Additional file 1: Supplementary information

Arrhenius-Based Capacity and Dispatch Optimization of a Wind–Photovoltaic–Storage Microgrid Using Task-Preserving, Degradation-Aware Refinement

Sustainable Energy Research

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Four-season hourly inputs, model and search parameters, and sensitivity data for the 12-run study.
Each representative day is independently closed and weighted.

Table S3. Effective coefficients for the hourly Arrhenius degradation model.

Quantity	Value	Implementation meaning
Activation energy Ea	25,000 J/mol	arrhenius_Ea
Gas constant R	8.314 J/(mol K)	arrhenius_R
Reference temperature	25 °C / 298.15 K	arrhenius_T_ref_C
Cycle coefficient Acyc	1.2×10^{-5}	Coefficient for numerical r in EFC/h and Δt in h
Calendar coefficient Acal	2.5×10^{-6} day^{-1}	Acal/24 per hour
Rate exponent z	0.65	z_cycle
Cycle stress gain	0.18	Multiplier of min(1.5, r/0.030)
Cycle stress cap	1.5	Cap on the normalized rate term
Reference EFC rate	0.030 EFC/h	arrhenius_efc_rate_reference
High SOC gain	0.75	Quadratic residence term
SOC reference / scale	0.62 / 0.33	Fractions of nominal SOC

Table S4. Physical constraints and operating settings.

Quantity	Value	Definition
Rated battery power	18–45 MW	Sizing variable P
Nominal battery energy	50–115 MWh	Sizing variable E
Nominal duration E/P	2.2–3.0 h	Hard sizing constraint
SOC lower / upper / initial	0.10 / 0.90 / 0.55	Fractions
Charge / discharge efficiency	0.95 / 0.95	AC power to internal energy mapping
Maximum DC rate	0.50 h^{-1}	Engineering planning limit
Grid import / export limit	180 / 36 MW	Fixed exchange capacities
Time step	1 h	All four representative days
Cell/cabin input range	18.8–29.0 °C	All released temperature records
Terminal SOC tolerance	10^{-5}	Fraction, equal for both repair arms
SOC path tolerance	10^{-10}	Fraction
Power balance tolerance	10^{-8} kW	Representative and paired-dispatch checks

Table S5. Economic and emission coefficients.

Quantity	Value	Unit or accounting basis
PCS capital cost	400	CNY/kW
Battery capital cost	650	CNY/kWh
Discount rate	0.08	Annual fraction
PCS / battery planning period	15 / 10	Years, for annualization only
PV / wind O&M	0.03 / 0.05	CNY/kWh of input generation
Battery O&M	0.01	CNY/kWh of charge + discharge
Export / purchase price ratio	0.62	Concurrent hourly price
Curtailment penalty	0.30	CNY/kWh
Unserved-demand penalty	50	CNY/kWh
Terminal-SOC coefficient	8.0×10^7	CNY per weighted excess SOC fraction
Purchased-electricity emissions	0.80	$kgCO_2e$/kWh purchased
PV generation intensity	80	gCO_2e/kWh generated
Wind generation intensity	15	gCO_2e/kWh generated
Battery embodied intensity	50	$kgCO_2e$/kWh installed

For the annual objectives, battery investment and embodied emissions use an assumed 10-year allocation period, while PCS investment uses 15 years. The 8% discount rate applies to both investment terms through the capital recovery factor. These fixed assumptions are distinct from first-year modeled degradation and are not estimates of actual service life. Wind and PV emission coefficients are stated in gCO_2e/kWh and converted to $kgCO_2e$/kWh in Equation (8d). Grid exports receive no avoided-emission credit. The terminal-SOC penalty uses the weighted mean excess over the 10^{-5} tolerance; the annual objective includes each daily operating cost once.

Table S9. Common repeated-run protocol.

Setting	Released value or rule
Algorithms	Improved NSGA-II, Standard NSGA-II, SPEA2, MOEA/D
Decision dimension / population	98 / 96 for each algorithm
Independent repeats	Reported results: 12; released full-protocol default: 12
Search evaluations	24,000 per algorithm per repeat
Budget coverage	Initial population, extra warm seeds and local candidates
Generation guard	ceil(24,000/96) + 2 = 252; actual stop is budget-based
Common pilot	120 candidates, seed 20260423; outside the search budget
Main run seeds	20260424 + r; first two seeds are 20260425 and 20260426
RNG through reproduction entry	twister
Main initialization	Same repaired uniformly sampled population for all four algorithms
Solver runtime scope	Excludes pilot, report re-evaluation, statistics and graphics

Table S10. Algorithm operator settings.

Algorithm	Operator details
Improved NSGA-II	17 extra warm seeds within budget; DE fraction 0.52, scale 0.88 + 0.20(1−gen/G), crossover 0.96; SBX exponent 16; polynomial mutation exponent 18. Adaptive crossover 0.88–0.999 and mutation 1/98–3/98, with branch-specific floors 0.020 or 0.016.

Algorithm	Operator details
Improved local search	Every fourth generation: up to eight nondominated seeds, four structured candidates per seed. Envelope-preserving environmental selection. No external elite archive; periodic envelope reinjection disabled.
Standard NSGA-II	Nondominated sorting and crowding selection; SBX probability 0.90 and exponent 20; polynomial mutation probability 1/98 and exponent 20.
SPEA2	Archive size 96; strength/density fitness and distance truncation; SBX probability 0.90; polynomial mutation probability 1/98; both exponents 20.
MOEA/D	96 deterministically selected weight vectors; neighborhood 8; scaled Tchebycheff replacement; SBX probability 0.90 and exponent 20; mutation probability 1/98 and exponent 20.

Power is in MW, temperature in °C, and purchase tariff in CNY/kWh. At each hour the export tariff equals 0.62 times the purchase tariff.

Table S12. Spring hourly inputs; 90 days.

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
1	68.256	0.000	62.900	22.5	0.28
2	73.980	0.000	60.000	22.3	0.28
3	79.715	0.000	57.800	22.0	0.28
4	86.349	0.000	57.000	21.8	0.28
5	88.510	0.000	60.000	21.8	0.28
6	80.288	0.000	69.100	22.0	0.28
7	68.598	0.000	85.554	22.5	0.28
8	56.700	30.900	106.560	23.0	0.28
9	46.800	70.600	120.080	23.8	0.52
10	39.500	118.701	128.064	24.5	0.52
11	35.500	163.758	136.000	25.0	0.90
12	34.300	193.158	139.000	25.5	0.90
13	37.600	200.178	141.800	25.8	0.52
14	44.600	174.200	142.000	25.8	0.52
15	55.500	128.270	143.700	25.5	0.52
16	70.761	77.100	138.516	25.0	0.52
17	86.940	32.800	136.895	24.5	0.52
18	104.544	6.400	134.138	24.0	0.90
19	119.790	0.000	127.182	23.6	0.90
20	131.712	0.000	112.955	23.2	0.90
21	127.680	0.000	94.963	22.8	0.52
22	113.630	0.000	80.654	22.6	0.52
23	97.524	0.000	71.100	22.5	0.52
24	79.380	0.000	63.600	22.4	0.52

Table S13. Summer hourly inputs; 92 days.

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
1	65.300	0.000	70.100	24.5	0.30
2	70.600	0.000	66.900	24.3	0.30
3	76.300	0.000	64.600	24.0	0.30
4	82.300	0.000	62.900	23.8	0.30
5	83.800	0.000	66.100	23.8	0.30
6	77.600	0.000	75.000	24.0	0.30
7	67.200	10.200	98.100	24.8	0.30
8	57.500	46.200	125.600	25.6	0.30
9	47.700	100.000	141.500	26.5	0.60
10	39.900	163.400	148.300	27.2	0.60
11	35.400	213.248	152.300	28.0	1.05
12	34.300	245.410	155.100	28.6	1.05
13	37.500	253.558	158.700	29.0	0.60
14	44.400	225.498	160.000	29.0	0.60
15	54.900	167.706	162.300	28.6	0.60
16	67.700	102.700	163.800	28.0	0.60
17	81.300	43.100	165.032	27.4	0.60
18	96.492	10.100	162.960	26.8	1.05
19	109.386	0.700	155.879	26.2	1.05
20	119.080	0.000	139.944	25.8	1.05
21	116.865	0.000	117.711	25.3	0.60
22	106.155	0.000	101.200	25.0	0.60
23	92.248	0.000	86.800	24.8	0.60
24	77.112	0.000	76.800	24.6	0.60

Table S14. Autumn hourly inputs; 91 days.

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
1	73.008	0.000	63.700	21.8	0.28
2	79.056	0.000	60.800	21.6	0.28
3	84.958	0.000	58.600	21.4	0.28
4	91.806	0.000	57.800	21.2	0.28
5	93.916	0.000	60.800	21.3	0.28
6	85.280	0.000	70.000	21.6	0.28
7	72.924	0.000	87.220	22.2	0.28
8	60.400	21.200	108.384	23.0	0.28
9	50.000	60.500	121.790	23.8	0.52
10	41.700	105.400	129.600	24.5	0.52
11	37.500	146.718	139.100	25.0	0.90

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
12	36.300	174.537	141.900	25.5	0.90
13	39.700	179.500	144.700	25.6	0.52
14	47.100	158.267	145.000	25.4	0.52
15	58.400	116.484	146.900	25.0	0.52
16	75.088	67.000	140.352	24.4	0.52
17	92.008	25.300	138.932	23.8	0.52
18	110.417	4.100	136.431	23.2	0.90
19	126.112	0.000	129.642	22.8	0.90
20	138.510	0.000	116.755	22.5	0.90
21	133.227	0.000	98.455	22.2	0.52
22	120.102	0.000	83.888	22.0	0.52
23	102.276	0.000	74.200	21.9	0.52
24	83.475	0.000	66.500	21.8	0.52

Table S15. Winter hourly inputs; 92 days.

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
1	96.910	0.000	72.700	19.5	0.30
2	104.280	0.000	69.500	19.3	0.30
3	111.289	0.000	67.200	19.0	0.30
4	118.260	0.000	65.600	18.8	0.30
5	120.268	0.000	69.400	18.8	0.30
6	109.515	0.000	79.100	19.0	0.30
7	93.524	0.000	96.530	19.5	0.30
8	77.100	0.000	116.736	20.2	0.30
9	63.600	25.200	127.015	21.0	0.55
10	53.600	54.390	132.672	21.8	0.55
11	47.900	86.884	136.200	22.3	0.95
12	46.500	112.778	135.400	22.8	0.95
13	50.700	116.025	139.600	23.0	0.55
14	60.400	95.584	144.200	22.8	0.55
15	74.100	59.388	156.900	22.5	0.55
16	95.576	27.000	160.923	22.0	0.55
17	117.165	7.000	163.020	21.5	0.55
18	139.260	0.000	159.800	21.0	0.95
19	159.895	0.000	150.400	20.5	0.95
20	174.915	0.000	134.400	20.2	0.95
21	170.545	0.000	114.366	20.0	0.55
22	151.984	0.000	98.505	19.8	0.55
23	130.582	0.000	85.400	19.7	0.55

Hour	Wind MW	PV MW	Load MW	Cell temperature °C	Purchase tariff CNY/kWh
24	107.696	0.000	75.700	19.6	0.55

Sensitivity reductions are paired relative changes from common closure. The reranked pool uses a nonincrease acceptance guard. S04 is included below although omitted from the main figure; two S04 fixed-trajectory reductions are negative.

Table S22. Declared sensitivity cases.

Case	Changed term	Setting
S01	Nominal	Original coefficients
S02	Rate exponent	0.50 with reference-rate anchor
S03	Rate exponent	0.80 with reference-rate anchor
S04	Linear cycling response	z = 1; rate-stress gain = 0; anchored
S05	Activation energy	20,000 J/mol
S06	Activation energy	30,000 J/mol
S07	Rate-stress gain	0
S08	Rate-stress gain	0.09
S09	Rate-stress gain	0.27
S10	High-SOC gain	0
S11	High-SOC gain	0.375
S12	High-SOC gain	1.125
S13	Cycling coefficient	0.5 × nominal
S14	Cycling coefficient	2 × nominal
S15	Calendar coefficient	0.5 × nominal
S16	Calendar coefficient	2 × nominal
S17	Temperature sensitivity	Ea = 0; Arrhenius factor equals one

Table S25. Sensitivity results for 12 paired candidates, mean ± sample standard deviation.

Case	Fixed iterative reduction %	Reranked pool reduction %
S01 baseline	10.698 ± 1.112	3.205 ± 0.533
S02 z 0.50	16.189 ± 1.542	4.786 ± 0.764
S03 z 0.80	5.251 ± 0.691	1.770 ± 0.281
S04 anchored linear rate	0.388 ± 0.275	0.912 ± 0.193
S05 Ea 20 kJ	10.755 ± 1.097	3.273 ± 0.541
S06 Ea 30 kJ	10.636 ± 1.129	3.144 ± 0.522
S07 no rate stress	13.016 ± 1.306	4.050 ± 0.604
S08 rate gain 0.09	11.759 ± 1.191	3.557 ± 0.565
S09 rate gain 0.27	9.790 ± 1.063	2.969 ± 0.478

Case	Fixed iterative reduction %	Reranked pool reduction %
S10 no high-SOC stress	10.142 ± 0.990	3.068 ± 0.513
S11 SOC gain 0.375	10.423 ± 1.048	2.977 ± 0.455
S12 SOC gain 1.125	10.969 ± 1.182	3.470 ± 0.581
S13 cycle coefficient x0.5	10.313 ± 1.138	3.470 ± 0.540
S14 cycle coefficient x2	10.924 ± 1.106	3.120 ± 0.478
S15 calendar coefficient x0.5	10.924 ± 1.106	3.120 ± 0.478
S16 calendar coefficient x2	10.313 ± 1.138	3.470 ± 0.540
S17 no temperature sensitivity	10.937 ± 1.048	3.616 ± 0.580