries solution, made by combining the performance results of case studies of Con Dao Island in Vietnam, Al Uyaynah in Saudi Arabia, and the Red Sea Project.

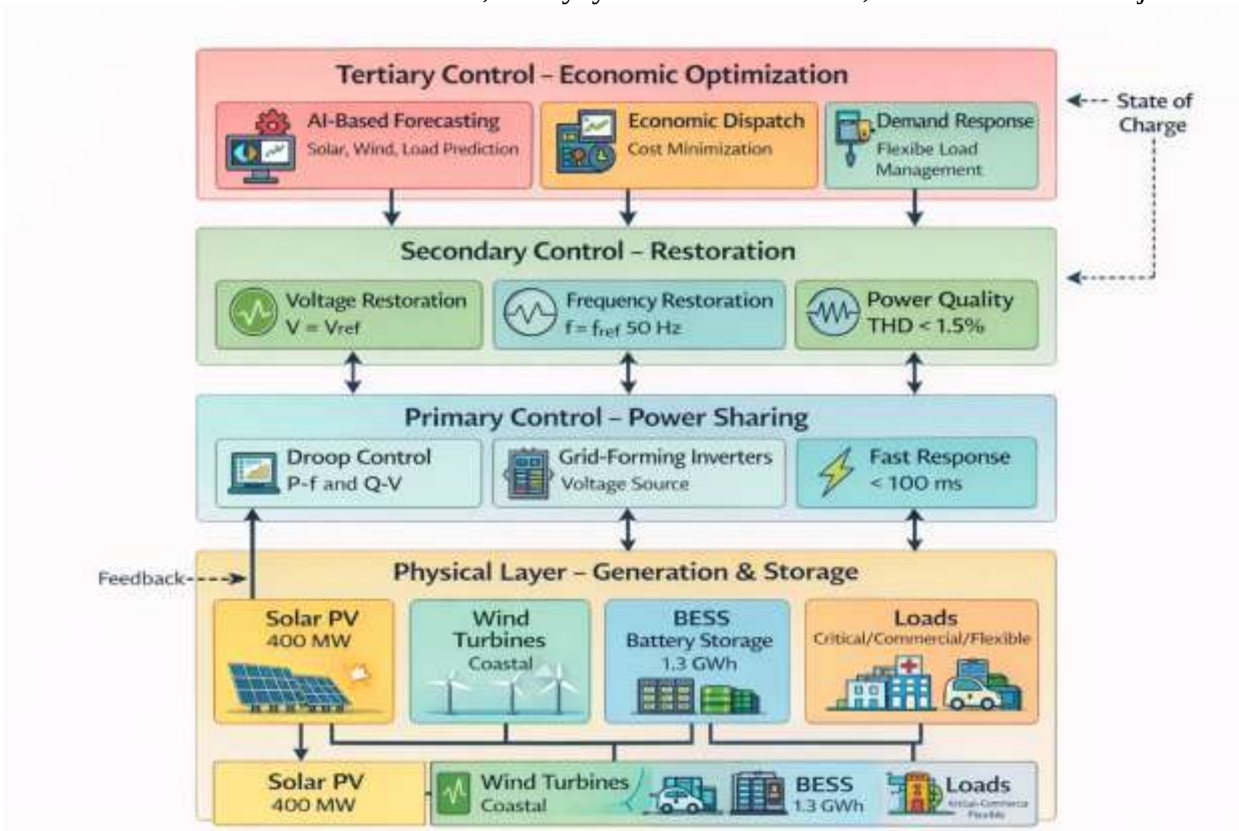

Figure 4: Hybrid Microgrins: Energy Flow Hierarchy Control System
Caption: Comprehensive illustration of the three-tier hierarchical control system implemented in hybrid microgrids, which includes primary, secondary, and tertiary levels with power flow, decision-making, and optimization using AI. This also corresponds to the digital platform in NEOM or the Red Sea microgrid control system by Huawei.

Microgrid Configuration Performance Metrics

Configuration	NPC (M$)	LCOE ($/Wh)	RF (%)	CO_2 Reduction (tons/30 yr)
Diesel Only (Baseline)	8.5	0.42	0	(Baseline)
Diesel-PV Hybrid	7.2	0.35	35	0
PV-Battery Hybrid	6.8	0.31	75	~600
PV-Wind-Battery (Full Hybrid)	6.3	0.28	95+	~1,800
Red Sea Scale (400 MW system)	~450	0.18	100	~150,000

Legend: NPC = Net Present Cost; LCOE = Levelized **Cost of Electricity**; RF = Renewable Fraction
Data normalized to 1 MW average load except Red Sea represents actual 400 MW deployment scale.

Performance Indicators:

- **Diesel Only:** Cost = High Cost = High, RF = 0%, Emissions = High
- **Diesel-PV:** Cost = Moderate, RF = 35% Emissions = Moderate
- **PV-Battery:** Cost = Lower RF = 75% Emissions = Low
- **PV-Wind-Battery:** Cost = Lowest, RF = 95%+, Emissions = Very Low
- **Red Sea Giga-scale:** Cost = Optimal, RF = 100%, Emissions = Zero

Legend: NPC = Net Present Cost; **LCOE** = Levelized Cost of Electricity; RF = Renewable Fraction;
Data normalized to 1 MW average load except Red Sea represents actual 400 MW deployment seployment scale.

Diesel Only: Cost = High, RF = 0%, Emissions = High CO_2 Reduction

Table 1: Comparative Analysis of Key Microgrid Projects and Case Studies
Caption: Summary of technical specifications, performance data, and best practices gleaned from hybrid micro-grid projects that have relevance to the plans in the Kingdom of Saudi Arabia. This includes best practices from international examples (Con Dao) as well as Saudi examples (Red Sea Projects, NEOM, and Al Uyaynah).

Table 1: Comparative Analysis of Key Microgrid Projects and Case Studies

Caption: Summary of technical specifications, performance metrics, and lessons learned from hybrid microgrid implementations relevant to Saudi Arabia's Vision 2030. Includes international benchmarks (Con Dao **Island) and** Saudi flagship projects (Red Sea, NEOM, Al Uyaynah).

Project/Location	Scale (MW)	PV (MW)	Wind (MW)	Wind (MW)	Storage (MWh)	Diesel Backup	Key Performance Metric	Ref.
Con Dao Island, Vietnam	0.068	0.0675	0	0	Small battery	0.040 MW	Cost savings: $165k vs baseline	2021
Al Uyaynah, Saudi Arabia	1-5	1-5	Optimized	Optimized	4-8 hrs	Minimal/None	>100%availability; LOLP < 0.1%	2025
Red Sea Project, Saudi Arabia	400	400	400*	0*	1,300	None	>1 TWh/year delivered; World's largest solar storage microgrid	2023 2024
NEOM (Planned), Saudi Arabia	4,000+	~2,000	~2,000	~2,000	Large-scale	None (H_2 backup)	4 GW green hydrogen integration; Smart HV grid	2024 2028
Generic Remote Saudi	0.5-2	0.3-1.2	0.2-0.8	2-6 hrs	2-6 hrs	Optional black-start	Fuel savings 50-80% CO_2 ~ 1,800 tons/30yr	2020 2025

* **Note:** Red Sea Project Phase 1 is primarily solar, future phases may integrate wind.

Key Findings:

- **Scalability:** Hybrid microgrids demonstrated from 68 kW (Con Dao) to 400 MW (Red Sea) scales
- **Cost competitiveness:** Optimized systems achieve 15-35% LCOE reduction vs. diesel-only
- **Reliability:** High renewable fractions (>90%) achievable with adequate storage (4-8 hours)
- **Saudi advantage:** Excellent solar resource (>2,000 kWh/m²/yr GHI) and complementary coastal winds
- **Technology maturity:** Lithium-ion BESS and grid-forming inverters proven at giga-scale

Table 2: Comparative Study of Energy Storage Technology for Desert Microgrids _Caption:_ Technical and economic comparison of the energy storage technologies that can be considered in the context of the extreme desert climate of Saudi Arabia for the application of the NEOM and Red Sea projects.

Table 2: Energy Storage Technology Comparison for Desert Microgrid Applications

***Caption:** Technical and economic comparison of energy storage technologies suitable for hybrid microgrids in Saudi Arabia's extreme desert climate conditions. Analysis considers round-trip efficiency, cycle life, thermal tolerance, and applicability to NEOM and Red Sea-type projects.

Technology	Round-Trip Efficiency (%)	Cycle Life (cycles)	Energy Density (WhL)	Power Rating (MW)	CAPEX ($/kWh)	Desert Climate Suitability	Current Deployment Status	Key Advantages	Key Challenges
Lithium-ion (NMC)*	85-92%	3,000-5,000	200-400	0.1-100+	300-500	Moderate (requires cooling)	Red Sea: 1,300 MWh deployed	High efficiency Mature technology	Thermal degradation
Lithium-ion (LFP*)	85-90%	5,000-8,000	150-250	0.1-100+	250-400	Good (better thermal stability)	NEOM planned; Widely used	Safer chemistry Longer life	Lower energy density o NMC
Vanadium Flow Battery	65-75%	10,000-20,000	20-35	0.5-50	400-600	Excellent	Pilot stage in ME	Long duration Decoupel/power	Lower efficiency Large footprint
Zinc-Bromine Flow *bettey	65-70%	10,000+	30-50	0.1-10	4-10	4-10	Limited deployment	Long life	Moderate efficiency
Compressed Air (CAES**	40-55%	10,000+	-	10-300	40-24+	100-200	Not yet in KSA	Very low cost Long duration	Low efficiency site comljsint,
Thermal Storage (Sensible)	60-90%	Unlimited	Varies	1-100	6-18	30-60	CSP integration potential	Applicationspecific, (CSP-HWAC)	Application specific, (CSP-HVAC)
Green Hydrogen (Evctrelysis - FC)*	30-40%	20,000+	Low (tank dependent)	1-1000+	100-1,000+	100-1,000+	NEOM: 4 GW planned	Seasonal storage Export value	Very low efficiency High cost

Selection Criteria for Saudi Microgrids:

- **Short-duration (1-6 hrs):** Lithium-ion (LFP preferred for safety and cost)
- **Medium-duration (6-12 hrs):** Flow batteries for high-cycling applications
- **Long-duration C-12 hrs):** Thermal storage (cooling loacis) or hydrogen (seawe,port)
- Critical considerations: Thermal management, dust protection, water availability (for H_2 H_2)

CAES = Compressed Air Energy Storage (geo-dependentSamo in kS-Ea

Table 3: Policy Framework and Microgrid Deployment Roadmap Year
Caption: Hybrid micro-grid deployment strategy and alignment with the Saudi goals of adding renewable capacity and displacing fossil fuel usage in remote sites depending upon the categories of the sites and the necessary measures by the government.

Table 3: Vision 2030 Policy Framework and Microgrid Deployment Roadmap

***Caption:** Strategic roadmap aligning hybrid microgrid deployment with Saudi Vision 2030 targets, showing phased implementation across different remote site categories, required policy actions, and expected outcomes for renewable capacity addition and fossil fuel displacement.

Phase	Timeline	Target Sites	Capacity Target (MW)	Policy Actions Required	Technology Focus	Expected Outcomes	Alignment with Vision 2030	Vision 2030 targetsmet
Phase 1: Flagship Demonstrations	2020-2024	NEOM, Red Sea, Project, Sudair	400-1,000	• Giga-project licensing • International partnerships	• Grid-forming Inverters • Large-scale BESS (> 1 GWh)	• Red Sea: 400 MW + 1.3 GWh opera- • >1 TWh green electricity/year • Technology validation		• 50% renewable mix demonstration • CO_2 reduction showcase
Phase 2: Remote Community Scale-Up	2024-2027	Al Uyaynah, border facilities, desert research stations, 50+ remote villages	100-300	• Standardized microgrid codes. • Green financing schemes	• Modular PV-wind • AI-based EMS • Dust-resilient designs	• 50-100 communitie electrified • 70-100% diesel displacement • 500k+ tons CO_2 avoided		50% renewable mix • Elin, reduction showcase
Phase 3: Industrial & Hydrogen Integration	2025-2028	NEOM hydrogen plant, Oxragon industrial zone; coastal desalination	4,000-600	• Power-to-X regulations • Export infrastructure renewadey	• Green hydrogen electrolysis • Multi-GW wind farms	• NEOM: 4 GW renewables → 600 t/yh, • 100% renewable industry clusters • Export revenue diversification		• 130 GW total renewable • 278 Mt CO_2 reduction achieved • 10,000+ Jobs created
Phase 4: National Network of Microgrids	2027-2030	200+ remote sites, tourisan genes, agricultural projects	2,000-4,000	• Microgrid interconnection • Virtual power plant frameworks	• CSP integration potential • CSP integration potential	• Economic diversification: Green industry • Econonmic diversification • Domeslic manufacturing		• Vision 2030 targets met • 80-50 gas-renewable mix • Domesic mandaturing ecosystem

Critical Success Factors:
1. Regulatory darity: Microgrid licensing-grid codes, and tariff structures established by 2025
2. Financing mechanisms: Green bonds, PPAs, and public-private partnerships scaleby 2026
3. Technology localization: 30% local content by 2027, 50% by 2030 (i6)
4. Warkforce development, 5000+ trained engineers and technicians by 2028. ★ for H_2)
5. RS.D infrastructure: Saudi-specific testing facilties for extreme-dimate valdatin

Key Performance Indicators (NATIOIOLL LEVET):
- Renewable capacity from microgrids: 7,000 - 12,000 MW by 2030 (5-9% of 130 GW target)
- Remote communites electrified: 200-300 sites. (100% coverage)
- Diesel displacement: 1-2 billion liters/year saved → CO_2 emissions avoided

Table 4 : Technical Challenges and Mitigation Strategies in a Saudi Hybrid Microgrid
Caption: Technical identification and articulation of key technical challenges in hybrid micro-griding in Saudi Arabia's harsh desert and sea climate, and ways to address these through proven and upcoming solutions from experience in Red Sea Project development, NEOM, and world-class models and improvements.

Table 4: Technical Challenges and Mitigation Strategies for Saudi Hybrid Microgrids

***Caption:** identification of key technical challenges specific to hybrid microgrid deployment in Saudi Arabia's extreme desert and coastal envirenments, with proven and emerging mitigation strategies drawn from Red Sea Project experience, NEOM planning and international best practices.

Challenge Category	Specific Issue	Impact Severity	Current Mitigation Strategies	Emerging Solutions	Implementation Priority	Cost Impact (% of CAPEX)
Extreme Temperature	Ambient temps 45-55°C	High	• Active cooling systems • Derating of components	• Bifacial + tracking PV • Advanced thermal management (phase-change materials)	Critical	5-8%
Dust & Sand	Soiling losses 2-5%day [illegible]	High	• Automated cleaning systems • Anti-soiling coatings • Filtration for electronics	• Hydrophobic nano-coatings • Robotic dry-cleaning • Dust forecasting & predictive cleaning	Critical	3-5%
Grid-Forming Stability	High inverter penetration (100%) [illegible]	Medium-High	• Grid-forming inverter algorithms • Huawei FusionSolar • Fast protection schemes	• AI-based adaptive control • Virtual synchronous machines	High	2-4%
Long Feeder Protection	Red Sea → >100 km infrastructure fault detection and isolation	Medium	• Differential protection • Communication-based schemes • Sectionalizing switches	• AI fault location • Self-healing grid topologies • Digital twins for predictive maintenance	High	1-3%
Extreme Weather Modeling	Limited water for PV cleaning soiling hydrogen production	Medium-High	• Multi-year meteorological data • Explicit extreme-day scenarios • Conservative capacity factors	• Machine learning for extreme event • Climate-change adjusted planning • Probabilistic reliability modeling	High	5-10% (capacity overhead)
Water Scarcity	Limited water for PV cleaning, coolings, [illegible]	Medium	• Dry cleaning methods • Air-cooled systems • Desalination integration	• Atmospheric water harvesting • Ultra-efficient water recycling • Seawater cooling (coastal sites)	Medium	5-1% (capacity overhead)
Cybersecurity	Remote micro-[illegible]	Medium	• Network segmentation, • Encryption proteicols • Redundant control systems	• Blackchain for grid transactions • AI-based mirosion detection • Quantum-safe-encryption	Medium	1-2%

Lessons from Red Sea Project:

- **Proven effective:** Grid-forming inverters maintain THD < 1,5% off-grid; automated cleaning reduces soiling to <1%/week
- **Ongoing optimization:** AI-based forecasting reduced storage oversizing by 15-20%
- **Key succegs factor:** Extensive pre-construction testing under local conditions (thermaj-dust) [illegible]

NEOM-Specific Considerations: • Integration of 4 GW hydrogen plant requires advanced multi-vector optimization

- Smart HV grid with 50% reduced corridor footprint demands innovative protection schemes • 230+ wind turbines in coastal [illegible] salt environment

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