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DIGITAL–PHYSICAL INTEGRATION AND ECONOMIC PERFORMANCE IN INDUSTRIAL INTEGRATED ENERGY SYSTEMS: A SCENARIO-BASED ANALYSIS OF SMART GRID CONTROL, BATTERY ENERGY STORAGE, AND DIGITAL TWINS

Abstract: To identify the independent and synergistic effects of digital capabilities and physical flexibility on the economic performance of industrial integrated energy systems, this study develops a representative electricity–heat–gas integrated energy system for Kazakhstan's oil and gas processing sector. Annual electricity and useful-heat demands are fixed at 100 GWh and 150 GWhth, respectively. On a common physical infrastructure, eight 2³ technology scenarios are constructed using smart-grid control (SG), a 4 MW/16 MWh battery energy storage system (BESS), and a digital twin (DT). The analysis combines 8,760-hour chronological dispatch, a 20-year incremental cash-flow assessment, Shapley value decomposition, sensitivity analysis, and Latin hypercube sampling to compare operating costs, peak grid purchases, renewable-energy curtailment, net present value (NPV), and marginal technology contributions. The results show that full integration under S7 reduces annual operating costs from USD 4.974 million to USD 4.189 million, generates annual savings of USD 785.0 thousand, and achieves the lowest grid-purchase peak and renewable-energy curtailment. However, its NPV of USD 2.251 million is lower than the USD 2.508 million achieved by S5, which combines smart-grid control and a digital twin. The annual Shapley contributions of SG, BESS, and DT are USD 281.0 thousand, USD 222.6 thousand, and USD 281.4 thousand, respectively, while synergy accounts for 25.2% of the total value of S7. Under the NPV criterion, the contribution of storage is negative, indicating that BESS can improve system operation without necessarily covering its capital and replacement costs. Sensitivity analysis shows that S7 outperforms S5 when battery costs decline by approximately 8.2%, electricity-price volatility increases by approximately 18.7%, renewable-energy scale increases by approximately 30.7%, or the real discount rate falls below approximately 6.7%. Accordingly, the study proposes a staged investment pathway in which forecasting and control capabilities are established first, followed by storage deployment once the relevant threshold conditions are met. The results represent a scenario simulation of a representative system under transparent assumptions rather than the observed performance of a specific firm.

Keywords: integrated energy system; smart grid; battery energy storage; digital twin; Shapley value; techno-economic assessment

1. Introduction

Integrated energy systems (IESs) coordinate electricity, heat, natural gas, renewable energy, storage, and flexible loads, thereby providing an important pathway for energy-intensive industries to reduce costs, improve reliability, and advance low-carbon transformation. As wind

power, photovoltaics, combined heat and power (CHP), and multiple load categories are connected simultaneously, system economic performance increasingly depends on hourly supply–demand matching, equipment condition, and forecast quality rather than installed capacity alone. Smart-grid control provides metering, communication, demand response, and equipment coordination; battery energy storage provides intertemporal energy shifting and rapid reserve; and digital twins connect operating data, equipment models, and forecasting algorithms to support load forecasting, fault identification, and predictive maintenance. These three technologies represent information connectivity, physical flexibility, and forward-looking decision capability, respectively, and their joint value may exceed the simple sum of their stand-alone benefits.

Global battery-storage costs have declined substantially. IRENA reports that the total installed cost of utility-scale BESS fell from USD 2,571/kWh in 2010 to USD 192/kWh in 2024; the IEA further reports that global additions of battery-storage capacity reached 108 GW in 2025, approximately 40% higher than in 2024. Nevertheless, cost reductions do not imply that all industrial users can achieve a positive NPV. Storage revenues remain constrained by peak–off-peak price spreads, maximum-demand charges, curtailment levels, degradation, and replacement costs. Compared with storage, smart control and digital twins can simultaneously affect electricity purchases, fuel consumption, equipment efficiency, forecast deviations, and unplanned outages, but their economic benefits must also cover software, sensors, data governance, and maintenance expenditures.

Kazakhstan provides a representative context for examining this issue. In 2024, the country generated 117.915 TWh of electricity and consumed 119.996 TWh, while renewable generation was approximately 7.56 TWh, or 6.4% of total generation. The national energy balance shows that oil and petroleum products, natural gas, heat, and electricity accounted for 32.9%, 21.1%, 16.9%, and 16.4% of final energy consumption, respectively. Continuous processing industries such as oil and gas processing must therefore improve energy utilization and digital operations while maintaining electricity and heat supply and production continuity.

The existing literature has three limitations. First, smart grids, storage, and digital twins are usually evaluated separately, with limited use of complete three-factor scenarios. Second, short-term operating-cost optimisation is rarely translated into NPV, internal rate of return (IRR), and investment sequencing. Third, the value of technology combinations is often not allocated fairly, making it difficult to distinguish stand-alone technology values from synergistic value. This study develops eight strictly comparable scenarios for a representative industrial IES and links hourly operation, life-cycle investment assessment, Shapley decomposition, and uncertainty analysis. It focuses on four questions: through which mechanisms do the three technologies create value; does joint deployment generate synergy; is the operating optimum also the financial optimum; and what staged investment sequence should firms adopt?

2. Literature Review and Research Positioning

Research on smart grids and integrated demand response shows that advanced metering, dynamic pricing, and cross-energy coordination can transform part of an industrial load into a dispatchable resource. Jiang et al. (2024) systematically reviewed load reduction and shifting, energy substitution, contractual response, and market interaction mechanisms; Wu et al. (2024) further connected capacity configuration, demand response, and predictive control. However, these studies generally focus on representative days or short-term operating costs and pay insufficient attention to the life-cycle returns of digital infrastructure.

Energy-storage research has gradually expanded from stand-alone arbitrage to value stacking that includes peak shaving, renewable-energy integration, reserve provision, and ancillary services. Goulart et al. (2024) emphasised the importance of function stacking for the economics of customer-side BESS, while Koubar et al. (2025) showed that market prices and service portfolios can substantially change storage payback periods. A techno-economic assessment of storage must incorporate charging costs, efficiency, degradation, calendar life, and mid-life replacement; otherwise, investment value may be overstated. Existing studies still rarely compare the marginal value of storage across different levels of digital maturity.

Digital-twin research has moved from equipment visualisation towards forecasting, scenario testing, and closed-loop optimisation. do Amaral et al. (2023) noted that energy digital twins can span production, storage, transmission, distribution, and consumption. Aguilera et al. (2024) combined online-calibrated models, demand forecasting, and MILP-based scheduling, demonstrating that economic benefits depend on forecast accuracy and equipment degradation. Nevertheless, enterprise-level assessments still lack a unified treatment of digital-twin capital costs, maintenance expenditure, and avoided outage losses.

This study positions SG, BESS, and DT within the same representative industrial IES, uses a 2^3 full-factorial scenario design to identify stand-alone and combined values, and applies the Shapley value to allocate average marginal contributions. Unlike causal empirical research, this is a techno-economic scenario analysis based on transparent parameters. Its contribution is to identify mechanisms, investment boundaries, and technology sequencing rather than estimate an average treatment effect for all firms in Kazakhstan.

3. Research Design and Methods

3.1. System Boundary, Data, and Core Assumptions

The study object is a representative industrial IES for Kazakhstan's oil and gas processing sector. The base year is 2024, the project operates for 20 years, and all monetary values are expressed in constant 2024 USD. Annual electricity demand is fixed at 100 GWh and annual useful-heat demand at 150 GWhth. The model uses standardised industrial hourly load and weather series and does not simulate changes in product output. The system includes the public grid, gas-fired CHP, a gas boiler, waste-heat recovery, 12 MW of photovoltaic capacity, 12 MW of wind capacity, and an optional 4 MW/16 MWh BESS. Net electricity exports and external heat sales are not permitted; thermal storage is excluded; and carbon pricing, green certificates, firm-specific subsidies, and product revenues are not included.

National electricity generation, consumption, and energy-structure data are drawn from official Kazakhstan statistics and KEGOC. Technology-cost ranges are based on DOE, IRENA, and peer-reviewed studies. Because firm-level contracts and SCADA data are unavailable, electricity prices, natural-gas prices, capacity charges, forecast deviations, and outage losses are represented by reproducible baseline scenario parameters.

Table 1. Core parameters and evaluation boundary of the representative system

Parameter	Baseline value	Unit	Description
Annual electricity/useful-heat demand	100 / 150	GWh / GWhth	Fixed in all scenarios
PV/wind capacity	12 / 12	MW	Capacity factors: 18% / 35%
CHP electricity/heat capacity	5.09 / 6.50	MW / MWth	Electrical efficiency: 36%; thermal efficiency: 46%
Boiler/waste-heat-recovery capacity	18.0 / 2.4	MWth	Boiler efficiency: 90%
BESS	4 / 16	MW / MWh	Activated only in S2, S4, S6, and S7
Average grid energy price	48	USD/MWh	Calibrated scenario parameter
Maximum-demand/capacity charge	30,000	USD/(MW·year)	Calibrated scenario parameter
Natural-gas price	18	USD/MWhLHV	Calibrated scenario parameter
Baseline imbalance/reliability cost	270 / 220	thousand USD/year	Expected annual loss parameters
Project life/real discount rate	20 / 8%	years / %	General inflation excluded

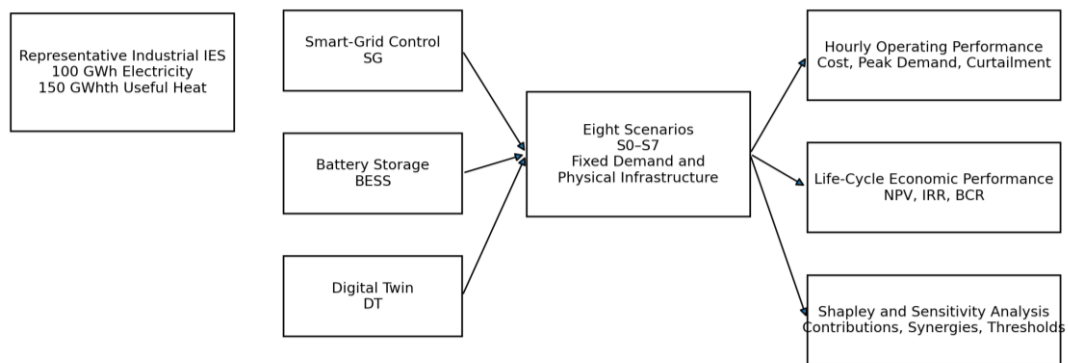


Figure 1. Research framework and 2³ technology scenarios

3.2. Technology Scenarios

All scenarios use the same demand, weather, basic equipment capacities, and price series; only the availability of SG, BESS, and DT changes. S0 is not an unoptimised legacy plant but an “optimised physical baseline” without the three additional technologies, ensuring that all scenarios are comparable under the same dispatch boundary. SG enables intraday demand response, peak management, and real-time coordination; BESS provides charging, discharging, peak shaving, and reserve; and DT affects operation by reducing forecast errors, improving equipment availability and efficiency, and reducing unplanned outages.

Table 2. Eight technology scenarios for SG, BESS, and DT

Scenario	SG	BESS	DT	Principal capability
S0	0	0	0	No additional digital–physical technologies
S1	1	0	0	Demand response and coordinated control
S2	0	1	0	Stand-alone storage dispatch
S3	0	0	1	Forecasting, diagnosis, and maintenance optimisation
S4	1	1	0	Control plus physical flexibility
S5	1	0	1	Forecasting plus control
S6	0	1	1	Forecasting plus storage
S7	1	1	1	Forecast–control–execution closed loop

3.3. Hourly Operation and Economic Assessment

The model minimises annual operating costs, including electricity purchases, natural gas, operation and maintenance of basic equipment, demand-response compensation, storage degradation, digital-platform operation and maintenance, forecast-imbalance costs, and reliability losses. Electricity and heat balances are satisfied in every hour, subject to CHP and boiler output limits, renewable-energy availability, BESS state-of-charge constraints, mutually exclusive charging and discharging, and energy neutrality for demand response.

$$\min C_s^{op} = \sum_t (C_t^{grid} + C_t^{gas} + C_t^{OM} + C_t^{DR} + C_t^{deg} + C_t^{imb} + C_t^{out}) + C_s^{fix} \quad (1)$$

$$P_t^{grid} + P_t^{CHP} + P_t^{PV} + P_t^{WT} + P_t^{dis} = L_t^e + D_t^{up} - D_t^{down} + P_t^{ch} \quad (2)$$

$$Q_t^{CHP} + Q_t^{boiler} + Q_t^{WHR} = L_t^h \quad (3)$$

$$E_t = (1 - \lambda)E_{t-1} + \eta_{ch}P_t^{ch} - P_t^{dis}/\eta_{dis} \quad (4)$$

DT does not enter the objective function through a uniform “energy-saving rate”; instead, it modifies forecast errors, equipment availability, and efficiency parameters. In the baseline calibration, DT increases CHP and boiler efficiency by 1.5% and 1.0%, respectively, on a relative basis and reduces expected imbalance and reliability losses. SG and BESS absorb temporal deviations through flexible-load and state-of-charge constraints. These improvement rates are varied in the sensitivity analysis.

Annual cost savings are defined as $AS_s = C_o^{op} - C_s^{op}$. The investment assessment uses 20-year incremental cash flows and includes initial investment, a digital-platform upgrade in Year 10, battery replacement in Year 12, and terminal residual value.

$$NPV_s = -I_{s,0} + \sum_{y=1}^{20} \frac{AS_s - I_{s,y}^{rep}}{(1+r)^y} + \frac{SV_s}{(1+r)^{20}} \quad (5)$$

Table 3. Scenario cash-flow assumptions (million constant 2024 USD)

Scenario	Initial investment	Annual net savings	Mid-life upgrade/replacement	Residual value	Principal assets
S1	1.05	0.2046	Year 10: 0.15	0.030	SG
S2	3.20	0.1533	Year 12: 1.12	0.320	BESS
S3	1.30	0.2294	Year 10: 0.20	0.040	DT
S4	3.85	0.4450	Year 10: 0.12; Year 12: 0.98	0.121	SG+BESS
S5	2.15	0.4865	Year 10: 0.28	0.050	SG+DT
S6	4.25	0.4210	Year 10: 0.18; Year 12: 1.02	0.121	BESS+DT
S7	5.00	0.7850	Year 10: 0.28; Year 12: 0.92	0.180	SG+BESS+DT

3.4. Shapley Decomposition and Uncertainty Analysis

SG, BESS, and DT are treated as players in a cooperative game, and the annual savings or incremental NPV of each scenario relative to S0 is used as the coalition value. The Shapley value of technology i is the weighted average of its marginal contribution when added to every possible coalition:

$$\phi_i(v) = \sum_{A \subseteq N \setminus \{i\}} \frac{|A|!(n-|A|-1)!}{n!} [v(A \cup \{i\}) - v(A)] \quad (6)$$

The one-factor analysis varies battery cost, electricity-price volatility, renewable-energy scale, load flexibility, DT cost, outage loss, and the discount rate. The two-dimensional scenarios focus on battery cost–electricity-price volatility, outage loss–DT cost, and load flexibility–electricity-price volatility. Joint uncertainty is evaluated using 300 Latin hypercube samples drawn from independent triangular distributions.

4. Results

4.1. Baseline Operating Performance

S0 satisfies annual electricity demand of 100 GWh and useful-heat demand of 150 GWhth without electricity or heat load shedding. The 12 MW PV and 12 MW wind installations provide 55.71 GWh of available generation, of which 55.28 GWh is utilised and 0.432 GWh is curtailed. CHP supplies 36.32 GWh of electricity, while 8.399 GWh is purchased from the public grid. Heat demand is supplied by 19.34 GWhth of waste-heat recovery, 46.41 GWhth of CHP heat, and 84.25 GWhth of gas-boiler heat.

The annual operating cost of S0 is USD 4.974 million. Natural-gas purchases account for USD 3.501 million, or 70.4% of the total. Grid-energy and capacity charges total USD 0.585 million, operation and maintenance of basic equipment amounts to USD 0.398 million, and imbalance and reliability losses total USD 0.490 million. The maximum grid-purchase power is 6.059 MW. This cost structure indicates that the value of digital technologies arises not only from electricity savings but also from fuel efficiency, reduced forecast deviations, and equipment reliability.

4.2. Operating and Investment Performance of the Technology Scenarios

Table 4. Core operating and investment results for S0–S7 (cost and NPV: million USD; savings: thousand USD/year; peak: MW; curtailment and natural gas: GWh)

Scenario	Annual cost	Annual savings	Grid-purchase peak	Curtailment	Natural gas	NPV	Investment assessment
S0	4.974	0.0	6.059	0.432	194.50	0.000	Baseline
S1	4.769	204.6	5.912	0.253	193.52	0.896	Marginally viable
S2	4.821	153.3	3.374	0.108	194.50	−2.071	Not viable under baseline conditions
S3	4.745	229.4	6.059	0.432	192.08	0.868	Marginally viable
S4	4.529	445.0	2.845	0.020	193.18	0.100	Marginally viable
S5	4.487	486.5	5.802	0.185	190.92	2.508	Strongly viable
S6	4.553	421.0	3.102	0.041	192.08	−0.579	Not viable under baseline conditions
S7	4.189	785.0	2.520	0.005	189.75	2.251	Strongly viable

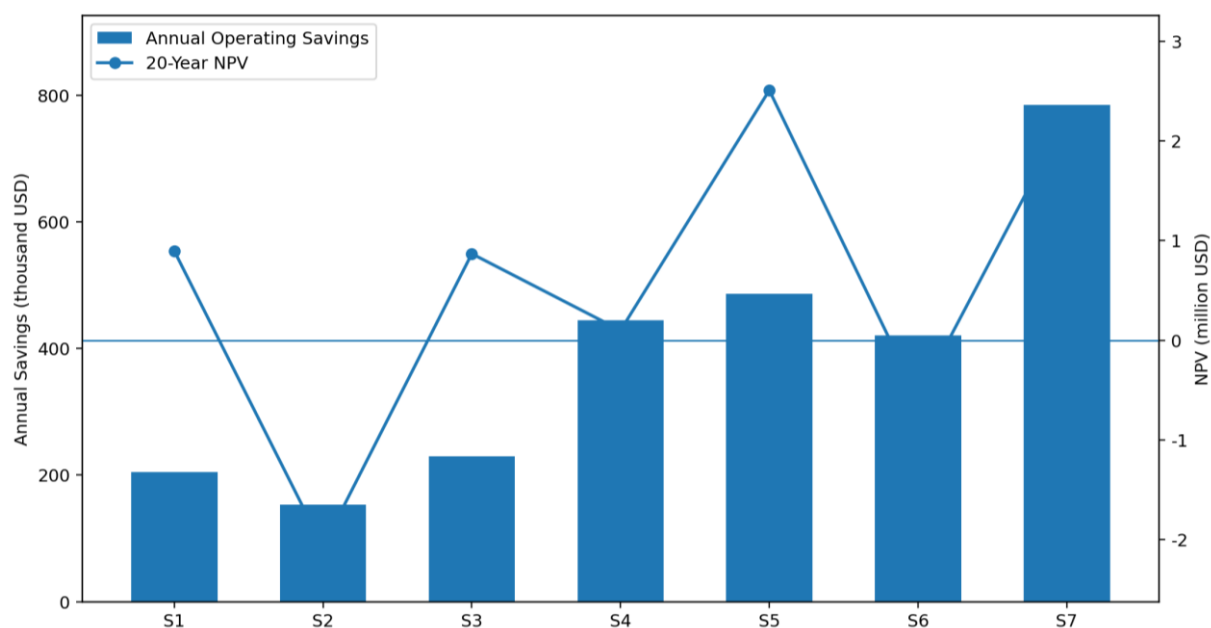


Figure 2. Annual operating value and life-cycle investment value of S1–S7

Among the stand-alone technologies, S3 produces the largest annual savings (USD 229.4 thousand), followed by S1 (USD 204.6 thousand) and S2 (USD 153.3 thousand). S1 mainly reduces imbalance and management costs, while S3 primarily lowers fuel use, outage losses, and maintenance costs. S2 reduces the grid-purchase peak from 6.059 MW to 3.374 MW and

lowers curtailment, but its stand-alone NPV is –USD 2.071 million. This result shows that physical flexibility has operating value but remains constrained by battery capital and replacement costs.

All pairwise combinations generate positive operating synergies. S4 has the strongest pairwise interaction benefit, USD 87.1 thousand/year, but its NPV is only USD 0.100 million, indicating a narrow safety margin. S5 generates annual savings of USD 486.5 thousand and an NPV of USD 2.508 million, making it the financially most valuable option under baseline conditions. S6 improves peak demand, forecasting, and reliability, but its NPV remains –USD 0.579 million.

S7 achieves the lowest annual operating cost, USD 4.189 million, which is 15.8% below S0. It reduces the maximum grid-purchase power to 2.520 MW and curtailment to 0.005 GWh and generates annual savings of USD 785.0 thousand. Its NPV is USD 2.251 million, its IRR is 13.8%, and its BCR is 1.41, indicating that the integrated project is economically viable. However, its NPV remains below that of S5. The incremental NPV of adding storage to S5 to form S7 is approximately –USD 0.257 million, demonstrating that the operating optimum is not necessarily the optimal capital-allocation decision.

Table 5. Twenty-year financial performance of the technology scenarios

Scenario	Initial investment	NPV	IRR	BCR	Discounted payback period	Principal conclusion
S1	1.05	0.896	18.3%	1.80	6.87 years	Low capital intensity and relatively rapid payback
S2	3.20	–2.071	–2.9%	0.43	Not recovered within 20 years	Stand-alone storage is not viable
S3	1.30	0.868	16.2%	1.62	7.85 years	Substantial reliability value
S4	3.85	0.100	8.4%	1.02	19.17 years	Near break-even
S5	2.15	2.508	21.8%	2.10	5.68 years	Highest NPV
S6	4.25	–0.579	6.0%	0.88	Not recovered within 20 years	Still constrained by storage costs
S7	5.00	2.251	13.8%	1.41	9.41 years	Operating optimum and overall viability

4.3. Shapley Value and Synergy

The Shapley decomposition of annual coalition value satisfies the efficiency property: the contributions of smart-grid control, battery storage, and the digital twin are USD 281.0 thousand/year, USD 222.6 thousand/year, and USD 281.4 thousand/year, respectively, summing to USD 785.0 thousand/year. The three stand-alone values total USD 587.3 thousand/year, while synergy is USD 197.7 thousand/year, accounting for 25.2% of the total value of S7. The SG–BESS, SG–DT, and BESS–DT synergies are USD 87.1 thousand/year, USD 52.5 thousand/year, and USD 38.3 thousand/year, respectively, and the higher-order three-way synergy is USD 19.8 thousand/year.

Under the NPV criterion, the Shapley contributions of SG, BESS, and DT are USD 1.877 million, –USD 1.150 million, and USD 1.524 million, respectively, summing to USD 2.251 million. The positive annual contribution but negative NPV contribution of storage reveals the coexistence of operating flexibility and a substantial capital burden. SG and DT make positive contributions under both the operating-value and investment-value criteria.

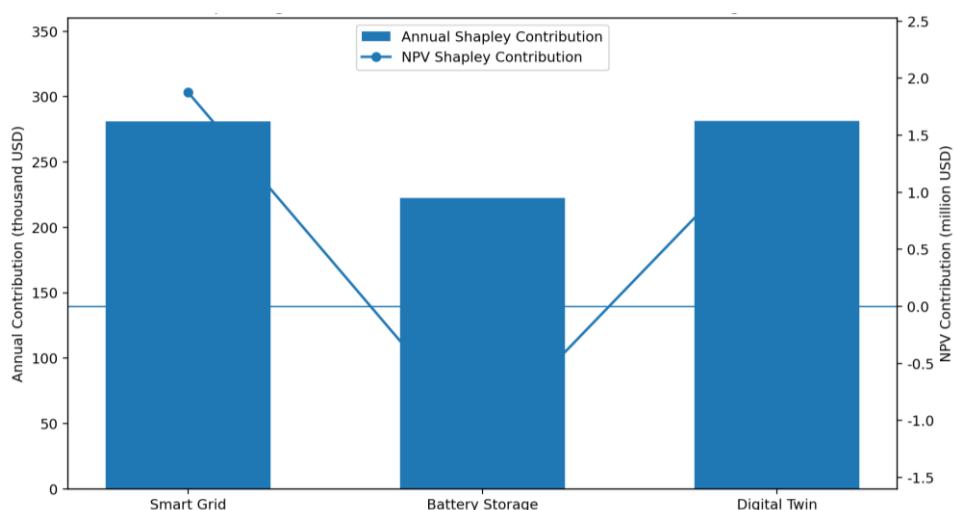


Figure 3. Annual operating contributions and life-cycle investment contributions of the three technologies

Table 6. Shapley contributions and synergistic value (annual value: thousand USD/year; NPV: million USD)

Technology/synergy	Annual value	Share of S7 value	NPV Shapley contribution	Interpretation
Smart-grid control	281.0	35.8%	1.877	High capital efficiency of control and demand response
Battery energy storage	222.6	28.4%	–1.150	Positive operating value but high capital cost
Digital twin	281.4	35.8%	1.524	Forecasting, efficiency, and reliability benefits

Technology/synergy	Annual value	Share of S7 value	NPV Shapley contribution	Interpretation
Total synergy	197.7	25.2%	—	Digital capabilities increase the value of physical flexibility

4.4. Sensitivity and Uncertainty

Under baseline conditions, S5 has the highest NPV, whereas S7 has the lowest operating cost. Threshold analysis shows that the NPV of S7 exceeds that of S5 when battery investment and replacement costs decline by approximately 8.2%, electricity-price volatility increases by approximately 18.7%, renewable-energy scale increases by approximately 30.7%, or the real discount rate falls below approximately 6.7%. By contrast, stand-alone storage under S2 requires a battery-cost reduction of approximately 57.9% to achieve an NPV of zero, indicating that digital control and forecasting capabilities substantially lower the economic threshold for storage.

Across 300 Latin hypercube samples, the probabilities of positive NPV are 100.0% for S5 and 99.7% for S7. S5 has the highest NPV in 57.3% of the samples, while S7 ranks first in 42.7%. The probabilities of positive NPV are 67.3% for S4 and 29.3% for S6, whereas S2 does not achieve a positive NPV in any sample. Joint uncertainty therefore supports a strategy of prioritising digital infrastructure and upgrading to storage conditionally.

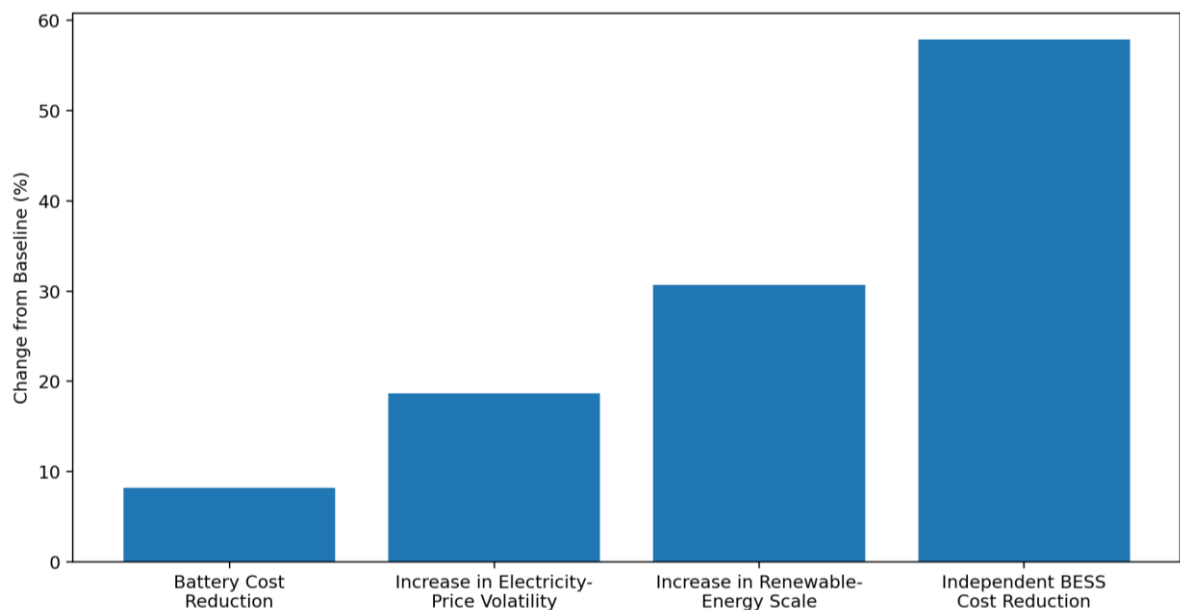


Figure 4. Key thresholds that change the investment ranking

Table 7. Key economic thresholds and investment implications

Decision question	Threshold condition	Baseline interpretation	Managerial implication
S7 exceeds S5	Battery cost decreases by 8.2%	Incremental NPV of storage becomes positive	Continuously update battery quotations and replacement costs
S7 exceeds S5	Electricity-price volatility increases by 18.7%	Arbitrage, peak-shaving, and balancing value increase	Monitor contractual price spreads and capacity charges
S7 exceeds S5	Renewable-energy scale increases by 30.7%	Temporal mismatch and curtailment value increase	Coordinate storage planning with additional wind and PV
S7 exceeds S5	Discount rate falls below 6.7%	Present value of long-term savings increases	Pursue low-cost green financing
S2 stand-alone BESS reaches NPV = 0	Battery cost decreases by 57.9%	Stand-alone arbitrage cannot cover capital costs	Avoid procuring storage independently of digital infrastructure

5. Discussion

5.1. Why the Operating Optimum Differs from the Investment Optimum

The fact that S7 has the best operating performance while S5 has the highest NPV is the central finding of this study. Hourly dispatch analysis asks how existing assets can be operated at minimum cost, whereas NPV analysis asks whether additional assets can cover initial investment, mid-life replacement, and the opportunity cost of capital. Compared with S5, S7 generates approximately USD 298.5 thousand in additional annual savings but requires USD 2.85 million in additional initial investment and battery replacement in Year 12. At an 8% discount rate, these incremental savings do not produce a positive incremental NPV.

5.2. Why Digital Infrastructure Increases the Value of Storage

The substantially negative NPV of stand-alone storage under S2, the near-break-even result for S4, and the overall viability of S7 show that storage value depends on system observability, predictability, and controllability. SG coordinates price signals and loads, allowing the battery to operate during high-value periods. DT reduces forecast deviations and unnecessary reserve occupancy, enabling more effective use of limited power and energy capacity. The SG–BESS synergy is the strongest pairwise synergy and supports an investment sequence in which digital infrastructure is established before physical flexibility is deployed.

5.3. Theoretical and Methodological Contributions

This study integrates digital capability and physical flexibility within a single techno-economic framework. The 2³ scenario design avoids the attribution problem created when only a baseline and a fully integrated scenario are compared. The Shapley decomposition further shows that approximately one quarter of the annual value of S7 arises from synergy. The dual decomposition of annual value and NPV also reveals that a technology can make a substantial operating contribution while generating a negative investment contribution because of capital costs. This result extends the concept of “flexibility value” in multi-energy-system research by incorporating both functional value and capital efficiency.

5.4. External Applicability and Research Limitations

The study uses a representative system and standardised hourly series and is therefore neither a firm-level empirical analysis nor a causal identification exercise. Electricity prices, outage losses, and digital-technology improvement rates are scenario parameters. BESS capacity is fixed at 4 MW/16 MWh rather than optimised endogenously. Net electricity exports, ancillary-service revenues, thermal storage, carbon pricing, taxation, and firm-specific subsidies are excluded. The sensitivity analysis uses independent triangular distributions and cannot be interpreted as an objective probability forecast of future markets.

6. Conclusions and Managerial Implications

This study compares the stand-alone, pairwise, and fully integrated values of smart-grid control, BESS, and digital twins in a representative industrial IES. The results show that the S5 combination of smart-grid control and a digital twin has the highest NPV under baseline conditions, while S7 full integration achieves the lowest annual operating cost and the best performance in peak demand, curtailment, and reliability. Storage consistently creates operating flexibility, but its stand-alone and average NPV contributions remain constrained by capital and replacement costs. Digital–physical synergy accounts for 25.2% of the annual value of full integration, indicating that stand-alone asset assessments underestimate the value of joint deployment.

Firms should adopt a staged pathway. First, they should establish unified metering, data governance, and an energy baseline. Second, smart-grid control and an energy management system should be deployed to enable demand response and multi-equipment coordination. Third, digital twins should be applied to load forecasting, equipment-condition identification, and predictive maintenance. Fourth, battery costs, electricity-price volatility, renewable-energy scale, and financing costs should be monitored continuously, and storage should be installed or expanded only after its incremental NPV becomes positive. Operating departments should use peak demand, curtailment, imbalance, and reliability KPIs to assess technical functionality, whereas investment departments should use incremental NPV, IRR, and BCR to make capital-budgeting decisions.

For Kazakhstan's oil and gas processing sector, the primary question in digital transformation is not whether all technologies should be adopted simultaneously, but how information and decision capabilities can first be established at the lowest capital cost and physical flexibility subsequently added according to observable market and operating thresholds. This pathway balances near-term economic returns with the option to upgrade towards a complete digital–physical closed loop in the future.

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МАЗМҰНЫ – СОДЕРЖАНИЕ – CONTENT

ӘЛЕУМЕТТІК-ЭКОНОМИКАЛЫҚ ЖӘНЕ ҚҰҚЫҚ ҒЫЛЫМДАРЫ - СОЦИАЛЬНО-ЭКОНОМИЧЕСКИЕ И ЮРИДИЧЕСКИЕ НАУКИ - SOCIO-ECONOMIC AND LEGAL SCIENCES

Төлегенов Тимур Сейфуллаулы

**ДИНАМИКА ТУРИСТСКИХ ПОТОКОВ И ЭФФЕКТИВНОСТЬ ИНФРАСТРУКТУРЫ
ТУРКЕСТАНА: ОТ ЭКСТЕНСИВНОГО РОСТА К СМАРТ-УПРАВЛЕНИЮ 10**

Alexander Gorevoy

**WHICH INEQUALITY STATISTICS SURVIVE AN ADMINISTRATIVE BOUNDARY CHANGE?
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