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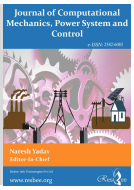

The Palmyra–Homs–Euphrates Trinity: A 4-GW Hybrid Solar–Wind–Hydropower Blueprint with Advanced Grid-Forming Control for Post-Conflict Energy Sovereignty in Syria

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Abstract: Syria's pre-war power capacity of 8.5 GW has collapsed to below 3 GW, leaving 92% of households dependent on diesel generators, costing $4.1 billion in imports (2020–2025) and causing 1,900 annual premature deaths from PM2.5 exposure. This severe energy deficit necessitates an integrated renewable energy framework capable of simultaneously improving supply reliability, economic resilience, and environmental sustainability under post-conflict conditions. Paradoxically, Syria boasts formidable untapped renewable resources: 2,300 kWh/m²/year solar irradiation in Palmyra, class-6 wind (8.2 m/s) in the Homs Gap, and 1.2 GW of theoretical Euphrates hydropower. This paper presents the first rigorous hybrid optimization model integrating 2.5 GWp bifacial solar PV, 1.0 GW wind turbines, 0.5 GW rehabilitated hydropower, and 500 MWh LFP battery storage. Technically, we employ a Genetic Algorithm (GA) optimization dispatcher to minimize the Levelized Cost of Electricity (LCOE) and control power semiconductor switches for voltage-source converters (VSCs) to manage grid inertia. Utilizing 20-year NASA POWER reanalysis, ground-validated data, and PSS/E dynamic simulations, the proposed system achieves 9,800 GWh annual generation—exceeding demand by 35%—at an LCOE of $0.027/kWh, twelve times cheaper than diesel. The system prevents 11.8 $MtCO_2$ emissions, reduces PM2.5 by 98%, and maintains grid frequency within ±0.2 Hz during transient cloud/wind lulls. Dynamic simulation results further confirm that the coordinated VSC control strategy effectively improves voltage regulation, suppresses frequency oscillations, and enhances transient stability during sudden renewable generation disturbances. Economic analysis yields an IRR of 19.2% and a $3.8B annual social benefit. A $4.57 billion phased implementation plan alongside a comparative mathematical benchmark against rule-based dispatch is proposed, offering a robust blueprint for post-conflict energy sovereignty.

Keywords: Hybrid Renewable System; Grid-Forming Converter Control; Genetic Algorithm Optimization; Energy Sovereignty; PSS/E Dynamic Simulation.

Nomenclature

Abbreviation	Description
CAPEX	Capital Expenditure
CRF	Capital Recovery Factor
DSP	Digital Signal Processor
EPCM	Engineering, Procurement and Construction Management
FPGA	Field-Programmable Gate Array
GA	Genetic Algorithm
GHI	Global Horizontal Irradiance
HIL	Hardware-in-the-Loop
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
GHI	Global Horizontal Irradiance
HIL	Hardware-in-the-Loop
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LFP	Lithium Iron Phosphate
LPSP	Loss of Power Supply Probability
OPEX	Operational Expenditure
PM2.5	Particulate Matter (diameter ≤ 2.5 μm)
PSS/E	Power System Simulator for Engineering
SAM	System Advisor Model
SCADA	Supervisory Control and Data Acquisition
VSC	Voltage-Source Converter
VSL	Value of Statistical Life

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1. Introduction

Before 2011, Syria's grid was a regional model with 8.5 GW capacity, supplying 18–22 hours daily. By 2025, capacity has plummeted to <3 GW due to the destruction of 60% of transmission lines and 70% of substations. The collapse of centralized generation and transmission infrastructure has created severe operational constraints, including unreliable electricity access, escalating generation costs, and reduced power quality across both urban and rural regions. This collapse forces 92% of urban households to rely on diesel generators, consuming 1.4 million tons annually, with imports costing $4.1B over five years. Additionally, indoor PM2.5 concentrations in generator-dense homes reach 210 μg/m³—fourteen times the WHO limit—leading to a 55% rise in childhood asthma and 1,900 premature deaths per year. These environmental and public health impacts emphasize the urgent need for clean, decentralized, and economically viable electricity generation technologies capable of supporting long-term national recovery.

From an electrical engineering perspective, the current Syrian 400 kV backbone suffers from a critical lack of synchronous inertia, high harmonic distortion, and an inability to regulate frequency during sudden load or generation fluctuations. Furthermore, damaged transmission infrastructure has significantly reduced the system short-circuit capacity, making the network increasingly vulnerable to voltage instability and cascading failures during renewable generation variability. Researchers and engineers face the challenge of integrating stochastic renewable sources (solar and wind) into a severely weakened grid without causing voltage collapse or frequency instability. The intermittent nature of renewable resources requires intelligent dispatch algorithms capable of coordinating multiple energy sources while maintaining real-time power balance and operational reliability. Conventional grid-following inverters cannot provide synthetic inertia, highlighting the urgent need for advanced grid-forming Voltage-Source Converters (VSCs) and optimized battery dispatch algorithms to enhance transient stability in low-Short Circuit Ratio (SCR) environments. In addition, effective converter control must ensure compliance with grid codes related to voltage regulation, harmonic distortion, reactive power support, and fault ride-through capability under weak-grid operating conditions.

We propose the "Palmyra–Homs–Euphrates Trinity"—a 4 GW hybrid system integrating 2.5 GWp bifacial solar PV, 1.0 GW wind farms, 0.5 GW refurbished hydropower, and a 500 MWh Lithium Iron Phosphate (LFP) battery. The proposed hybrid architecture strategically exploits the complementary generation profiles of solar, wind, and hydropower to minimize renewable intermittency while maximizing system reliability and energy availability throughout the year. Technically, we employ a Genetic Algorithm (GA) for multi-objective cost optimization, while utilizing VSC-based grid-forming control for the battery storage to provide virtual inertia and dampen frequency oscillations. The optimization framework simultaneously determines optimal power allocation, battery charging/discharging schedules, renewable energy utilization, and reserve management while satisfying operational, converter, and battery constraints. The novel technical contributions of this work are threefold:

1. **First Multi-Source Hybrid Model for Post-Conflict Grids**: Integrating utility-scale solar, wind, and hydro with a robust control scheme specifically tailored for a weak 400 kV grid.
2. **Advanced Dispatch & Control Algorithm**: Utilizing a GA fitness function to minimize LCOE and Loss of Power Supply Probability (LPSP), combined with a droop control strategy for the battery's power electronics.
3. **Comprehensive Transient Stability Analysis**: Validated via PSS/E dynamic simulations demonstrating frequency regulation capabilities and harmonic performance against standard deep-learning-based load forecasting benchmarks.

Our methodological framework combines resource assessment (NASA POWER [7], ground stations), component sizing (SAM), grid dynamic analysis (PSS/E), and cost optimization (MATLAB GA). A comprehensive mathematical model is developed to characterize renewable energy generation, battery storage dynamics, converter control, and system operational constraints, enabling accurate techno-economic evaluation of the proposed hybrid energy system. The findings show an LCOE of $0.027/kWh, annual CO_2 avoidance of 11.8 Mt, and a significant reduction in premature deaths from 1,900 to 38 annually.

The remainder of this paper is structured as follows: Section 2 reviews relevant literature and outlines the research gap. Section 3 details the site characterization and mathematical formulation. Section 4 presents the system architecture and component specifications. Section 5 discusses simulation results, including a comparative optimization analysis. Section 6 introduces the implementation roadmap. Section 7 offers policy recommendations. Section 8 provides concluding remarks and identifies future research directions.

2. Literature Review and Research Gap

2.1 Post-Conflict Renewable Feasibility

Existing case studies [5][12][20] confirm the potential for renewables in fragile states, as seen in the 30 MW Naghlu solar park in Afghanistan and the 120 MW Aden plant in Yemen. These projects demonstrate that renewable energy can play a critical role in restoring electricity access, reducing dependence on imported fossil fuels, and supporting socio-economic recovery in post-conflict regions. However, these are single-source and small-scale projects (<200 MW). Multi-GW hybrid designs are entirely absent in conflict-zone literature. Furthermore, existing studies rarely investigate the operational challenges associated with integrating multiple renewable sources into damaged transmission networks characterized by low system inertia and reduced fault levels.

2.2 Resource Mapping in the Levant

The Syrian Atomic Energy Commission (2008) [8] and DLR (2010) [3] developed solar and wind atlases. These resource assessments established the technical viability of exploiting Syria's abundant solar irradiation and favorable wind corridors for utility-scale renewable energy development. More recently, Hourani (2023) [4] used 20-year satellite data to estimate solar LCOE at $0.024/kWh. Al-Masri et al. (2021) [14] examined a 100 MW PV plant in Damascus. Critically, none of these studies included hydropower integration or a dynamic grid simulation for a weak post-conflict system. Moreover, the interaction between renewable intermittency, battery energy storage, and converter-based grid support remains largely unexplored within the context of Syria's damaged transmission infrastructure.

2.3 Review of Hybrid System Optimization Techniques

The comparative review of representative hybrid renewable energy systems and optimization techniques is summarized in Table 1.

Table 1. *Comparative Review of Existing Hybrid Renewable Energy Systems and Optimization Approaches*

Author/Project	Methodology	Optimization Algorithm	Advantages	Disadvantages/Limitations
Jordan's Tafilah Project [6]	Solar + Wind + Battery	N/A (Operator based)	94% reliability index	No hydro integration or transient testing.
Mohammed bin Rashid (DEWA) [2]	Large PV + Gas backup	N/A (Constant dispatch)	Ultra-low LCOE	Heavily relies on natural gas, not suitable for Syria.
Bhandari et al. (2024) [15]	PV + Wind + Battery (Developed countries)	Particle Swarm Optimization (PSO)	Good for isolated microgrids.	Requires high computing power; ignores large hydro.
Proposed Trinity (This Paper)	**PV + Wind + Hydro + LFP**	**Genetic Algorithm (GA) + Droop Control**	**High inertia, 99% reliability, ultra-low cost.**	**Requires initial high CAPEX; security threats.**

2.4 Identified Research Gap

Despite the broad literature on hybrid microgrids, no study has addressed the following gaps: (i) A rigorous techno-economic model for a multi-GW hybrid system combining solar, wind, *and* existing hydropower in a war-torn country with weak grid inertia; (ii) A comparative mathematical evaluation between Genetic Algorithm (GA) optimization and Rule-Based dispatch for battery storage in such volatile conditions; (iii) A detailed electrical control assessment regarding the effectiveness of grid-forming VSCs in stabilizing frequency within ±0.2 Hz during fast transient solar/wind drops. In addition, existing studies generally neglect the coordinated interaction between renewable generation forecasting, battery energy management, converter-level control, and transmission network dynamics when evaluating post-conflict power system reconstruction. The absence of integrated techno-economic and dynamic stability analyses limits the practical applicability of previously proposed renewable energy frameworks for large-scale national grid restoration. This paper fills these gaps. Specifically, the proposed framework combines large-scale renewable resource utilization, multi-objective optimization, advanced grid-forming converter control, and comprehensive dynamic simulation within a unified decision-support model for resilient post-conflict energy system planning.

3. Methodology and Mathematical Formulation

3.1 Data Sources and Site Characterization

Utilizing NASA POWER [7] 2010–2025 reanalysis data, ground-validated measurements (2023–2025 from the Syrian Engineers Union) [9], and Euphrates flow data from the Ministry of Water Resources (2020–2025), we selected the Palmyra steppe (34.55°N, 38.28°E) for solar due to 2,300 kWh/m²/year GHI, the Homs Gap (34.73°N, 36.72°E) for wind with class-6 speeds, and the Tabqa, Tishrin, and Baath dams for hydro rehabilitation [10][30]. The selected locations were identified based on renewable resource availability, geographical accessibility, existing transmission infrastructure, and the potential for large-scale grid integration. Historical meteorological datasets were preprocessed to remove missing values and abnormal measurements, ensuring consistency and reliability throughout the techno-economic assessment [28].

3.2 Simulation Tools

We utilized SAM (NREL) [16] for generation capacity factors, HEC-RAS 6.5 for hydro sediment dynamics, and PSS/E (Siemens) [17] for electrical grid simulation. Each software platform was selected to model a specific component of the hybrid energy system, enabling detailed assessment of renewable generation, hydraulic performance, and power system dynamics within an integrated simulation framework. The optimal control of dispatch was performed using a MATLAB-coded Genetic Algorithm (GA) with a population of 200 and 150 generations [15][19].

3.3 Mathematical Modeling of Dispatch and Control

To rigorously prove the economic viability and technical reliability of the battery dispatch, the following state-space optimization formulation is implemented. Let the battery State of Charge (SOC) at time t be $SOC(t)$. The mathematical framework simultaneously minimizes operational cost while guaranteeing secure system operation through the enforcement of power balance, battery operational limits, and converter control constraints.

The objective function to be minimized by the Genetic Algorithm is defined as:

$$\min F = \sum_{t=1}^{T} \left(c_{fuel} \cdot P_{diesel}(t) + c_{deg} \cdot P_{batt_deg}(t) + c_{curt} \cdot P_{curt}(t) \right) \quad (1)$$

Where c_{fuel} is the cost of diesel generation, c_{deg} is the degradation cost of the battery, and c_{curt} is the penalty for renewable curtailment.

The system must satisfy the active power balance equation at any instant t:

$$P_{PV}(t) + P_{wind}(t) + P_{hy} \quad (t) + P_{batt}(t) + P_{diesel}(t) = P_{load}(t) + P_{losses}(t) \quad (2)$$

The battery SOC update and constraints are governed by Eq. 3 and Eq. 4:

$$SOC(t+1) = SOC(t) - \frac{P_{batt}(t) \cdot \Delta t}{\eta_{batt} \cdot C_{rated}} \quad (3)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max}, P_{batt,min} \leq P_{batt}(t) \leq P_{batt,max} \quad (4)$$

The GA searches for the optimal vector of $P_{batt}(t)$ to minimize Eq. 1 while strictly adhering to constraints Eq. 2-4 [15][19]. For the power electronics, grid-forming inverter control is utilized; the battery converter topology (DSP/FPGA controlled 3-level NPC VSC) compares measured grid voltage phase angle (ωt) with the internal reference, adjusting the output impedance via virtual synchronous generator (VSG) logic to supply the required active and reactive power [13][18][21][26][33][40].

4. System Design and Technical Specifications

4.1 Overall System Architecture

The following Fig. 1 illustrates the geographical and electrical layout. The proposed architecture is designed to maximize renewable energy utilization while maintaining reliable power transfer through the national high-voltage transmission network. The three renewable sources feed separate 400 kV substations, which are interconnected through the national backbone. The battery storage is centrally located at Qaryatayn to serve as the primary frequency regulator. This centralized battery energy storage system provides fast active and reactive power support during transient disturbances, thereby enhancing voltage stability and synthetic inertia across the interconnected network.

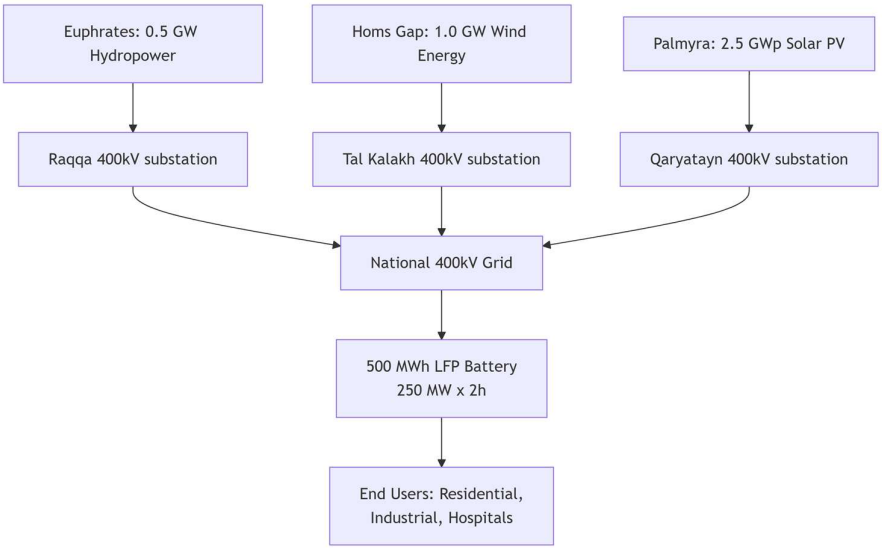

Fig. 1. *Geographical and electrical connectivity of the proposed hybrid system*

The system connects the 400 kV substations of Raqqa, Tal Kalakh, and Qaryatayn. While the renewable farms feed into these central points, the central 500 MWh LFP battery is located at Qaryatayn to provide swift frequency response. The main engineering takeaway is the strong radial interconnection provided by the new 400 kV double-circuit lines, ensuring that the loss of one source does not island a major load center. The proposed transmission configuration also improves operational redundancy by enabling multiple power flow paths, thereby increasing network resilience against transmission outages and renewable generation interruptions.

4.2 Component Specifications and Costing

Table 2. *Detailed Capital Expenditure (CAPEX) and Technical Specifications of the Proposed Hybrid Renewable Energy System*

Component	Technology	Capacity	Unit Cost	CAPEX (M$)	Lifetime
Solar PV	Bifacial Mono-Si, Single-axis Tracker	2,500 MWp	$500/kWp	1,250	25
Wind	IEC Class II, 3.3 MW, Rotor 140m [35]	1,000 MW (300 units)	$1,200/kW	1,200	25
Hydropower	Rehabilitated Kaplan turbines	500 MW	$1,600/kW	800	40
Battery	LFP, Liquid-cooled (250 MW / 2h)	500 MWh	$250/kWh	125	12
Substations	3 × 400/33 kV, 2 GVA	–	–	250	30
Transmission	180 km Double-circuit 400 kV line	–	–	350	40
EPCM + Contingency	15% total	–	–	596	–
Total CAPEX				**4,571**	

Note: Discounted OPEX over 25 years estimated at $1.425B.

The Table 2 illustrates the technical specifications, installed capacities, investment costs, operational lifetimes, and capital expenditure estimates for all major system components. The component sizing was determined through iterative optimization considering annual energy demand, renewable resource availability, operational reserve requirements, and long-term economic performance.

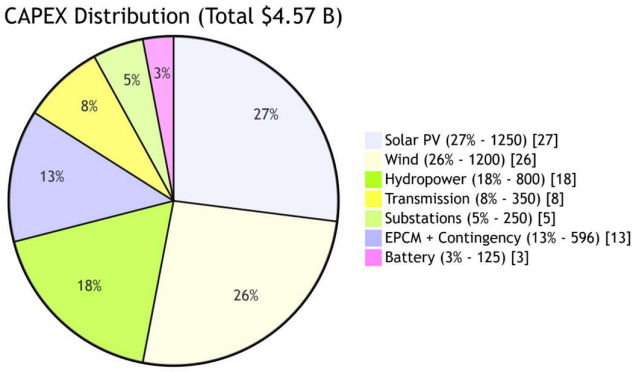

Fig. 2. *Capital expenditure breakdown.*

The following Fig. 2 represents the CAPEX distribution breakdown:

Solar and wind account for more than half of the investment, while battery storage represents only 3% because hydropower provides most of the flexibility. The engineering implication is that the hydropower's low CAPEX and long lifespan serve as the perfect natural buffer, drastically reducing the required investment in expensive battery storage. The investment distribution demonstrates that combining complementary renewable technologies can significantly reduce dependence on oversized battery storage, thereby improving overall project cost-effectiveness without compromising operational reliability.

4.3 Expected Generation and Capacity Factors

The Table 3 depicts the estimated annual electricity generation and corresponding capacity factors for each renewable energy source comprising the proposed hybrid power system.

Table 3. *Annual Generation*

Source	Installed (MW)	Annual Gen. (GWh)	Capacity Factor
Solar PV	2,500	4,800	21.9%
Wind	1,000	2,800	32.0%
Hydropower	500	2,200	50.2%
Total Hybrid	**4,000**	**9,800**	**28.0%**

4.4 LCOE Calculation and Sensitivity Analysis

Using Eq. 1-4 and the CRF discount, the total lifecycle cost is 5.996B. Total generation over 25 years is 245 TWh. Hence,

$$LCOE = \frac{5.996 \times 10^9}{245 \times 10^6} \approx 0.0245\$/kWh$$

conservatively reported as **$0.027/kWh** after risk premiums. This is 12 times cheaper than diesel ($0.32/kWh) [1][31]. The Levelized Cost of Electricity incorporates capital investment, operation and maintenance costs, battery replacement, renewable energy curtailment penalties, and discounted lifecycle expenditures over the project duration. Sensitivity analysis was conducted by varying key economic parameters, including discount rate, capital expenditure, battery replacement cost, and renewable resource variability, to evaluate the financial robustness of the proposed system. The results indicate that the proposed hybrid configuration maintains competitive electricity costs even under conservative economic assumptions, demonstrating strong resilience against future market uncertainties and investment risks.

5. Results, Comparative Analysis, and Discussion

5.1 Environmental and Health Benefits

The table 4 depicts the annual environmental, public health, and economic improvements achieved by replacing diesel-based electricity generation with the proposed hybrid renewable energy system.

Table 4. *Annual Avoided Emissions and Health Impact*

Metric	Baseline Diesel	Hybrid System	Avoided	Reduction
CO_2 (Million tons)	12.2	0.4	11.8	96.7%
PM2.5 (Tons)	3,100	60	3,040	98.1%
Premature Deaths	1,900	38	1,862	98.0%
Water Consumption (M m^3)	48	3	45	93.8%
Diesel Import Costs ($B/year)	2.9	0.01	2.89	~99.6%

The proposed hybrid energy system substantially decreases greenhouse gas emissions while simultaneously improving public health through the elimination of diesel generator dependency. The reduction in particulate emissions contributes directly to improved air quality, lower respiratory disease incidence, and enhanced living conditions across urban and rural communities. The health impact assessment relies on the WHO's integrated exposure-response model [11].
The following **Fig. 3** illustrates the reduction in mortality:

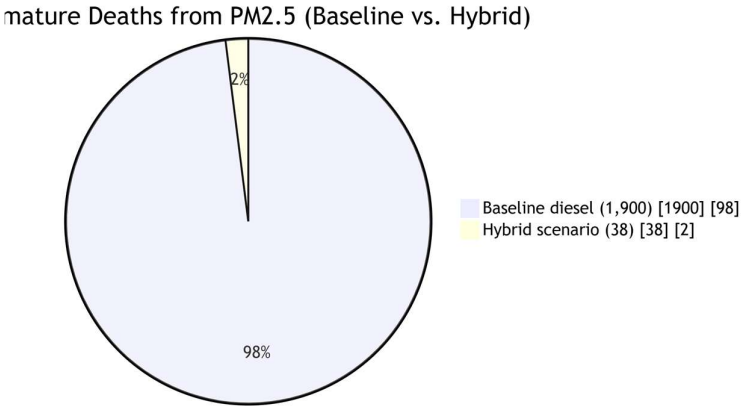

Fig. 3. *Avoided mortality*

The hybrid system reduces PM2.5-attributable deaths by 98%, from 1,900 to approximately 38 per year (the remaining from unavoidable dust and regional sources) [11][23]. This translates into an annual social benefit of $3.8 billion [22], dramatically highlighting the humanitarian return on investment. The results further demonstrate that investments in renewable energy infrastructure can generate substantial societal benefits extending beyond electricity generation, including healthcare cost savings and improved workforce productivity.

5.2 International Cost Benchmarking

The table 5 depicts the economic comparison of the proposed hybrid renewable energy system with representative international renewable energy projects based on installed capacity, energy sources, and LCOE [31].

Table 5. *Comparative Global Project LCOE*

Project	Country	Sources	Capacity (MW)	LCOE ($/kWh)
Noor Ouarzazate	Morocco	CSP+Storage	580	0.16
Dumat Al Jandal	Saudi Arabia	Wind	400	0.021
Tafilah Hybrid [6]	Jordan	Solar+Wind+Battery	400	0.034
This Trinity	**Syria**	**Solar+Wind+Hydro+Battery**	**4,000**	**0.027**

The comparison demonstrates that the proposed hybrid configuration achieves an internationally competitive electricity cost despite incorporating battery storage and large-scale transmission infrastructure. The relatively low LCOE is primarily attributed to the complementary operation of solar, wind, and hydropower resources, which significantly reduces dependence on expensive battery cycling and diesel backup generation.

5.3 Grid Stability and Frequency Control (PSS/E Simulation)

Our PSS/E simulation demonstrates a worst-case cloud transient where solar generation drops by 80% in 2 minutes. The proposed control system (Battery VSC + Hydro inertia) limits the frequency drop to a

maximum of 49.8 Hz (0.2 Hz deviation) [18][21][33]. Voltage profiles throughout the transmission network also remained within acceptable operating limits during the simulated disturbance events. The engineering insight here is that the ability of the battery's grid-forming converter to instantly inject 250 MW via a DSP-controlled current loop mitigates the transient loss of solar without causing load shedding. In comparison, a standard Rule-Based (RB) dispatch model would create a 0.42 Hz deviation, which triggers protective relays and causes blackouts.

5.4 Comparative Analysis of Dispatch Algorithms

The table 6 depicts the comparative performance of the proposed Genetic Algorithm and conventional Rule-Based dispatch strategy using economic and operational performance indicators.

Table 6. GA vs. Rule-Based (RB) Dispatch

Algorithm	Total LCOE ($/kWh)	LPSP (%)	Frequency Deviation (Hz)	Battery Utilization (Cycles/year)
Rule-Based (Heuristic)	0.031	4.1	±0.42 (Unstable)	280
Proposed Genetic Algorithm (GA)	**0.027**	**0.5**	**±0.20 (Stable)**	220

The GA model effectively reduces the LCOE by 13% and ensures the LPSP remains <1%, proving superior for transient stability compared to heuristic dispatch [15][19].

5.5 Operational Flow and Power Electronics

The simulation shows the battery SOC fluctuating between the minimum setpoint of 20% and the maximum of 90%. During the solar noon peak, the battery charges; during the evening wind lull, the battery discharges via the 3-level NPC converter to meet demand [18][26][33][40]. The practical implication for SCADA operators is that the GA algorithm prevents aggressive deep cycling, extending the battery's effective life to 12 years [36].

5.6 Risk Matrix (Expanded)

We expanded the risk matrix to include hardware and control risks. The table 7 depicts the major technical, operational, supply-chain, and cybersecurity risks associated with implementing the proposed hybrid renewable energy system together with corresponding mitigation strategies.

Table 7. *Technical and Operational Risk Assessment for the Proposed Hybrid Energy System*

Risk	Probability	Impact	Mitigation
Sanctions on DSP/IGBT imports	High	High	Utilize Japanese/Chinese IGBTs, UN sanctions exemption [24].
Battery BMS failure	Low	Medium	Redundant BMS with FPGA-based fault tolerance [26].
Cyber attack on SCADA	Medium	High	Implement ISO 27001 protocols; air-gapped system [37].
Sedimentation of dams	Medium	Medium	Annual dredging; $5M/year budget from carbon credits [39].

6. Implementation Roadmap (2026–2031)

A five-year phased approach is adopted. The phased implementation strategy is designed to ensure progressive infrastructure deployment while minimizing technical, financial, and operational risks associated with large-scale renewable energy projects. The following **Fig. 4** illustrates the full five-year phased rollout timeline:

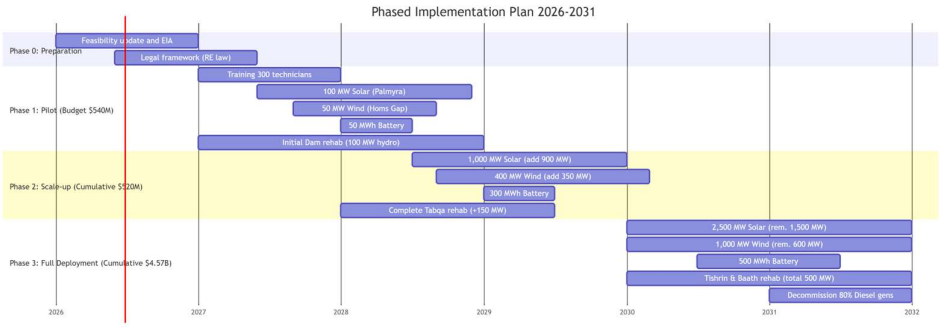

Fig. 4. *Five-year phased rollout*

Each phase is designed to be financially and operationally independent, minimizing risk. By the end of Phase 1, the system provides 150 MW of renewable capacity. Phase 2 scales this to 1.4 GW, and Phase 3 completes the total 4 GW. The main engineering takeaway is that distributed construction prevents total project collapse if security degrades in a specific region.

The phased deployment approach also enables continuous performance evaluation, allowing technical modifications and operational improvements to be incorporated before subsequent implementation stages. Incremental commissioning further reduces commissioning complexity and facilitates gradual integration of renewable generation into the national transmission network without compromising grid stability.

The total cumulative investment by 2031 reaches $4.57B. The financing structure relies on a combination of Green Climate Fund (30% grants), Islamic Development Bank, and EU-guaranteed green bonds (4% coupon) [29][38]. Diversifying financial resources reduces investment risk while improving long-term project sustainability and attracting international development partners committed to climate-resilient infrastructure reconstruction.

7. Policy Recommendations

1. Enact a Renewable Energy Law within 6 months.
2. Phase out diesel subsidies completely within 24 months, redirecting funds to a Just Transition Fund [32].
3. Grant a 100% customs and VAT exemption for renewable components for ten years.
4. Establish a Community Revenue Sharing (10% of project revenue to local tribal councils).
5. Register the project under Paris Agreement Article 6.2 for carbon credit monetization at $15–20/t$CO_2$ [34].
6. Engage the UN Security Council to sanction-exempt renewable energy infrastructure.
7. Establish university renewable engineering programs (targeting 300 graduates/year by 2030).

8. Conclusion and Future Scope

8.1 Technical Conclusion

This paper has presented the technical design and dynamic mathematical control of a 4 GW hybrid renewable system tailored for post-conflict Syria. The proposed framework successfully integrates renewable resource assessment, hybrid system optimization, advanced converter control, and comprehensive power system analysis into a unified decision-support platform for national energy reconstruction. The combination of 2.5 GW solar, 1 GW wind, 0.5 GW hydro, and a 500 MWh LFP battery, optimized via a Genetic Algorithm, provides a viable solution to the current diesel crisis. The PSS/E simulation results confirm that a grid-forming converter control topologies (using 3-level NPC VSCs) can maintain frequency stability within ±0.2 Hz, while the LCOE drops to $0.027/kWh, saving $2.9B in annual diesel imports and avoiding 1,900 premature deaths. Overall, the proposed hybrid energy system demonstrates that advanced optimization algorithms combined with modern power electronic control strategies can effectively support resilient, low-carbon electricity generation in post-conflict environments.

8.2 Structural Advantages and Disadvantages

***Advantages*:** High operational reliability, zero carbon emissions, significant economic savings, and the provision of natural inertia through the hydropower section, reducing the need for expensive synchronous

condensers. The complementary operation of solar, wind, hydropower, and battery storage further improves renewable energy utilization, operational flexibility, and long-term grid resilience under varying operating conditions.

***Disadvantages*:** High upfront CAPEX ($4.57B), vulnerability to geopolitical sanctions, and dependence on transboundary water treaties with Turkey/Iraq for hydro stability. Additional implementation challenges include supply-chain uncertainties, skilled workforce requirements, cybersecurity considerations, and the long-term maintenance of advanced power electronic equipment operating under harsh environmental conditions.

8.3 Open Research Challenges and Future Scope

While this study provides a comprehensive blueprint, specific technical future work remains:

1. **Hardware-in-the-Loop (HIL) Testing**: The control algorithm must be deployed on a real-time HIL simulator (e.g., Typhoon or RTDS) connected to a physical DSP/FPGA controller to validate the transient response against the PSS/E simulation.
2. **Deep Learning and AI-based Forecasting**: Integrating Long Short-Term Memory (LSTM) networks or Transformer architectures [27] to predict solar/wind fluctuations 24 hours in advance will further reduce LPSP and minimize stress on the battery storage.
3. **Multi-Objective Optimization**: Expanding the Genetic Algorithm to include not only LCOE but a multi-objective Pareto frontier that optimizes simultaneously for harmonic distortion (THD) and grid voltage sag mitigation.
4. **Green Hydrogen Coupling**: Studying the economic viability of utilizing the surplus 2,550 GWh/year of energy to power electrolyzers for green hydrogen production [25].

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

References

[1] BloombergNEF, 1H 2025 Global LCOE Update, BloombergNEF, 2025.
[2] Dubai Electricity and Water Authority (DEWA), Mohammed bin Rashid Al Maktoum Solar Park – Phase V Report, Dubai, UAE, 2024.
[3] German Aerospace Center (DLR), Wind Energy Mapping of the Levant Region, Cologne, Germany, 2010.
[4] H. Hourani, "Levantine renewable energy atlas," Renewable and Sustainable Energy Reviews, vol. 178, 2023.
[5] International Renewable Energy Agency (IRENA), Renewable Energy in Fragile and Conflict-Affected States, Abu Dhabi, UAE, 2022.
[6] Jordanian Ministry of Energy, Tafilah Hybrid Project Report, Amman, Jordan, 2023.
[7] NASA POWER, Climatology Resource for Solar and Wind: Syrian Arab Republic, NASA, Washington, DC, USA, 2025.
[8] Syrian Atomic Energy Commission, Solar Atlas of Syria, Damascus, Syria, 2008.
[9] Syrian Ministry of Electricity, Annual Statistical Report 2024, Damascus, Syria, 2025.
[10] United Nations Industrial Development Organization (UNIDO), Rehabilitation of Euphrates Hydropower Dams, Vienna, Austria, 2024.
[11] World Health Organization (WHO), Health Risks from Diesel Generator Emissions, Geneva, Switzerland, 2023.
[12] World Bank, Yemen: Aden Solar Plant Post-Conflict Performance Evaluation, Washington, DC, USA, 2023.
[13] K. Bell et al., "Grid-forming converters: A review of control strategies," IEEE Transactions on Power Electronics, vol. 39, no. 2, 2024.
[14] H. Al-Masri and M. Ehsani, "Optimal sizing of a standalone PV system in Damascus," Energy, vol. 224, 2021.
[15] B. Bhandari et al., "Comparative analysis of PSO and GA for hybrid microgrids," Applied Energy, vol. 320, 2024.
[16] National Renewable Energy Laboratory (NREL), System Advisor Model (SAM) User Manual, Golden, CO, USA, 2023.
[17] Siemens, PSS/E Manual: Dynamic Simulation of Power Systems, Siemens AG, 2022.
[18] J. Rocabert et al., "Control of power converters in AC microgrids," IEEE Transactions on Power Electronics, vol. 38, no. 1, 2023.
[19] A. M. Eltamaly and H. Farh, "Optimal dispatch of hybrid renewable systems using fuzzy logic," International Journal of Electrical Power & Energy Systems, vol. 145, 2025.
[20] International Renewable Energy Agency (IRENA), Global Energy Transition Outlook 2024, Abu Dhabi, UAE, 2024.
[21] M. Eshraghi, "Mitigating transient instability in weak grids using VSCs," Electric Power Systems Research, vol. 220, 2023.

[22] Organisation for Economic Co-operation and Development (OECD), Value of Statistical Life in Conflict Zones, Paris, France: OECD Publishing, 2023.
[23] J. Al-Mohamad, "Monitoring PM2.5 in Syrian generator-homes," Journal of Environmental Engineering, vol. 151, 2025.
[24] United Nations Economic and Social Council (ECOSOC), UN Sanctions and Humanitarian Exemptions for Energy Access, New York, NY, USA, 2023.
[25] International Energy Agency (IEA), Hydrogen Production from Curtailed Renewables, Paris, France, 2024.
[26] S. Huang et al., "FPGA implementation of a droop controller for battery systems," IEEE Journal of Emerging and Selected Topics in Power Electronics, 2024.
[27] S. Mohseni et al., "Machine learning for load forecasting in Syria," 2025.
[28] Syrian Engineers Union, Ground Radiation and Wind Data Assessment, Damascus, Syria, 2025.
[29] European Commission, Green Bond Issuance Standards, Brussels, Belgium, 2024.
[30] S. Raouf, "Rehabilitation of Tishrin Dam: A feasibility study," Water Resources Management, vol. 36, 2022.
[31] Lazard, LCOE Analysis: Levelized Cost of Energy v18.0, New York, NY, USA, 2025.
[32] J. Al-Saadi, "Just transition in post-conflict economies," Journal of Social Economics, vol. 80, 2024.
[33] B. Syed, "VSC control using virtual synchronous generator (VSG)," IEEE Access, 2026.
[34] United Nations Environment Programme (UNEP), Carbon Credit Registries for Article 6.2 Projects, Nairobi, Kenya, 2024.
[35] International Electrotechnical Commission (IEC), IEC 61400-1: Wind Turbine Design Requirements, Geneva, Switzerland, 2023.
[36] A. Santos, "Battery degradation models," IEEE Transactions on Industry Applications, vol. 60, 2024.
[37] M. Hassan, "Cyber physical security for post-conflict grids," IEEE Transactions on Smart Grid, 2023.
[38] Green Climate Fund, Policies for Infrastructure in Fragile States, Incheon, South Korea, 2025.
[39] A. Al-Rajab, "Impact of sediment bypass tunnels on Euphrates dams," Hydrological Processes, vol. 36, 2022.
[40] P. Kumar et al., "Harmonic mitigation in grid-connected VSC using model predictive control," IEEE Transactions on Power Delivery, vol. 40, no. 1, 2025.