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OPERATING OPTIMISATION FOR A DIRECT-CONNECTED GREEN-ELECTRICITY HYDROGEN-AMMONIA PARK BASED ON MIXED-INTEGER AND CONTINUOUS LINEAR PROGRAMMING

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Abstract: This paper studies the operation optimisation of a direct-connected wind-photovoltaic hydrogen-ammonia park and evaluates how production flexibility, energy storage and islanded operation affect power balance, renewable-electricity indicators and operating cost. Some applications have been developed for full-load operation, discrete production scheduling, continuous power regulation, islanded dispatch, storage sizing and grid-connected comparison. The park has 40 MW of wind power, 64 MW of photovoltaic power, and hydrogen-ammonia loads for 36 t/d and 72 t/d production. At a 36 t/d full-load baseline, the self-consumption, green-electricity and export ratios are 28.16%, 69.21% and 35.92%, respectively; 54 t/d is the lowest-cost feasible output in discrete scheduling, and the unit cost is 4591.27 yuan/t. The total annual cost of continuous regulation is 1.9005 million yuan, and all three indicators have been achieved in 210 of the 360 weighted days. In islanded operation, 5000 MWh of storage increases the annual output to 25920 t, but the unit cost is still higher than that of grid-connected systems. Flexible production and storage increase the utilisation of renewable energy; however, economic feasibility requires integrated planning of production, storage and grid operation.
Keywords: Green-electricity direct connection; Hydrogen-ammonia park; Power balance; Flexible scheduling; Energy storage; Islanded operation

1 INTRODUCTION

Directly connect wind and photovoltaic power plants to the industrial user for consumption of variable renewable energy and reduced-carbon-intensity chemical production. Hydrogen and ammonia are chemical routes for electricity-to-storage conversion; however, the resulting park needs to coordinate intermittent supply from electrolysis, ammonia synthesis, traditional demand, and grid connection. An Energy Management System for electrolysis, storage and ammonia demand response can reduce operating costs and increase the use of green hydrogen [1-3].

Recently, some studies of energy hubs have considered hydrogen and ammonia as flexible carriers and compared mixed-integer scheduling with data-driven control [4]. Coordinated scheduling models have also shown that storage in hydrogen-related networks can generate economic value through time-shifting of energy [5]. Hybrid hydrogen-ammonia storage and advanced learning-based control have further shown that the use of renewable energy, grid dependency and operating value should be considered together [6]. Dynamic operation of green ammonia is required due to fluctuations in the scale of production, renewable capacity factors and ramping capabilities of the process [7].

There is an operating problem of uneven distribution of energy supply and demand. The output of renewable energy may exceed the current demand and need to be exported; otherwise, in a low-output period, grid purchase or production curtailment will be required. A flexible renewable multi-generation configuration can be employed for the storage of hydrogen and ammonia for short-term and long-term use, but its performance is limited by hourly scheduling, production constraints and storage capacity [2]. Therefore, cost-optimal design studies aim to achieve both capacity planning and operation in the same period for electricity and ammonia production coupled with storage [3].

The actual problems of a direct-connected hydrogen-ammonia plant are as follows: How much production flexibility is required to meet the green-electricity goals? Does continuous regulation improve on/off operation? How much renewable power is required for islanded autonomy? Has the amount of savings covered the investment expenses? Multi-time-scale planning and electrolyser-level operating decisions are being integrated into integrated electricity-hydrogen models [8-9], and wider sustainability studies have pointed out the necessity of balancing production, cost and system-level resource use [10].

This paper constructs a multi-scenario optimisation framework for a park with 40 MW of wind power, 64 MW of photovoltaic capacity, an initial hydrogen-ammonia load of 20.75 MW at 36 t/d, and a scaled-up load of 41.5 MW at 72 t/d; the conventional-load peak is 6 MW. Full-load operation of the framework, discrete-output scheduling, continuous-power regulation, islanded operation, storage sizing and grid-connected comparison. Based on the three green-electricity requirements mentioned above, show the results of different scenarios and use the same cost and equipment assumptions in all comparisons.

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2 SYSTEM DESCRIPTION AND MODEL

2.1 System Parameters and Operating Indicators

The park has wind power plants, photovoltaic power stations, alkaline and PEM electrolysis equipment, an ammonia synthesis unit, conventional loads and grid connections. The initial full-load baseline is 20.75 MW, of which 20 MW is for electrolysis and 0.75 MW for ammonia synthesis; thus, the output of ammonia is 36 t/d or 1.5 t/h. For the later 72 t/d case, the rated hydrogen-ammonia load is scaled to 41.5 MW (40 MW electrolysis and 1.5 MW ammonia synthesis), corresponding to 3 t/h. Wind and photovoltaic capacities are 40 MW and 64 MW, respectively. The maximum of the conventional load is 6 MW, and it follows the published 24-hour per-unit profile. Six wind scenarios and four photovoltaic scenarios form 24 combined scenarios; each scenario represents 15 days, so the annual statistic contains 360 days.
The three operating indicators are self-consumption of renewable electricity, the proportion of green-electricity in total consumption, and the export share of renewable generation. Their requirements are 60%, 30% and 20%, respectively. Wind generation and photovoltaic generation are calculated by multiplying the installed capacity by the corresponding per-unit profile.

$$P_w(t) = P_w^{\text{inst}} p_w(t),\ P_{\text{pv}}(t) = P_{\text{pv}}^{\text{inst}} p_{\text{pv}}(t) \tag{1}$$

$$P_L(t) = P_{\text{conv}}(t) + P_{\text{HA}}(t) \tag{2}$$

$$\eta_{\text{self}} = \frac{E_L - E_{\text{sell}} - E_{\text{buy}}}{E_{\text{ren}}} \geq 0.60 \tag{3}$$

$$\eta_{\text{green}} = \frac{E_{\text{ren}} - E_{\text{sell}}}{E_L} \geq 0.30 \tag{4}$$

$$\eta_{\text{export}} = \frac{E_{\text{sell}}}{E_{\text{ren}}} \leq 0.20 \tag{5}$$

2.2 Operating Modes

Full-load baseline maintains electrolysis and ammonia synthesis at the original 36 t/d reference power and evaluates the resulting power balance. Discrete mode is a production switch that chooses several full-load hours from many in a day for the desired output. Continuous mode can adjust hydrogen-ammonia power continuously above 10% of the rated level and has an overall-energy requirement for each target output. Islanded mode does not connect to the grid for import or export. Wind, photovoltaic generation, conventional demand and, if any, storage need to balance the continuously regulated hydrogen-ammonia load. The storage is modelled by charge/discharge and state-of-charge variables, with a 90% charge/discharge efficiency and 0.2% hourly self-loss.

2.3 Cost Model

Operating costs include wind and photovoltaic generation costs, time-of-use grid purchase fees, hydrogen-ammonia operation and maintenance expenses, minus export income. The unit cost of the reported items is 0.15 yuan/kWh for wind power, 0.12 yuan/kWh for photovoltaic power, 0.8024, 0.6074 and 0.3424 yuan/kWh for peak, flat and valley grid periods, respectively, and 0.3779 yuan/kWh for exported electricity.

$$C_{\text{day}} = c_w E_w + c_{\text{pv}} E_{\text{pv}} + \sum_{t=1}^{24} p_{\text{buy,t}} E_{\text{buy,t}} - p_{\text{sell}} E_{\text{sell}} + c_{\text{om}} \sum_{t=1}^{24} P_{\text{HA,t}} \tag{6}$$

3 OPTIMISATION MODELS

3.1 Full-Load Power Balance

At full load, every hour satisfies instantaneous power balance. Positive surplus is exported and negative surplus is covered by grid purchases.

$$P_w(t) + P_{\text{pv}}(t) + P_{\text{buy}}(t) = P_L(t) + P_{\text{sell}}(t) \tag{7}$$

3.2 Discrete Production Scheduling

For a target output q, the number of full-load hours K is fixed by a production rate of 3 t/h. Let x_t be a binary operating decision. Since the hourly operating increments are separable, sort the incremental costs and select the K lowest-cost hours for the minimum-cost schedule.

$$\min_x \sum_{t=1}^{24} \Delta c_t x_t \tag{8}$$

$$\sum_{t=1}^{24} x_t = K,\ x_t \in (0,1) \tag{9}$$

3.3 Continuous Linear Scheduling

$P_{\text{HA,t}}$ is a continuous decision variable for regulation. The total daily energy demand is fixed by the target output, and at the same time, each hour's power should not exceed its upper or lower limits.

$$P_{\min} \leq P_{\text{HA,t}} \leq P_{\max},\ \sum_{t=1}^{24} P_{\text{HA,t}} = E_{\text{req}} \tag{10}$$

A continuous model is a linear program because, under the above assumptions, power balance, production-energy relation, cost function and operating bounds are all linear. The same three green-electricity indicators are calculated from the optimised schedule, and each scenario is weighted by 15 days for annual statistics.

3.4 Islanded Operation and Storage

Storage is represented by charge $P_{ch,t}$, discharge $P_{dis,t}$ and state of charge S_t.

$$S_{t+1} = (1-\alpha)S_t + \eta_{ch}P_{ch,t} - \frac{P_{dis,t}}{\eta_{dis}} \tag{11}$$

$$0 \le S_t \le S_{max},\ 0 \le P_{ch,t},\ P_{dis,t} \le P_{ess} \tag{12}$$

Test whether the minimum storage capacity can meet the demand of the maximum-curtailment case. Fix the configured capacity for all 24 scenarios, and then maximise daily ammonia production under the constraint of storage dynamics in each scenario. The annual output is equal to the total weighted sum of the 15-day scenario outputs.

4 RESULTS AND DISCUSSION

4.1 Full-Load Baseline

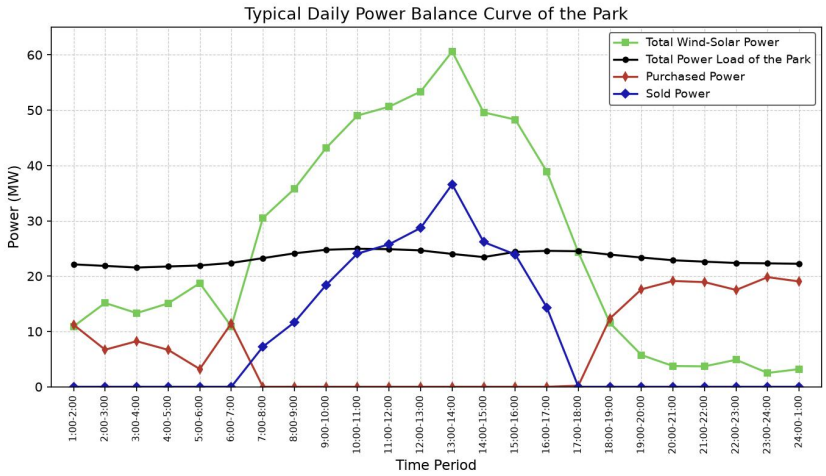


Figure 1 Typical-Day Power Balance under Full-Load Operation

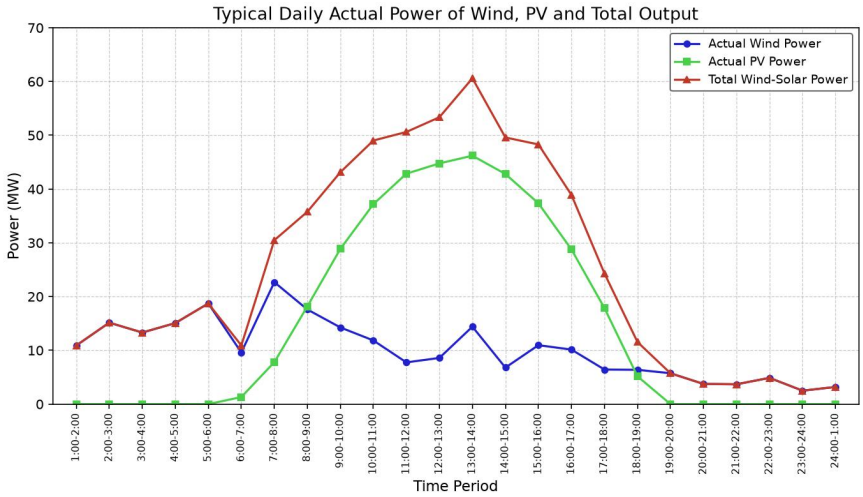


Figure 2 Wind, Photovoltaic and Total Renewable Power Profiles

Figures 1 and 2 show the typical-day power balance and renewable-generation profiles, respectively. At the beginning of full-load operation, the hydrogen-ammonia equipment consumes 20.75 MW, and so does the rest of the plant. The 40 MW wind and 64 MW photovoltaic capacities can generate a large amount of electricity during several hours of the day, but grid purchase is required at night and during low-output periods. The resulting indicators are shown in Table 1 below.

Table 1 Full-Load Green-Electricity Indicators

Indicator	Value	Requirement	Result
Self-consumption ratio	28.16%	>60%	Fail
Green-electricity share	69.21%	>30%	Pass
Renewable export ratio	35.92%	<20%	Fail

The two failed indicators have the same structural reason: a rigid hydrogen-ammonia load cannot follow the midday photovoltaic peak, so surplus electricity is exported; at night, it purchases a deficit from the grid. Therefore, the baseline shows why production flexibility and storage are needed even if the annual renewable generation is large.

4.2 Discrete Production Regulation

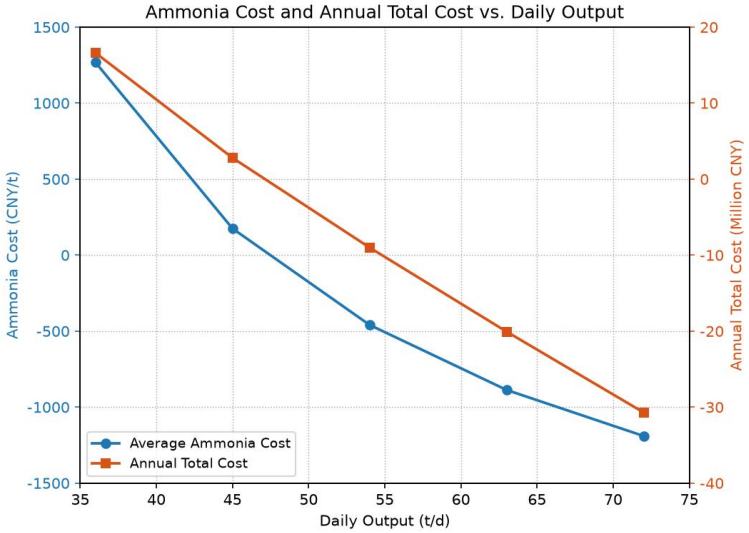


Figure 3 Variation of Unit Ammonia Cost and Annual Total Cost with Daily Output

Table 2 Discrete Production Schedules and Green-Electricity Indicators

Output (t/d)	Full-load hours	Self-use	Green share	Export	Cost (yuan/t)	Indicator
72	24	86.52%	53.26%	6.74%	6219.14	Pass
63	21	84.33%	59.66%	7.83%	5328.06	Pass
54	18	80.16%	67.30%	9.92%	4591.27	Pass
45	15	50.98%	66.67%	24.51%	3944.54	Fail
36	12	10.50%	59.68%	44.75%	3191.67	Fail

Figure 3 shows how unit ammonia cost and annual total cost vary with daily output, while Table 2 summarises the corresponding schedules and green-electricity indicators. The smallest unit cost of all the discrete outputs is at 36 t/d, but this schedule does not meet either the self-consumption or export requirements. Among the feasible schedules, 54 t/d has the lowest cost of 4591.27 yuan/t. The above result shows that minimising private production costs and meeting a system-level renewable-electricity policy are not necessarily aligned. A lower output reduces the operating hours of the equipment; thus, it is less economically feasible for use in a park with high demand. Figure 4 further summarises the annual satisfaction categories under the discrete production outputs.

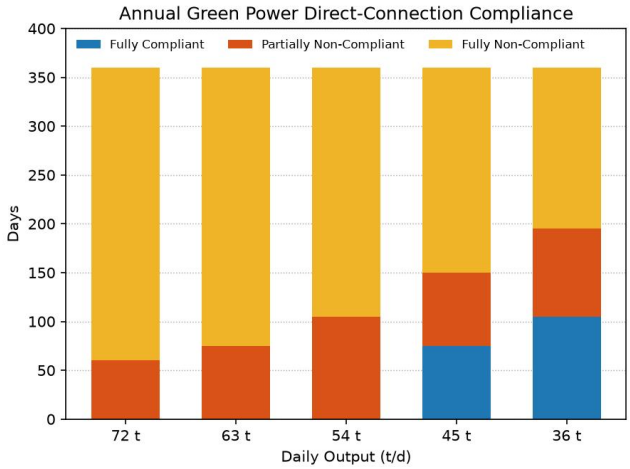


Figure 4 Annual Satisfaction Categories under Discrete Production Outputs

4.3 Continuous Power Regulation

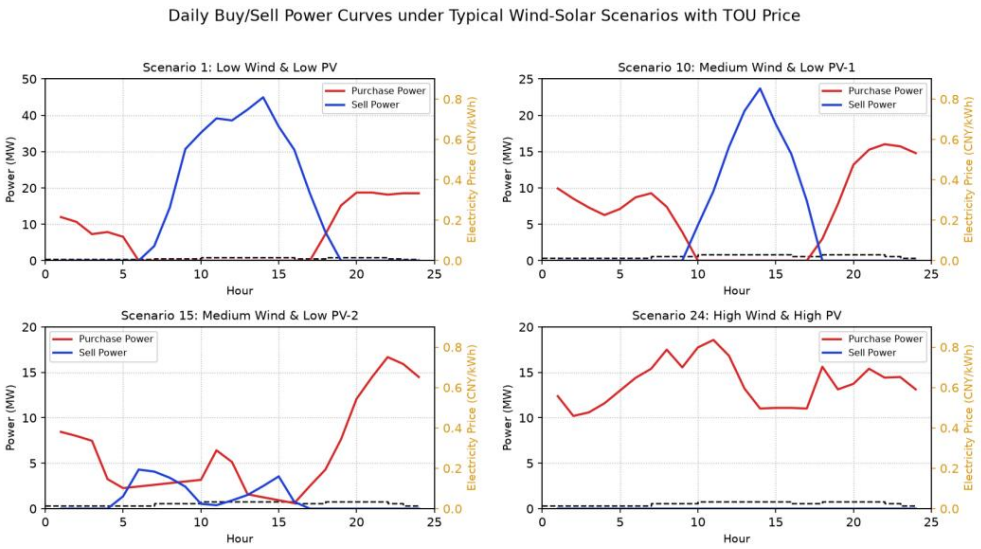


Figure 5 Representative Continuous-Scheduling Power Profiles and Time-of-Use Prices

Figure 5 presents representative continuous-scheduling power profiles and time-of-use prices. Continuous regulation can make the hydrogen-ammonia load follow renewable output and time-of-use prices, rather than only selecting complete operating hours. The reported annual total cost is 1.9005 million yuan, and the average unit cost is 5279.17 yuan/t. Among the 360 weighted days, all three indicators were met on 210 days (58.3%), partially met on 150 days (41.7%), and not met at all on zero days.

The scenario cost ranges from about 2850 yuan/t under high-wind and high-photovoltaic conditions to 4120 yuan/t in low-wind and low-photovoltaic conditions. Continuous regulation has reduced the unit cost by an average of 9.8% compared with discrete scheduling, and this reduction is about 12% in a low-resource scenario. The self-consumption ratio has risen by 7.5 percentage points, the proportion of green electricity has increased by 5.6 percentage points, and the export ratio has fallen by 5.4 percentage points. Continuously adjust; thus, it will be economically scheduled and meet the three indicators.

4.4 Islanded Operation and Storage

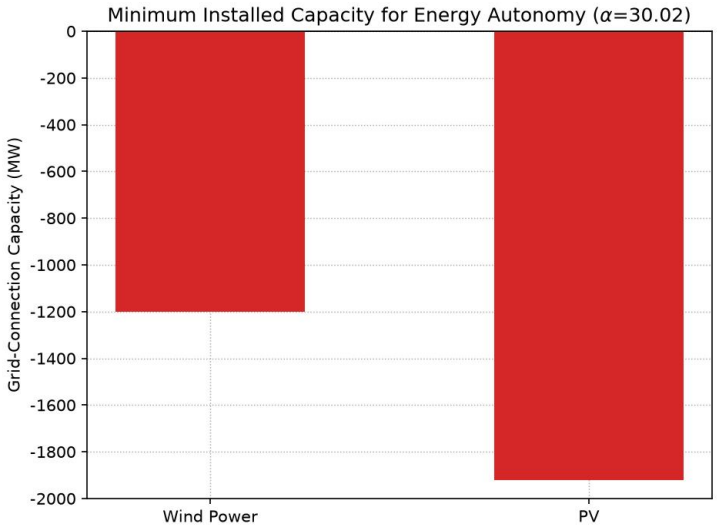


Figure 6 Estimated Minimum Wind and Photovoltaic Capacities for Energy Autonomy

Scenario 13 has the highest curtailment and a curtailed electricity amount of 177.29 MWh/d. The minimum storage capacity of the target operation is 5000.0 MWh. With this fixed capacity in all cases, the annual output will be 25920 tonnes, full utilisation will be achieved, and the reported average unit cost including storage investment will be 15519.14 yuan per tonne. Storage can avoid the production shortfall and dissipate surplus renewable energy, but it is also relatively expensive.

Figure 6 is the estimated wind and photovoltaic power required for energy self-sufficiency. Without grid exchange and storage, the 24 scenarios have produced a total of 9781.56 t over the weighted year and have an average capacity utilisation rate of 37.74%. Renewable utilisation is 91.72%, but on some days, the renewable power cannot reach the minimum operating level or meet the conventional load requirements. With a constant wind-to-photovoltaic capacity ratio, the minimum uninterrupted autonomy capacities are estimated to be 156.0 MW of wind and 249.6 MW of photovoltaics.

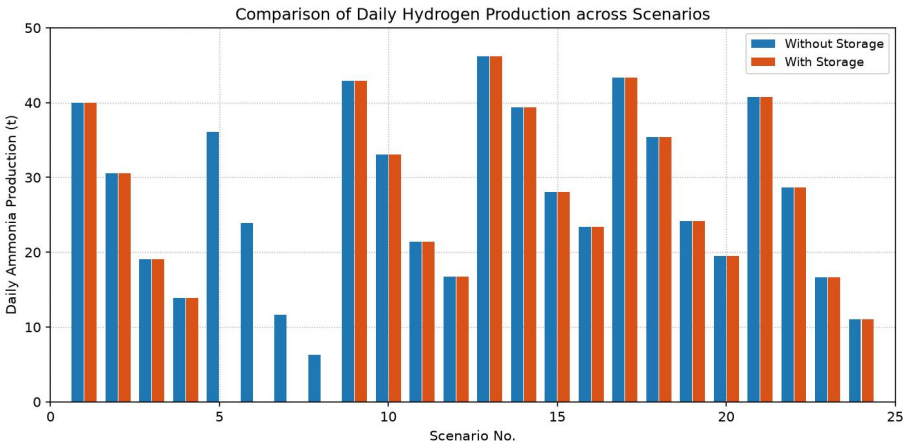


Figure 7 Scenario Comparison of Daily Production with and without Storage

Figure 7 compares daily production across scenarios with and without storage. At the same production demand, the reported grid-connected average unit cost is 15026.33 yuan/t, and that of islanded operation with storage is 15519.14 yuan/t. Therefore, based on the above data, grid connection has a lower cost by 492.81 yuan/t; however, islanded storage also provides independence and renewable-absorption services that are not reflected in the unit price.

5 CONCLUSIONS

Therefore, the operation of renewable energy generation and flexible hydrogen-ammonia production can be coordinated. The full-load baseline does not meet the requirements for self-consumption and export; therefore, a discrete schedule of 54 t/d will be employed. Continuously adjust to improve the matching of time and reduce the average unit cost by 9.8% compared with discrete scheduling. Storage can improve the autonomy and renewable use of islanded operations, but it is relatively expensive. A 5000 MWh storage system has an annual output of 25920 t and full-capacity utilisation; however, its unit cost is still higher than that of grid-connected installations. Therefore, the operating mode will be autonomous and use renewable energy or operate to reduce costs.

Overall, the framework can support preliminary feasibility assessment and operating-mode comparison for direct-connected hydrogen-ammonia parks under the stated assumptions.

The analysis is restricted by the simplified handling of equipment start-up losses, low-load efficiency degradation, electrolyser state transitions, demand-shortfall penalties, storage degradation and grid constraints. In the future, non-linear equipment efficiency, stochastic renewable forecasts, degradation-aware storage and joint annual planning of renewable capacity, storage and grid services will be added to improve the engineering application.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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