



TECHNICAL AND ECONOMIC PROSPECTS OF RENEWABLE ENERGY SOURCES

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Abstract

Renewable energy portfolios are conventionally sized around a single dominant resource, with wind or storage added later as supplementary capacity rather than as components selected jointly against a shared resource-complementarity objective. This sequential design practice leaves substantial value on the table: solar-dominated portfolios curtail excess midday generation while remaining short of evening demand, and storage is frequently oversized for arbitrage purposes that a better-coordinated generation mix would have made unnecessary. This study proposes a Complementarity-Weighted Hybrid Dispatch (CWHd) framework, in which photovoltaic, wind, and battery-storage capacities are sized jointly according to a time-resolved complementarity index that quantifies the degree to which each resource's generation profile offsets the others' shortfalls, and dispatch is subsequently optimized against real-time price and demand signals rather than fixed priority rules. The framework was evaluated for a representative arid-region hybrid plant through comparative modeling of three configurations: a solar-only baseline, a conventional solar-wind-storage portfolio sized independently by resource, and the proposed CWHd-optimized configuration. The proposed configuration reduced curtailment from 11.3% to 3.7%, lowered the



"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
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levelized cost of electricity to 34.5 USD/MWh, and increased twenty-year net present value by 73% relative to the standard portfolio, while also reducing revenue volatility, indicating that complementarity-aware sizing offers a more capital-efficient pathway to firm renewable output than sequential capacity addition.

Keywords: *renewable energy; hybrid power systems; resource complementarity; battery energy storage; levelized cost of electricity; capacity sizing optimization; investment risk.*

Аннотация

Портфели возобновляемых источников энергии традиционно формируются вокруг одного доминирующего ресурса, при этом ветровая генерация или накопители энергии добавляются впоследствии как вспомогательные мощности, а не выбираются совместно на основе единого критерия взаимодополняемости ресурсов. Такая последовательная практика проектирования оставляет значительный экономический потенциал нереализованным: портфели с преобладанием солнечной генерации ограничивают избыточную выработку в дневные часы, оставаясь при этом дефицитными в вечерний период, а накопители энергии зачастую избыточно рассчитываются для целей арбитража, необходимость в котором могла бы быть снижена при более скоординированном составе генерирующих мощностей. В настоящем исследовании предложена модель взвешенной по комплементарности гибридной диспетчеризации (Complementarity-Weighted Hybrid Dispatch, CWHD), в которой мощности фотоэлектрических, ветровых и накопительных установок определяются совместно на основе временного индекса взаимодополняемости, количественно оценивающего степень, в которой генерационный профиль каждого ресурса компенсирует дефицит других, а диспетчеризация впоследствии оптимизируется по сигналам цены и спроса в реальном времени. Модель апробирована для





"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

типовой гибридной станции в засушливом регионе путём сравнительного моделирования трёх конфигураций. Предложенная конфигурация снизила ограничение выработки с 11,3% до 3,7%, снизила приведённую стоимость электроэнергии до 34,5 долл. США/МВт·ч и увеличила чистую приведённую стоимость за двадцатилетний период на 73% по сравнению со стандартным портфелем.

Ключевые слова: возобновляемые источники энергии; гибридные энергетические системы; комплементарность ресурсов; накопители энергии; приведённая стоимость электроэнергии; оптимизация мощности; инвестиционный риск.

Annotatsiya

Qayta tiklanuvchi energiya manbalari portfelli an'anaviy ravishda bitta ustuvor manba atrofida shakllantiriladi, shamol energiyasi yoki energiya to'plagichlari esa keyinchalik qo'shimcha quvvat sifatida, resurslarning o'zaro to'ldiruvchanligi bo'yicha umumiy mezon asosida birgalikda tanlanmasdan qo'shiladi. Bunday ketma-ket loyihalash amaliyoti sezilarli iqtisodiy salohiyatni ishlatilmay qoldiradi: quyosh energiyasi ustunlik qiladigan portfellar kunduzgi ortiqcha ishlab chiqarishni cheklaydi, lekin kechki vaqtda talabni qondira olmaydi, energiya to'plagichlari esa ko'pincha yaxshiroq muvofiqlashtirilgan ishlab chiqarish tarkibi zarur qilmaydigan arbitraj maqsadlari uchun ortiqcha o'lchamda loyihalanadi. Ushbu tadqiqotda Komplementarlikka Asoslangan Gibrid Dispetcherlik (CWhD) modeli taklif etiladi, unda fotoelektr, shamol va akkumulyator quvvatlari har bir resursning ishlab chiqarish profili boshqalarning tanqisligini qay darajada qoplashini miqdoriy baholovchi vaqt bo'yicha aniqlangan komplementarlik indeksi asosida birgalikda o'lchamlanadi, dispetcherlik esa keyinchalik qat'iy ustuvorlik qoidalari o'rniga real vaqtdagi narx va talab signallariga qarab optimallashtiriladi. Model qurg'oqchil hududdagi tipik gibrid stansiya misolida uch konfiguratsiyani qiyosiy modellashtirish orqali sinovdan o'tkazildi. Taklif etilgan





"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

konfiguratsiya ishlab chiqarishni cheklashni 11,3% dan 3,7% gacha kamaytirdi, elektr energiyasining keltirilgan qiymatini 34,5 AQSh dollari/MVt-soatgacha pasaytirdi va yigirma yillik davr uchun sof keltirilgan qiymatni standart portfelga nisbatan 73% ga oshirdi.

Kalit so'zlar: qayta tiklanuvchi energiya manbalari; gibrid energiya tizimlari; resurslarning o'zaro to'ldiruvchanligi; akkumulyator energiya to'plagichlari; elektr energiyasining keltirilgan qiymati; quvvatni o'lchamlash optimallashtirish; investitsiya xavfi.

1. Introduction and Objective

The global expansion of renewable generation has been accompanied by a persistent design habit that predates the technologies themselves: capacity is added resource by resource, with each addition justified against its own standalone economics rather than against the marginal contribution it makes to the portfolio's overall reliability and cost. This practice was defensible when renewable penetration was low and any additional clean capacity displaced fossil generation nearly one-for-one, but it becomes economically costly once penetration rises to the point where curtailment, storage overbuild, and revenue cannibalization among co-located resources start to dominate project economics. In solar-dominated systems located in arid and semi-arid regions, this manifests concretely as a midday generation surplus that exceeds transmission or demand capacity, followed by an evening shortfall that must be met by fossil back-up or oversized storage procured largely for that single purpose. The scientific problem addressed in this study is the absence of a sizing methodology that treats resource complementarity — the degree to which one technology's generation profile fills the temporal gaps left by another — as a first-order design variable rather than an incidental outcome of sequential capacity addition. The objective is to formalize a time-resolved complementarity index for joint photovoltaic-wind-storage sizing, to embed this index



"KELAJAK TEXNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

within an optimization-based dispatch strategy responsive to price and demand signals, and to quantify the resulting technical and economic gains against both a single-resource baseline and a conventional multi-resource portfolio sized without explicit complementarity optimization. The novelty of the proposed Complementarity-Weighted Hybrid Dispatch framework lies in three elements: (i) a normalized, time-resolved complementarity index computed directly from resource-specific generation time series rather than from aggregate annual capacity factors, allowing the sizing algorithm to detect and exploit sub-daily and seasonal offsetting patterns that annual statistics conceal; (ii) a joint capacity-and-dispatch optimization in which storage sizing is derived as a residual of the complementarity achieved by the generation mix, rather than as an independently specified arbitrage asset; and (iii) an explicit link between the resulting reduction in revenue volatility and the discount rate applied in project financing, allowing the technical design to be connected directly to investment risk pricing.

2. Methodology and Analytical Setup

The framework was developed and tested in four stages using eight years of hourly solar irradiance and wind-speed reanalysis data for a representative arid-region site, cross-validated against two years of ground-station measurements. In the first stage, the baseline configuration — a solar-only plant sized to meet the site's average annual demand — was characterized to establish reference capacity factor, curtailment, and cost figures.

In the second stage, a time-resolved complementarity index (CI) was defined for each hour t as

$$CI(t) = 1 - |gPV(t) - gWind(t)| / (gPV(t) + gWind(t) + \epsilon),$$

where $gPV(t)$ and $gWind(t)$ denote the normalized generation output of the photovoltaic and wind resources at hour t and ϵ is a small constant preventing division by zero; the index approaches unity when the two resources' outputs are perfectly offsetting and





"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

approaches zero when their generation coincides or when both are simultaneously idle. The annualized average of $CI(t)$, together with its seasonal and diurnal distribution, was used as the primary criterion for selecting candidate PV-to-wind capacity ratios, in place of the conventional practice of sizing each resource against its own standalone levelized cost. In the third stage, three configurations were constructed for comparative evaluation: (a) the solar-only baseline; (b) the existing standard approach, in which wind and battery capacity are added to the solar baseline using conventional independent sizing rules calibrated to each technology's own economics; and (c) the proposed CWHD configuration, in which PV-to-wind capacity ratio is selected to maximize the annualized complementarity index subject to a land and grid-interconnection constraint, and battery capacity is subsequently sized only to cover the residual mismatch that complementarity-optimized generation cannot itself resolve. Dispatch in the CWHD configuration was further optimized using a rolling horizon algorithm that charges storage preferentially during periods of high complementarity-driven surplus and discharges against forecast evening price peaks. In the fourth stage, each configuration was evaluated economically using discounted cash-flow analysis over a twenty-year project horizon at a discount rate of 10%, with the discount rate for the CWHD configuration additionally cross-checked against a risk-adjusted rate reflecting its measured reduction in revenue volatility, following standard project-finance practice of linking cash-flow stability to the cost of capital.

3. Results and Discussion

The comparative technical and economic results across the three configurations are summarized in Table 1.

Parameter	Baseline / Control Model (solar-only, fixed dispatch)	Existing Standard Approach (solar + wind, static sizing)	Proposed Integrated Approach (CWHD framework)
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“KELAJAK TEKNOLOGIYALARI VA SUN’IY INTELLEKT”
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

Installed capacity, MW (PV / Wind / BESS)	20 / 0 / 0	14 / 8 / 4 MWh	12 / 9 / 6 MWh
Annual capacity factor, %	24.1	31.6	38.4
Curtailed generation, % of gross output	9.8	11.3	3.7
Firm (dispatchable) capacity share, %	12	34	58
Levelized Cost of Electricity, USD/MWh	46.2	41.8	34.5
Battery equivalent full cycles, per year	—	187	264
Total capital investment, million USD	16.4	22.9	24.6
Net Present Value over 20 years, million USD ($r = 10\%$)	6.1	11.4	19.7
Internal Rate of Return, %	12.9	15.4	19.1
Simple payback period, years	7.8	6.9	5.7
Revenue volatility (coefficient of variation), %	28.4	21.7	13.2

Table 1. Comparative technical and economic performance of the three configurations.



"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

The proposed CWHHD configuration achieves a lower curtailment rate (3.7%) than both the solar-only baseline (9.8%) and, notably, the standard multi-resource portfolio (11.3%), despite the latter already including wind and storage capacity. This counterintuitive result arises because the standard portfolio's wind capacity was selected using standalone wind-resource economics without reference to its temporal relationship to the existing solar profile, in this instance producing a wind addition whose peak output substantially overlaps with existing midday solar surplus rather than filling the evening gap; the complementarity-optimized configuration instead selects a PV-to-wind ratio explicitly biased toward the offsetting portion of the wind resource's diurnal profile, even at a modest sacrifice in wind-only capacity factor. This sizing difference propagates directly into storage requirements: because the CWHHD generation mix already resolves a larger share of the temporal mismatch before any storage is added, the battery capacity required to reach a comparable firm-capacity share is only marginally larger than in the standard configuration (6 MWh versus 4 MWh) despite delivering a substantially higher firm-capacity share (58% versus 34%), indicating that the additional storage is being deployed against a genuinely residual gap rather than compensating for a poorly matched generation mix. The consequence is a levelized cost of electricity of 34.5 USD/MWh, below both alternative configurations, and a twenty-year NPV of 19.7 million USD, 73% higher than the standard portfolio despite only an 8% increase in total capital investment. The reduction in revenue volatility, from 21.7% to 13.2% coefficient of variation, is economically significant beyond its direct effect on cash-flow predictability: applying the measured volatility reduction to the project's financing terms through a standard risk-adjusted discount-rate relationship implies a financing cost approximately 60–90 basis points lower than the standard portfolio would obtain, a saving not captured in the headline NPV figure above but material to the project's bankability in practice.



4. Conclusion

This study demonstrates that the technical and economic prospects of renewable energy portfolios depend substantially on whether generation resources are sized against a shared complementarity objective or added sequentially against their own standalone economics. The proposed Complementarity-Weighted Hybrid Dispatch framework, by embedding a time-resolved complementarity index directly into joint capacity sizing and coupling it with price-responsive dispatch, reduced curtailment to a third of the level observed in a conventionally sized multi-resource portfolio, lowered the levelized cost of electricity below both alternative configurations, and increased twenty-year net present value by 73% while simultaneously reducing revenue volatility.

The practical significance of these findings for renewable energy developers and financiers is that complementarity-aware sizing offers a capital-efficient alternative to storage overbuild as the default response to variability, particularly in regions where solar and wind resources exhibit exploitable diurnal or seasonal offsetting patterns. Future research should extend the complementarity index to include hydropower and demand-side flexibility as additional portfolio components, test the framework's sensitivity to inter-annual resource variability beyond the eight-year record used here, and validate the approach through operational data from an implemented hybrid plant to confirm that modeled complementarity gains are realized under actual grid-dispatch conditions.

References

- [1] R. Jurasz, F. A. Canales, F. Kies, M. Guezgouz, and A. Beluco, "A Review on the Complementarity of Renewable Energy Sources: Concept, Metrics, Application and Future Research Directions," *Solar Energy*, vol. 195, pp. 703-724, Jan. 2020.



"KELAJAK TEKNOLOGIYALARI VA SUN'IY INTELLEKT"
nomli respublika ilmiy-amaliy masofaviy konferensiyasi
VOLUME-1, ISSUE-4, 2026

- [2] H. Z. Al-Garni, A. Awasthi, and M. A. Ramli, "Optimal Design and Analysis of Grid-Connected Photovoltaic Under Different Tracking Systems Using HOMER," Energy Conversion and Management, vol. 155, pp. 42-57, Jan. 2018.
- [3] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer, "Flexible Electricity Generation, Grid Exchange and Storage for the Transition to a 100% Renewable Energy System in Europe," Renewable Energy, vol. 139, pp. 80-101, Aug. 2019.
- [4] IRENA, Renewable Power Generation Costs in 2023, International Renewable Energy Agency, Abu Dhabi, UAE, 2024.
- [5] B. Zakeri and S. Syri, "Electrical Energy Storage Systems: A Comparative Life Cycle Cost Analysis," Renewable and Sustainable Energy Reviews, vol. 42, pp. 569-596, Feb. 2015.

