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PV-BESS-Electrolyzer Hybrid System: Dispatching Optimization with Experimental Validation[#]

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ABSTRACT

The increasing penetration of Power-to-X (PtX) assets introduces new challenges in power system operation, especially when integrating intermittent renewable energy sources. This paper presents the development, integration, and experimental validation of a kW-scale hybrid PV-Battery-Electrolyzer platform at DTU. A rule-based energy management system (EMS) was implemented to coordinate power flows between the photovoltaic (PV) source, lithium-ion battery energy storage system (BESS), and anion exchange membrane (AEM) electrolyzer. Component-level testing quantified key performance constraints, including ramp-rate limits, temperature sensitivity, and system-level round-trip efficiency. The data-driven model for asset performance validated against experimental data was further applied for sensitivity analyses of system sizing and control strategies. Results from hybrid operation show that the BESS buffering significantly improves hydrogen yield with 14.6% and 77.7% under different fluctuating solar profiles and significantly reduces the start-stop cycle from 10–34 times to 3 times per day, which has a great impact on electrolyzer lifetime. The findings highlight critical trade-offs between curtailment, system stress, and hydrogen productivity in such hybrid applications.

Keywords: Hybrid energy systems, anion exchange membrane (AEM) electrolyzer, energy management system (EMS), hydrogen production.

1. INTRODUCTION

The power-to-X system, also known as an electrolyzer for hydrogen production, has been an important component in modern power systems for converting electricity to hydrogen [1]. Hybrid renewable–battery–electrolyzer energy systems are emerging as a promising solution to address the intermittency of renewable power sources, as the high penetration of solar PV can induce rapid power fluctuations that challenge grid stability and energy balance [2,3]. Several technologies can help mitigate the grid challenges associated with increasing renewable energy penetration. Electrolyzers can directly support grid stability by rapidly adjusting their power demand in response to renewable energy fluctuations [4]. Meanwhile, Battery Energy Storage Systems (BESS) offer exceptionally fast response times, making them well-suited for handling rapid frequency deviations [5]. Each component, however, brings technical constraints. Electrolyzers operate most efficiently at steady loads and can be stressed by variable power input, while frequent start-stop cycles due to PV intermittency shorten electrolyzer lifespan. Operating an electrolyzer at partial loads may lower its efficiency and stability and excessive current fluctuations can accelerate degradation [6,7]. Batteries, in turn, suffer from limited cycle life, self-discharge, and capacity fade over time and cycles [5]. These challenges motivate the hybrid renewable-battery-electrolyzer approach, which leverages batteries for rapid balancing and hydrogen production for energy shifting. By coupling PV with energy storage and hydrogen production, these hybrid systems provide multi-scale flexibility: batteries offer fast response for short-term smoothing, while electrolyzer–hydrogen units enable long-term energy storage.

Energy management strategies (EMS) for hybrid systems have evolved from simple heuristics to advanced predictive controllers. Rule-based EMS (hard-coded control rules) are widely used in practice for PV-storage systems due to their simplicity and real-time responsiveness [8]. These controllers make on-the-fly decisions based on measurements, e.g., battery state of charge (SOC) or PV output, without requiring complex models or forecasts. While robust and easy to implement, rule-based schemes are not guaranteed to be optimal and may result in inefficient resource utilization under highly dynamic conditions. To improve

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performance, researchers have introduced predictive control approaches that optimize power flows using look-ahead forecasts. Model predictive control (MPC) is often employed, using solar generation and load predictions to dispatch battery and electrolyzer power over a receding horizon [8]. Predictive EMS can significantly increase hydrogen yield and reduce curtailment by proactively smoothing PV output, but they depend on forecast accuracy and incur higher computational effort. Optimization-based strategies have also been formulated (e.g., using mixed-integer programming or stochastic optimization) to determine the optimal power dispatch among PV, battery, and electrolyzer, often with objectives such as minimizing cost or maximizing efficiency. These methods can handle operational constraints and multi-objective trade-offs more rigorously than rule-based control. Under rapidly fluctuating PV conditions, each EMS approach faces limitations: heuristics might trigger excessive battery cycling or electrolyzer on/off switching, and even predictive controllers may encounter challenges if a sudden cloud causes large deviations from the forecast. Despite extensive simulation studies on hybrid renewable–battery–hydrogen control, a significant gap remains in experimental validation under real-world conditions. Experimental testbeds and field demonstrations are urgently needed to evaluate EMS performance in the presence of physical hardware dynamics, environmental disturbances, and system nonlinearities. Most reported EMS strategies in the literature have been verified via software simulation with limited integrated experiments [9]. As a result, uncertainties persist regarding how theoretical EMS optimizations translate to practical operation (e.g., response delays, measurement noise, or unmodeled degradation effects).

In this work, we address the experimental validation gap by presenting the development, integration, and testing of a kW-scale hybrid PV–BESS–Electrolyzer platform implemented at DTU PowerLabDK. Section 2 describes the system architecture and component interfaces. Section 3 outlines the experimental methods used for component-level characterization and the implementation of a rule-based EMS. Section 4 presents experimental results demonstrating improved hydrogen production and system resilience, along with validation of a simplified power-flow model. Section 5 discusses operational trade-offs and control challenges. Finally, Section 6 concludes with key findings and directions for future research.

2. SYSTEM DESCRIPTION AND BEHAVIOR

The hybrid system comprises three main components:

- PV array: Rooftop solar photovoltaic system consisting of 120 panels at a total installed capacity of 22.3 kWp.
- XOLTA BESS: 35kW/79 kWh NMC battery system
- AEM Electrolyzer: Enapter EL 4.1, three-stack system with thermal management.

A local EMS governs real-time active power flow, prioritizing the electrolyzer's uptime, stability, and hydrogen production, while using the BESS as a buffer for the PV power input. Communication across components is achieved via MODBUS, HTTP API, and MQTT protocols. A visualization of the system's connectivity and its data and power flow is provided in Fig. 1.

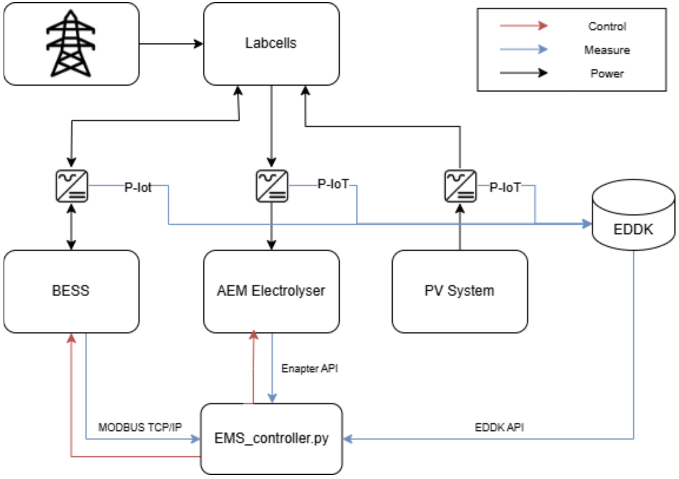

Fig. 1 PV–BESS–Electrolyzer system schematic

TABLE 1 Hardware characteristics

Feature	Unit	Datasheet	Measured
BESS: XOLTA BAT-79 NMC			
Nominal power	kW	30	–
Energy	kWh	79	69.41 (discharge)
Capacity	Ah	–	99.43 (discharge)
System efficiency	%	96.6	96.7–99.4*
Battery voltage range	V	614–797	640–798
Electrolyzer: Enapter El 4.1 AEM†			
Production rate	NL/h	500	506
Operative power consumption	kW	2.4	2.4
System power-H_2 efficiency	%	62.6	55.2

* Round trip at 0.2C (η_C)–(η_E) respectively.
† Full load conditions for one stack

TABLE 2 Hardware dynamic behavior

Parameter	Unit	Value	
		BESS	AEM
Ramp time (up)	s	3–5	24.6–57.4
Ramp time (down)	s	1–5	5.8–6.3
Ramp rate (up)	%/s	20–33	0.4–0.7
Ramp rate (down)	%/s	27–53	1.7–6.3
Response time	s	1–4	2–3
Cold start time*	s	–	1125–1301

* Cold start from room temperature (23°C) to full load

2.1 Performances

The operational performance of the system's key components, the BESS and the electrolyzer, is detailed in this section. A feature analysis is presented in TABLE 1, which provides a direct comparison between the manufacturer-provided datasheet specifications and the measured values during individual characterization for both components. Furthermore, the dynamic response characteristics of each component, including ramp times and response times, are summarized in TABLE 2. Note that ramping parameters, particularly for the electrolyzer, are highly dependent on step size and temperature. Ramp rates are normalized at nominal conditions (30 kW battery charging and 100% electrolyzer stack production rate).

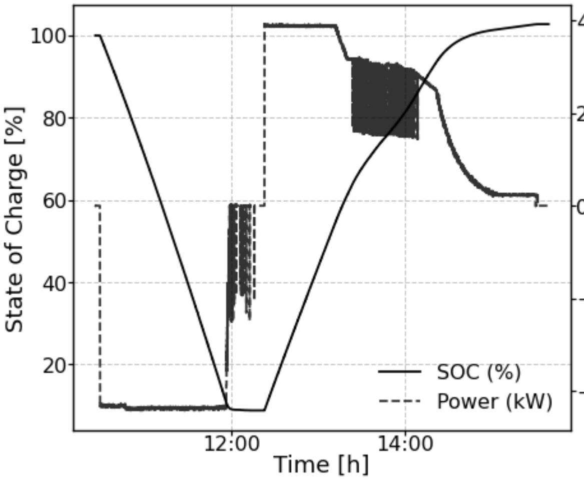

Fig. 2 Round-trip test of BESS at 0.2C

Beyond the static feature analysis, dynamic testing highlighted important operational behaviors of the BESS and electrolyzer. The BESS demonstrated immediate responsiveness and reliable ramping up to 0.5C within 5 s, confirming its suitability as a fast-acting buffer. Setpoint tracking accuracy was limited by asymmetric deviations during charging and discharging, requiring calibration to align the target setpoint with AC and DC measurements. Thermal protection was also observed above 48 °C, where current derating in the BMS caused oscillatory current behavior, after prolonged charging/discharging at 0.5C. Although problematic under high-stress testing, this effect is unlikely to occur during normal hybrid operation with lower charge rates. A conservative SOC window (10–90%) was adopted to ensure stable operation. Near high SOC charging currents decreased significantly as upper voltage thresholds approached. SOC estimation also exhibits drift over time, requiring periodic recalibration.

The electrolyzer operated within the range of 60–100% load specified by the manufacturer, likely imposed to mitigate gas crossover at low current densities. The electrolyzer stacks achieved higher system power-to-hydrogen efficiencies at greater loads, a result of the reduced impact of auxiliary power consumption. A major limitation was the slow startup, particularly a cold start, where reaching full operation could take up to 22 minutes. This shortcoming is critical for intermittent solar integration but could be mitigated through electrolyte preheating. Dynamic testing further showed that the electrolyzer is slow at handling rapid PV fluctuations and struggles to follow varying setpoint changes within seconds. Although it was capable of tracking load changes on a minute-basis within a 5% margin of error, steady-state convergence was slow. The dynamic behavior of the electrolyzer reflects inherent electrochemical and thermal inertia, unlike the near-instantaneous response of the BESS.

In combination, the findings underline the complementary roles of the two subsystems: the BESS provides rapid short-term balancing, while the electrolyzer benefits from smooth, sustained operation at high load.

2.2 PV scenarios

To evaluate the system under realistic operating conditions, multiple PV production profiles were derived from measurements at the PowerLabDK PV rooftop installations (March 2025), as shown in Fig. 3. These scenarios were applied in both hardware tests and simulations to capture variability in solar availability and to examine how the system responds to different challenges, such as power fluctuation and BESS depletion.

- S1 Cloudy day: Low but stable production.
- S2 Sunny day with clouds: High production with frequent spikes and intermittency.
- S3 Sunny day: High and stable production.

Additionally, a three-day profile combining variable, intermediate, and stable conditions was used to study extended operation and mixed scenarios. The selected cases highlight the short-term dynamics and coordination among PV, BESS, and electrolyzer subsystems. The weather conditions are not intended to represent seasonal variations or annual performance but are sufficient for this stage of performance evaluation.

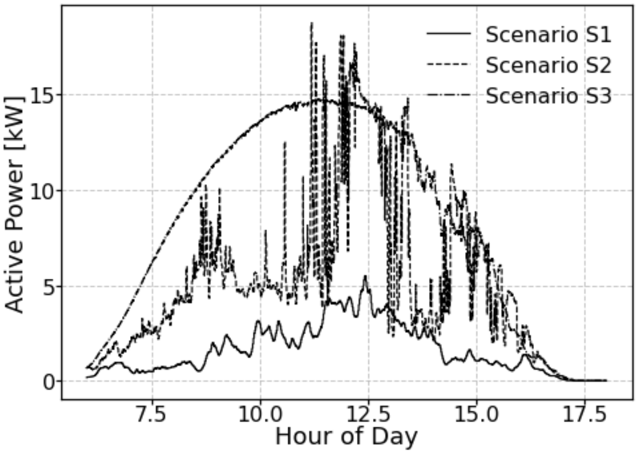

Fig. 3 Power profiles of PV irradiation scenarios

3. METHODOLOGY

3.1 *Components characterization*

Initial tests were performed to characterize the BESS and AEM electrolyzer under controlled conditions. These experiments established round-trip efficiency, dynamic behavior, and startup limitations, serving as input for later modeling and EMS design. For the BESS, round-trip capacity tests at 0.5 C (around 40 kW) and 0.2 C (around 16 kW) determined charge, energy capacity, and efficiency. Capacity and energy were obtained from time-integrated current and voltage,

$$Q = \int I(t)\, dt, \quad E = \int V(t) I(t)\, dt, \tag{1}$$

with Coulombic and energy efficiencies given by,

$$\eta_Q = \frac{Q_{\text{dis}}}{Q_{\text{chg}}} \cdot 100\%, \quad \eta_E = \frac{E_{\text{dis}}}{E_{\text{chg}}} \cdot 100\%. \tag{2}$$

Dynamic response was assessed using a step sequence from -30 to +30 kW, while real PV profiles (5–60 s resolution) evaluated latency and setpoint fidelity. Polynomial corrections compensated for setpoint–measurement mismatches. The electrolyzer was characterized using step and ramp tests (10% increments, 60–100% load) to extract efficiency, ramp rates (t_{lin}), and time constants (τ). Startup performance was measured under cold (23°C), mid (33°C), and warm (55°C) conditions, and preheater operation was isolated to quantify energy and time requirements for warmup of liquid electrolyte. Dynamic tracking capability was assessed by applying a 5-second PV-derived profile. Key performance indicators are summarized in Table 3.

TABLE 3 Hardware metric and reference test

Component	Metric	Reference Test
BESS	Round-trip efficiency (η_Q, η_E)	Round trip tests
	Ramp rate and response time	Step sequence
	Battery capacity (Q, E)	Round trip tests
Electrolyzer	System power-to-hydrogen efficiency	Step/ramp tests
	Ramp rate and constants (t_{lin}, τ)	Step/ramp tests
	Startup times (cold/warm)	Startup test
	Dynamic tracking delay	Dynamic test

3.2 *PV-Electrolyzer baseline testing*

To benchmark the added value of battery storage, a PV-electrolyzer baseline controller was first established, with the aim of testing the system without the BESS. A multi-stack fallback control strategy was developed to coordinate stacks under the 60–100% operating range to force load-following of the last stack, while avoiding deadband ranges. This both minimized curtailment and excessive cycling. A 15-minute cooldown hysteresis period was introduced to minimize cycling, and a Python mock-controller was used to validate logic without stressing real hardware.

3.3 *EMS Strategy:*

A rule-based EMS was developed using SOC thresholds and PV setpoint smoothing to coordinate system operation. In this configuration, the logic ensures that the BESS absorbs PV peaks and supports the electrolyzer stacks during intermittent periods, while maintaining the electrolyzer at near-nominal conditions to ensure stable operation. Start/stop cycling is minimized to reduce component degradation. The EMS was developed in Python as a rule-based controller, relying on real-time inputs of PV generation, BESS SOC, and electrolyzer operating state. The controller was structured around the following hierarchy of operational priorities:

1. Maximize hydrogen yield: AEM operation prioritized at 100% load whenever feasible.
2. Maximize uptime: A "power-saving mode" at 60% load is engaged when the SOC falls to 10–25%, avoiding unnecessary shutdowns.
3. Operate efficiently: Prefer full-load and stable operation, though subordinated to yield and uptime.
4. Avoid degradation: Enforce SOC limits (10–90%), stack hysteresis (15 min downtime), and 5% SOC deadbands to reduce cycling.

The EMS operated under a strict constraint of islanded PV-only supply, prohibiting grid import/export. Hysteresis rules were implemented to reduce fast switching, and low-power operation modes were used to extend electrolyzer continuity at low SOC. Lookup tables derived from component testing (e.g., AEM AC power mapping, idle losses, and setpoint correction polynomial) were integrated directly into the control logic.

3.4 *Hybrid testing*

System-level tests compared the EMS-based PV–BESS–electrolyzer operation against the baseline PV–electrolyzer setup. Performance indicators were hydrogen yield, AC consumption, efficiency, start/stop cycles, and PV curtailment. The two 4-hour scenarios were demonstrated: cloudy day (S1) and sunny day with clouds (S2), chosen to capture intermittency and ramping dynamics within realistic experimental constraints.

3.5 Modeling and Simulation

A simplified Python-based power-flow model was developed and validated to test EMS performance over extended multi-day scenarios and perform parametric sensitivity studies related to system design and dimensioning. It operates at the same 5-second resolution as the controller and follows a modular structure for each component. The model comprises four main elements. The electrolyzer is represented by a data-driven model that captures experimentally derived relationships between stack voltage, current, and temperature. It is complemented by a first-order heat balance equation to account for thermal effects and curve-fitted ramping and startup dynamics. The battery is modeled as an energy-based SOC tracker with efficiency and capacity taken from cycle tests, while sub-second dynamics are omitted to align with the high-level system scope. The EMS implements the actual controller logic adapted for multi-day operation, including night shutoff and minimum production thresholds. Model validation was performed against experiments using RMSE and MAE metrics, with PV–electrolyzer standalone and hybrid configurations.

4. RESULTS

Fig. 4 illustrates how BESS buffering helps smooth the electrolyzer's load in the scenarios S1 and S2, and TABLE 4 summarizes the key performance indicators. Hydrogen yield increased significantly in the hybrid setup (S1: +77.7%, S2: +14.6%) by avoiding unnecessary shutdowns and reducing curtailment during periods of low PV. Start/stop cycles were considerably reduced, resulting in decreased component stress and ensuring stable and continuous operation. SOC remained well below the upper limit in both scenarios, indicating the battery was oversized relative to the tested load and suggesting potential for capacity optimization. The EMS operated as intended with no major deviations; control delays (around 5 seconds) were consistent with the known communication latency.

The simulation model reproduced key system behaviors (ramping, startup, steady state) with small mean absolute errors for BESS power and SOC and moderate errors for electrolyzer startup dynamics. Despite these limitations, the model was adequate for parametric studies. Parametric simulations revealed that the battery capacity was likely oversized, indicating optimization potential depending on use case and performance targets. While hydrogen yield increased with larger capacity, marginal gains diminished beyond approximately 0.5–0.7 times the current battery size. Regarding control logic, disabling low-load operation slightly increased hydrogen yield but also led to greater curtailment. For very small batteries, low-load operation helped sustain uptime, whereas at larger sizes full-load cycling outperformed extended low-load operation.

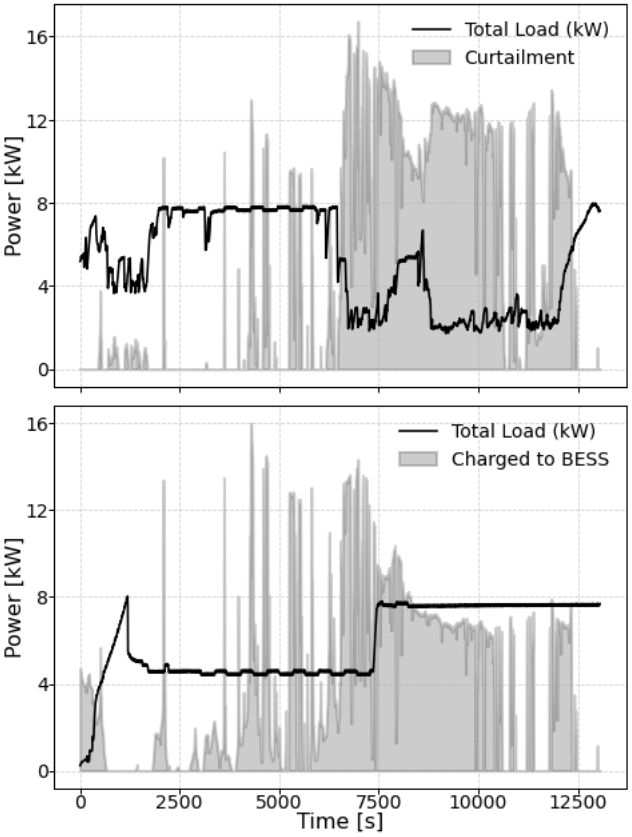

Fig. 4: System testing results of S2 for PV-Electrolyzer (upper) compared with PV–BESS–electrolyzer (lower).

TABLE 4 Comparison of Baseline (S1) and Hybrid Configurations (S2)

Metric	S1		S2	
	Baseline	Hybrid	Baseline	Hybrid
H_2 Yield (Nl)	2257.96	4019.25	3752.26	4298.00
Acc. AC Power (kWh)	11.58	20.32	18.72	21.17
PV (kWh)*	1.5	0.3	17.4	13.84
Start/Stop Cycles	4	3	8	3
Start/Stop Cycles (24h sim.)	10	3	34	3

* Baseline: curtailed PV. Hybrid: PV charged to BESS.

5. DISCUSSION

This study demonstrated that integrating a BESS with a PV–electrolyzer system can substantially increase hydrogen yield, improve continuity of operation, and reduce curtailment under variable solar conditions. Component testing confirmed that the BESS provides fast-response buffering for PV fluctuations, while the electrolyzer benefits from stable, high-load operation but is poorly suited to frequent ramping or deep cycling. These findings justified the rule-based EMS strategy and informed its SOC and load-threshold settings.

Experimental and simulated results revealed clear operational trade-offs. Battery capacity significantly influences hydrogen production but exhibits diminishing returns beyond approximately 0.5–0.7 times its current size. While large batteries minimize curtailment and support longer up-time, their high capital cost raises questions of economic feasibility, especially in the case of a relatively low market value of green hydrogen. Similarly, the implemented low-load operation mode extended electrolyzer continuity at low SOC but marginally reduced total hydrogen yield, indicating that intermittent full-load cycling may outperform continuous partial-load operation under many conditions. These outcomes highlight the need for more adaptive EMS strategies that dynamically optimize SOC thresholds, load settings, and startup behavior, rather than relying on fixed rules.

In a broader context, the study highlights the limitations of evaluating off-grid systems solely based on hydrogen yield. In real markets, fluctuating electricity prices and alternative revenue streams may render large batteries or continuous operation economically suboptimal. Under some conditions, it could be more profitable to curtail production, idle the electrolyzer, or export power to the grid. Although the present system was intentionally isolated to maximize hydrogen output, future work should incorporate grid connectivity, forecasting, and multi-objective optimization to reflect realistic dispatch decisions and techno-economic trade-offs.

6. CONCLUSION

This work presented the experimental development and evaluation of a kW-scale hybrid PV–BESS–electrolyzer system operated in laboratory operation. By combining component characterization with a rule-based EMS in parametric simulations, the study demonstrated that battery buffering can significantly improve hydrogen yield, reduce curtailment, and limit start/stop cycling compared to a standalone PV–electrolyzer configuration. The start/stop cycling is reduced from 10 to 3 and from 34 to 3 per day in two different weather scenarios, which gives 77.7% and 14.6% more hydrogen yielded accordingly. Although intentionally designed as an off-grid platform with hydrogen yield as the primary objective, the findings emphasize that such systems should be evaluated within a techno-economic framework. High battery costs and volatile electricity prices may render continuous operation economically suboptimal, and alternative strategies, such as grid connection, curtailed operation, or dynamic dispatch, may outperform purely yield-oriented control in practice. Despite these limitations, the study offers valuable experimental validation that links hardware testing, real-time EMS control, and simulation. It provides recommendations on battery sizing, control thresholds, and operational priorities for off-grid or pilot-scale systems, establishing a foundation for future research on optimized control, seasonal operation, and integrated techno-economic assessment.

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