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Cooperative Energy Optimization Between Residential Communities and Industrial Ports Under Carbon Emission Constraints

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Abstract

Energy cooperation between residential communities and industrial ports offers opportunities to enhance renewable energy utilization, improve electricity affordability, and facilitate compliance with carbon emission regulations. However, energy management in these sectors is typically optimized independently, limiting opportunities for coordinated resource allocation and electricity exchange. This study proposed the Multi-Agent Energy Sharing and Emission-Constrained Optimization (MESECO) framework, a deterministic mixed-integer optimization model that coordinated rooftop photovoltaic (PV) systems, wind power generation, battery energy storage systems, grid electricity purchases, and bidirectional electricity trading under real-time electricity pricing and port-specific carbon emission constraints. The reference case integrated a residential community and Tanjung Perak Port in Surabaya, Indonesia, using representative electricity demand and renewable energy resource profiles. Four electricity pricing and trading scenarios were evaluated, alongside sensitivity analyses. The scenario incorporating real-time pricing for both grid electricity procurement and inter-agent electricity exchange (Case 2) achieved the lowest combined annual operating cost, with community and port costs of USD 764,728.00 and USD 153,323.95, respectively. In contrast, fixed inter-agent electricity pricing (Case 3) generated net annual revenue of USD 120,564.18 for the port but increased community electricity expenditure to USD 1,038,616.13, highlighting potential inequalities in the distribution of economic benefits. Under the modeled conditions, approximately 54% community PV adoption enabled electricity self-sufficiency, while approximately 74% supported consistent monthly electricity exports. When carbon emission costs were incorporated, an inter-agent electricity tariff of approximately USD 0.084/kWh provided a balance between community affordability and port financial viability. The findings demonstrated that electricity pricing mechanisms, energy storage deployment, renewable energy penetration, and asymmetric carbon regulations substantially influenced the economic and operational performance of integrated community–port energy systems. The proposed MESECO framework provided a quantitative basis for evaluating cooperative energy management strategies under carbon emission constraints. Nevertheless, these findings were derived from model-based scenario analyses and required further validation using operational data before practical implementation.

INTRODUCTION

The transition toward sustainable energy systems has intensified interest in decentralized and locally managed renewable energy systems, particularly in energy-intensive coastal regions (Beşchea et al., 2026; Hasnat, 2025). These regions face increasing electricity demand and

climate-related risks while possessing substantial solar and wind energy potential (Buonomano et al., 2024; Ismail et al., 2024). However, ports and surrounding residential communities have historically relied on centralized electricity systems largely dependent on fossil fuels (Schulz et al., 2025). This dependence is particularly significant in the maritime sector, where international shipping contributes approximately 800–850 million metric tons of CO_2 emissions annually, representing approximately 2.3% of global anthropogenic CO_2 emissions (Wang et al., 2023; Zhang et al., 2024).

Integrated energy management has consequently emerged as a promising strategy for reducing operating costs, strengthening energy resilience, and mitigating greenhouse gas emissions. Incorporating renewable energy sources, particularly solar photovoltaic (PV) and wind power generation, can reduce dependence on fossil fuels while minimizing associated environmental impacts (Buonomano et al., 2024; Elkafas & Seddiek, 2024; Sun et al., 2025). Nevertheless, existing port energy management strategies predominantly focus on infrastructure and operations within port boundaries, with limited consideration of neighboring residential communities as active participants in energy generation, consumption, and exchange. Although ports and surrounding communities may share geographical proximity, electricity distribution infrastructure, and access to renewable energy resources, their energy systems are generally planned and operated independently. This fragmented approach restricts opportunities for coordinated renewable energy utilization, energy storage management, demand balancing, and bidirectional electricity trading.

Previous studies have proposed various optimization approaches for port and community energy systems. Port-oriented research has employed mixed-integer linear programming (MILP) for optimal energy dispatch and system component sizing (Ma et al., 2025; Zhang et al., 2023), stochastic optimization to account for renewable generation uncertainty (Ge et al., 2025; Guo et al., 2025), and scenario-based optimization models to support energy investment planning (Agrell et al., 2025; Li et al., 2024). At the residential community level, research has increasingly emphasized decentralized energy management through multi-agent systems, peer-to-peer (P2P) electricity trading, and cooperative control strategies (Mahuze et al., 2025; Mussawar et al., 2024; Tarhan, 2025). Dynamic electricity pricing, battery energy storage management, and demand response mechanisms have also been investigated to enhance energy self-sufficiency and economic efficiency (Chang et al., 2022; Dorahaki et al., 2025; Luo & Gao, 2025). Despite these developments, research on port energy systems and residential community energy management has largely progressed independently, leaving opportunities for cross-sectoral energy cooperation insufficiently explored.

An additional challenge arises from the growing influence of carbon emission regulations on port energy management decisions. Regulatory mechanisms such as the European Union Emissions Trading System (EU ETS) establish emissions allowance obligations for covered activities, requiring regulated entities to surrender sufficient allowances for verified emissions and imposing penalties for noncompliance (Kotzampasakis, 2025; Lagouvardou & Psaraftis, 2022). These carbon compliance obligations can influence electricity procurement strategies, renewable energy investment, and operational scheduling. However, carbon pricing and emissions trading mechanisms remain insufficiently integrated into port energy optimization frameworks, particularly when considered alongside real-time electricity pricing, variable renewable generation, and fluctuations in grid electricity conditions (Kim & Junghans, 2022; Luo & Gao, 2025). Furthermore, differences in regulatory obligations between industrial ports and

residential communities introduce additional complexities when coordinating electricity exchanges and allocating the economic benefits of cooperative energy management.

Accordingly, three principal research gaps were identified. First, existing optimization frameworks generally modeled port and residential energy systems independently, limiting the assessment of coordinated energy scheduling, resource sharing, and bidirectional electricity trading. Second, relatively few studies explicitly incorporated carbon emission limits, allowance procurement, and noncompliance penalties into integrated energy optimization models. Third, multi-agent energy management research predominantly examined relatively homogeneous participants, such as residential prosumers and interconnected microgrids, whereas cooperation between heterogeneous industrial and residential agents operating under different technical, economic, and regulatory conditions remained insufficiently investigated. These limitations highlighted the need for a regulation-aware energy optimization framework capable of representing heterogeneous electricity demand profiles, renewable generation capacities, energy storage characteristics, operational objectives, and carbon compliance obligations within a unified system. Such a framework could provide practical value for port authorities, energy planners, and policymakers by facilitating systematic evaluations of trade-offs among renewable energy deployment, electricity procurement, local energy trading, storage utilization, and carbon compliance costs. An integrated port–community energy management framework could therefore function as both an analytical optimization model and a decision-support tool for assessing alternative operational strategies and regulatory scenarios.

To address these limitations, this study proposed the Multi-Agent Energy Sharing and Emission-Constrained Optimization (MESECO) framework, which integrated a residential community and an industrial port within a coordinated energy management system. The proposed framework combined decentralized renewable electricity generation, bidirectional inter-agent electricity trading, coordinated battery energy storage operation, real-time electricity pricing, and asymmetric carbon emission constraints. Unlike conventional optimization approaches that treated ports and residential communities as independent energy systems, MESECO represented both agents within a unified deterministic mixed-integer optimization framework. The model explicitly incorporated port-specific carbon emission limits, emissions allowance procurement, and associated noncompliance penalties as modeled regulatory and economic constraints. This formulation enabled the simultaneous evaluation of cooperative electricity exchanges, operational costs, renewable energy utilization, and carbon compliance requirements under different electricity pricing and trading arrangements.

The study aimed to develop and evaluate a coordinated low-carbon energy management framework that captured interactions between residential communities and industrial ports with distinct electricity demand characteristics, renewable generation capacities, storage resources, and regulatory obligations. Specifically, the proposed model integrated carbon emission constraints, real-time electricity pricing, renewable electricity generation, battery energy storage dynamics, grid electricity procurement, and bidirectional inter-agent trading to investigate the potential of cooperative energy management to improve economic efficiency, energy self-sufficiency, and carbon compliance. The study contributed to the existing literature by extending multi-agent energy optimization to heterogeneous residential and industrial participants operating under asymmetric regulatory conditions. It also provided an analytical basis for examining interactions among carbon pricing, electricity tariff structures, renewable energy

penetration, energy storage coordination, and local electricity exchange. From a practical perspective, the framework could assist residential communities in enhancing energy autonomy, support industrial ports in reducing operating and carbon compliance costs, and provide policymakers with a quantitative decision-support approach for evaluating cooperative low-carbon energy strategies in coastal and semi-urban regions.

METHOD

This study employed a deterministic mixed-integer optimization approach to develop the Multi-Agent Energy Sharing and Emission-Constrained Optimization (MESECO) framework, integrating a residential community and an industrial port. The model minimized combined operating costs associated with grid electricity procurement, battery energy storage operation, inter-agent electricity trading, and port-specific carbon compliance, subject to energy balance, storage, trading, and emission constraints. The residential community incorporated rooftop photovoltaic (PV) systems and battery energy storage, while the port integrated PV generation, wind power, and large-scale battery storage. Hourly optimization determined electricity procurement, battery charging and discharging, renewable energy allocation, and bidirectional electricity transfers while maintaining energy balance between the two agents.

The reference case involved Tanjung Perak Port and a representative residential community in Surabaya, Indonesia. Port electricity demand was estimated using historical operational records, while residential demand profiles were derived from electricity consumption data provided by Perusahaan Listrik Negara (PLN). Solar irradiance and wind speed data were obtained from NASA POWER and the ERA5 reanalysis dataset, respectively. Potential renewable generation capacities were estimated based on available installation areas. The optimization employed a 24-hour scheduling horizon with hourly intervals, repeated across representative months. Under the baseline scenario, batteries were initially assumed to be fully discharged, and residential rooftop PV adoption was set at 20%. Port-specific carbon compliance costs were incorporated through a simplified emissions trading system (ETS)-based mechanism representing emission allowances and excess-emission penalties.

Four electricity pricing and trading scenarios were evaluated. Case 0 applied flat electricity tariffs without inter-agent trading. Case 1 introduced real-time pricing (RTP) for inter-agent electricity exchanges while maintaining fixed grid electricity tariffs. Case 2 implemented RTP for both grid electricity procurement and inter-agent trading. Case 3 combined dynamic grid electricity pricing with a fixed inter-agent trading tariff. The scenarios were compared based on annual and monthly operating costs, electricity trading volumes, grid dependence, battery storage utilization, and carbon compliance costs. Sensitivity analyses examined variations in residential rooftop PV adoption, inter-agent electricity tariffs, and initial battery state of charge in the second year. The resulting optimization outcomes were evaluated under the specified modeling assumptions to assess the economic and operational implications of cooperative energy management.

RESULT AND DISCUSSION

Simulation Results

The simulation results across the four cases demonstrate substantial differences in operational costs and energy flows between the community and the port. Table 1 summarizes monthly operational costs, where negative values indicate revenue or cost recovery from

electricity sales, while Table 2 presents electricity generation, storage, procurement, and inter-agent transactions.

Table 1. Monthly operational cost breakdown for the port and community across all simulation cases

Case 0 — operational costs (USD)

Month	Community	Port
Jan	$ 49,605.54	$ 685,515.89
Feb	$ 56,673.81	$ 21,000.00
Mar	$ 60,358.12	$ 21,000.00
Apr	$ 72,244.23	$ 21,000.00
May	$ 96,127.60	$ 21,000.00
Jun	$ 120,165.22	$ 21,000.00
Jul	$ 112,650.51	$ 21,000.00
Aug	$ 94,599.15	$ 21,000.00
Sep	$ 82,007.44	$ 21,000.00
Oct	$ 66,990.36	$ 21,000.00
Nov	$ 60,648.25	$ 21,000.00
Dec	$ 55,992.95	$ 21,000.00
Total Cost	$ 928,063.21	$ 916,515.89

Source: MESECO model results reported in the manuscript.

Case 1 — operational costs (USD)

Month	Community	Port
Jan	$ 47,110.50	$ 668,651.24
Feb	$ 53,660.08	$ 664.48
Mar	$ 57,080.53	$ (1,211.25)
Apr	$ 68,584.48	$ (3,790.28)
May	$ 92,076.99	$ (6,428.64)
Jun	$ 115,468.59	$ (10,883.40)
Jul	$ 108,188.94	$ (9,281.27)
Aug	$ 90,598.99	$ (6,136.33)
Sep	$ 78,433.83	$ (3,198.51)
Oct	$ 63,853.83	$ (167.87)
Nov	$ 57,944.28	$ 2,763.96
Dec	$ 53,332.53	$ 3,030.40
Total Cost	$ 886,333.57	$ 634,012.54

Source: MESECO model results reported in the manuscript.

Case 2 — operational costs (USD)

Month	Community	Port
Jan	$ 51,113.00	$ 635,938.95
Feb	$ 36,175.00	$ (15,175.00)
Mar	$ 49,700.00	$ (28,700.00)
Apr	$ 58,675.00	$ (37,675.00)
May	$ 80,125.00	$ (59,125.00)
Jun	$ 99,265.00	$ (78,265.00)
Jul	$ 93,600.00	$ (72,600.00)
Aug	$ 79,400.00	$ (58,400.00)
Sep	$ 66,975.00	$ (45,975.00)
Oct	$ 55,500.00	$ (34,500.00)
Nov	$ 49,700.00	$ (28,700.00)
Dec	$ 44,500.00	$ (23,500.00)
Total Cost	$ 764,728.00	$ 153,323.95

Source: MESECO model results reported in the manuscript.

Case 3 — operational costs (USD)

Month	Community	Port
Jan	$ 69,946.13	$ 617,105.82
Feb	$ 49,350.00	$ (28,350.00)
Mar	$ 68,150.00	$ (47,150.00)
Apr	$ 79,900.00	$ (58,900.00)
May	$ 108,100.00	$ (87,100.00)
Jun	$ 134,420.00	$ (113,420.00)
Jul	$ 126,900.00	$ (105,900.00)
Aug	$ 105,750.00	$ (84,750.00)
Sep	$ 91,650.00	$ (70,650.00)
Oct	$ 75,200.00	$ (54,200.00)
Nov	$ 68,150.00	$ (47,150.00)
Dec	$ 61,100.00	$ (40,100.00)
Total Cost	$ 1,038,616.13	$ (120,564.18)

Source: MESECO model results reported in the manuscript.

The baseline scenario (Case 0) represents independent operation without community–port electricity trading and with flat electricity tariffs. The community remains partly dependent on conventional grid electricity and records an annual cost of **$928,063.21**. In contrast, the introduction of cooperative trading in Case 1 reduces the community cost to **$886,333.57** and the port cost from **$916,515.89 to $634,012.54**, primarily because the port can monetize its surplus renewable generation through real-time-priced electricity trading.

Case 2 applies real-time pricing (RTP) to both grid procurement and inter-agent transactions and produces the most efficient system-wide outcome. The community records an annual cost of **$764,728.00**, while the port cost falls to **$153,323.95**. Dynamic pricing allows both agents to respond to hourly price signals, coordinate storage operation, optimize procurement, and increase renewable energy utilization. Case 3 produces a contrasting distributional outcome: the community incurs its highest cost of **$1,038,616.13**, whereas the port generates a net revenue of **$120,564.18**. This occurs because fixed inter-agent prices favor the renewable-surplus supplier while reducing the community's ability to adapt procurement decisions to changing market conditions.

Table 2. Summary of electricity flow and energy transactions across all system components (kWh)

Case 1 — electricity flow (kWh)

Month	Community from port	Community from grid	Port from community	Port from grid
Jan	231671.12	358871.08	0.00	4852.49
Feb	279385.62	395302.65	0.00	0.00
Mar	304964.81	413584.26	0.00	0.00
Apr	340396.79	519653.61	0.00	0.00
May	376642.81	767733.39	0.00	0.00
Jun	437653.98	992884.35	0.00	0.00
Jul	415674.79	925402.74	0.00	0.00
Aug	372530.46	753649.95	0.00	0.00
Sep	332298.48	643980.60	0.00	0.00
Oct	290824.37	506679.96	0.00	0.00
Nov	250592.39	471410.61	0.00	0.00
Dec	246865.99	419716.74	0.00	0.00

Source: MESECO model results reported in the manuscript.

Case 2 — electricity flow (kWh)

Month	Community from port	Community from grid	Port from community	Port from grid
Jan	727766.72	18286.38	0.00	4852.49
Feb	525000.00	0.00	0.00	0.00
Mar	725000.00	0.00	0.00	0.00
Apr	850000.00	0.00	0.00	0.00
May	1150000.00	0.00	0.00	0.00
Jun	1430000.00	0.00	0.00	0.00
Jul	1350000.00	0.00	0.00	0.00
Aug	1125000.00	0.00	0.00	0.00
Sep	975000.00	0.00	0.00	0.00
Oct	800000.00	0.00	0.00	0.00
Nov	725000.00	0.00	0.00	0.00
Dec	650000.00	0.00	0.00	0.00

Source: MESECO model results reported in the manuscript.

Case 3 — electricity flow (kWh)

Month	Community from port	Community from grid	Port from community	Port from grid
Jan	727766.72	18286.38	0.00	4852.49
Feb	525000.00	0.00	0.00	0.00
Mar	725000.00	0.00	0.00	0.00
Apr	850000.00	0.00	0.00	0.00
May	1150000.00	0.00	0.00	0.00
Jun	1430000.00	0.00	0.00	0.00
Jul	1350000.00	0.00	0.00	0.00
Aug	1125000.00	0.00	0.00	0.00
Sep	975000.00	0.00	0.00	0.00
Oct	800000.00	0.00	0.00	0.00
Nov	725000.00	0.00	0.00	0.00
Dec	650000.00	0.00	0.00	0.00

Source: MESECO model results reported in the manuscript.

Table 2 confirms that cooperative scenarios activate electricity exchange between the agents and reduce reliance on conventional supply. Under RTP, electricity flows respond more effectively to supply-demand conditions and price signals. The port increasingly functions as a renewable electricity supplier, while the community combines its own PV generation, storage, grid purchases, and port-sourced electricity to minimize costs.

Comparative Performance of Pricing Scenarios

From the community perspective, **Case 2 provides the lowest cost**, as full RTP enables flexible switching between grid and port electricity and improves battery utilization. Case 1 provides moderate savings compared with the baseline, but the continued use of subsidized flat grid tariffs weakens price responsiveness. Case 3 generates the highest community expenditure because fixed inter-agent pricing limits the benefits of dynamic procurement.

For the port, Case 3 provides the greatest financial benefit because renewable self-sufficiency and fixed selling prices create stable electricity-sale revenues. Case 2 also substantially improves port performance, although RTP creates greater revenue variability. Thus, the optimal scenario differs when each agent is considered separately. However, at the **system level, Case 2 provides the most efficient joint outcome**, indicating that uniformly applied RTP better aligns economic incentives, renewable utilization, and energy coordination.

These results demonstrate an important trade-off in cooperative energy markets. Dynamic pricing improves system-wide efficiency, whereas fixed prices may redistribute benefits toward the generation-dominant agent. Consequently, pricing mechanisms should be evaluated not only on total system costs but also on how economic benefits and risks are distributed between participating agents.

Sensitivity and Threshold Analysis

Sensitivity analysis was conducted to assess whether the main findings remained valid under changes in PV penetration, inter-agent tariffs, and storage conditions. The first analysis varied rooftop PV adoption from the baseline level of 20% to 100%.

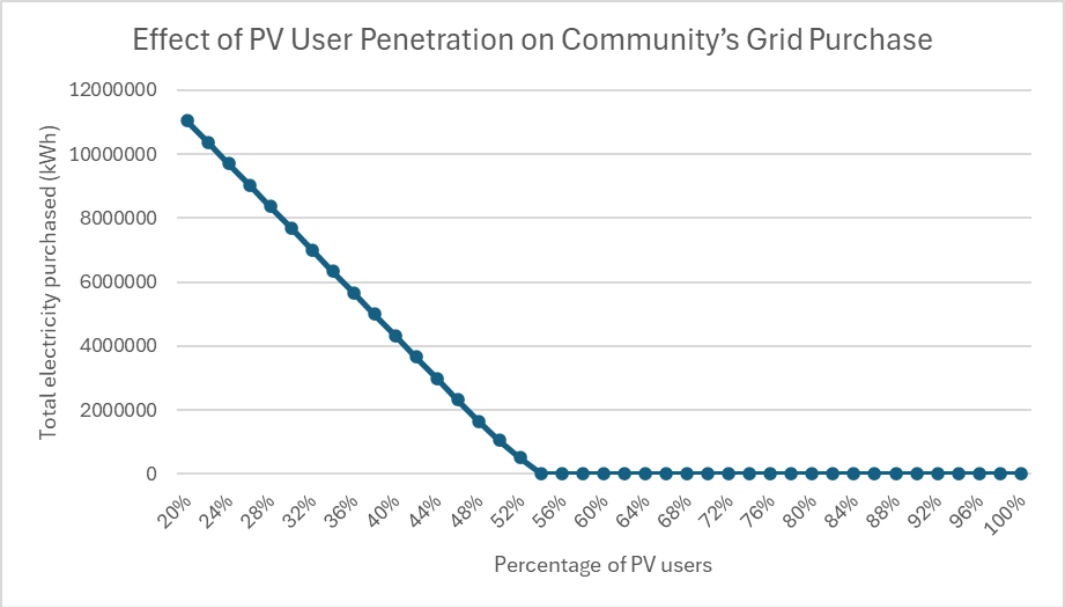


Figure 1. Percentage of PV users vs. total electricity purchased

Source: MESECO model simulation results reported in this study.

Figure 1 shows that increasing PV penetration progressively reduces community dependence on conventional electricity. Full energy self-sufficiency is achieved at approximately 54% PV adoption. Surplus electricity can first be exported to the port at 48% adoption, although only temporarily, while a penetration rate of approximately 74% is required to generate sufficient surplus for consistent monthly exports. These findings indicate that renewable adoption produces nonlinear transitions from grid dependence to self-sufficiency and eventually to a stable prosumer role.

The second analysis examined the effect of changing the flat electricity price between the port and community.

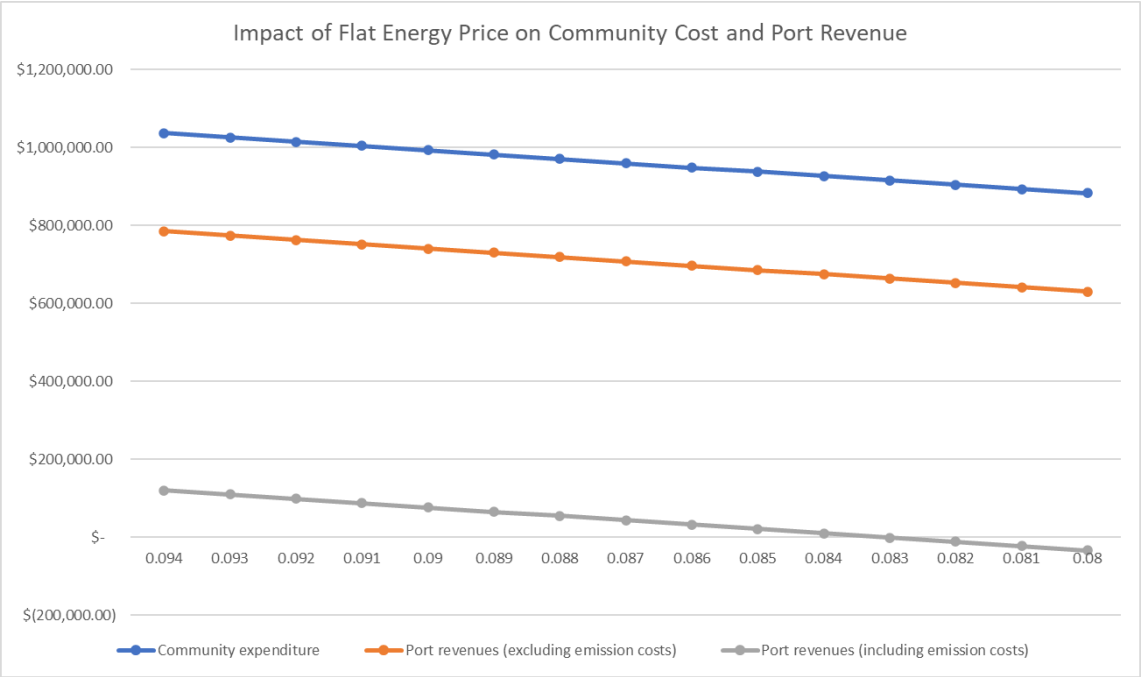


Figure 2. Effect of inter-agent flat pricing on community expenditure and port revenue

Source: MESECO model simulation results reported in this study.

Figure 2 demonstrates a clear trade-off between community affordability and port financial viability. Lower tariffs reduce community expenditure but also reduce port revenue, particularly when carbon-compliance costs are internalized. Under active emission regulation, **$0.084/kWh** represents a practical equilibrium in which the port retains a marginal positive return while community costs remain close to the baseline. Without carbon penalties, the economically favorable tariff can decrease to **$0.023/kWh**, reducing community expenditure to $253,754 while maintaining a small positive port margin of $1,754.

The third sensitivity analysis evaluated Cases 1–3 under second-year conditions with non-zero initial battery storage.

Table 3. Sensitivity Results for Cases 1–3 Under Second-Year Operational Conditions with Non-Zero Initial Storage

Case 1 — second-year costs (USD)

Month	Community	Port
Jan	$ 46,905.15	$ (1,096.83)
Feb	$ 53,496.79	$ (5,087.39)
Mar	$ 56,903.00	$ (7,552.10)
Apr	$ 68,383.21	$ (11,112.75)
May	$ 91,851.45	$ (14,754.54)
Jun	$ 115,200.27	$ (21,178.29)
Jul	$ 107,933.66	$ (19,086.79)
Aug	$ 90,375.27	$ (14,486.93)
Sep	$ 78,233.86	$ (10,567.48)
Oct	$ 63,681.57	$ (6,290.58)
Nov	$ 57,795.76	$ (2,377.14)
Dec	$ 53,186.36	$ (2,113.57)
Total Cost	$ 883,946.35	$ (115,704.38)

Source: MESECO model results reported in the manuscript.

Case 2 — second-year costs (USD)

Month	Community	Port
Jan	$ 40,866.60	$ (19,866.60)
Feb	$ 51,007.14	$ (30,007.14)
Mar	$ 44,600.00	$ (23,600.00)
Apr	$ 58,675.00	$ (37,675.00)
May	$ 80,240.00	$ (59,240.00)
Jun	$ 97,490.00	$ (76,490.00)
Jul	$ 91,825.00	$ (70,825.00)
Aug	$ 80,117.00	$ (59,117.00)
Sep	$ 66,975.00	$ (45,975.00)
Oct	$ 49,700.00	$ (28,700.00)
Nov	$ 49,700.00	$ (28,700.00)
Dec	$ 44,500.00	$ (23,500.00)
Total Cost	$ 755,695.74	$ (503,695.74)

Source: MESECO model results reported in the manuscript.

Case 3 — second-year costs (USD)

Month	Community	Port
Jan	$ 51,870.01	$ (20,454.94)
Feb	$ 64,624.55	$ (43,952.26)
Mar	$ 56,674.39	$ (32,834.78)
Apr	$ 74,261.69	$ (51,251.43)
May	$ 101,005.16	$ (78,266.85)
Jun	$ 122,986.66	$ (100,198.39)
Jul	$ 115,920.92	$ (93,095.75)
Aug	$ 100,079.96	$ (77,497.33)
Sep	$ 85,006.73	$ (62,032.09)
Oct	$ 62,719.81	$ (39,131.55)
Nov	$ 63,155.10	$ (39,930.43)
Dec	$ 56,590.02	$ (33,228.18)
Total Cost	$ 954,895.01	$ (671,873.99)

Source: MESECO model results reported in the manuscript.

Non-zero initial storage improves operational flexibility by reducing early grid dependence and enabling earlier electricity trading. Total community costs decrease and port revenues improve across the scenarios. Nevertheless, the relative performance of the pricing structures remains unchanged: **Case 2 continues to provide the lowest combined system cost**, whereas Case 3 remains financially advantageous to the port but comparatively costly for the community. This finding indicates that storage availability improves overall efficiency but does not eliminate structural inefficiencies created by flat or asymmetric pricing.

Table 3 further shows second-year total community costs of **$883,946.35, $755,695.74, and $954,895.01** for Cases 1, 2, and 3, respectively. The corresponding port values become net revenues of **$115,704.38, $503,695.74, and $671,873.99**, confirming that carry-over storage strengthens operational performance while maintaining the relative advantages and disadvantages of each pricing regime.

Discussion and Policy Implications

Overall, the findings demonstrate that effective port–community energy cooperation depends on the simultaneous alignment of **renewable-energy deployment, electricity pricing, storage utilization, and carbon regulation**. RTP consistently generates more adaptive and system-efficient outcomes because electricity procurement, storage, and trading decisions

respond directly to hourly market signals. In contrast, fixed inter-agent pricing can create asymmetric benefits by increasing supplier revenue while reducing demand-side flexibility.

The tariff sensitivity analysis further demonstrates that carbon regulation cannot be separated from electricity-pricing design. When ETS-related costs are internalized, tariffs must be sufficiently high to maintain port participation without making electricity unaffordable for the community. Carbon-indexed tariffs or mechanisms for sharing carbon-compliance costs may therefore provide more balanced incentives for cooperative energy trading.

PV adoption also has important planning implications. Below the 54% self-sufficiency threshold, policy support can focus on accelerating renewable adoption through investment incentives. Between 54% and 74%, greater attention is required for prosumer participation, dynamic pricing, and trading mechanisms. Beyond 74%, policies may focus on market integration and arrangements that enable consistent absorption of community-generated electricity by industrial consumers such as ports.

Taken together, the MESECO results show that technological capacity alone is insufficient to ensure successful energy cooperation. Pricing mechanisms, carbon-policy obligations, and renewable deployment must be jointly designed to prevent one agent from being structurally disadvantaged. The framework therefore provides a useful decision-support approach for port authorities, energy planners, and policymakers seeking to balance cost efficiency, energy autonomy, renewable integration, and emission compliance in coastal and semi-urban energy systems.

CONCLUSION

This study developed the Multi-Agent Energy Sharing and Emission-Constrained Optimization (MESECO) framework to coordinate renewable energy generation, battery energy storage, grid electricity procurement, and bidirectional electricity trading between residential communities and industrial ports under dynamic electricity pricing and port-specific carbon emission constraints. Under the modeled conditions, the scenario incorporating real-time pricing for both grid electricity procurement and inter-agent trading (Case 2) achieved the lowest combined annual operating cost, with expenditures of USD 764,728.00 for the residential community and USD 153,323.95 for the port. In contrast, the fixed inter-agent pricing scenario (Case 3) generated net annual revenue of USD 120,564.18 for the port but increased community electricity expenditure to USD 1,038,616.13. These findings demonstrated that minimizing aggregate operating costs did not necessarily ensure an equitable distribution of economic benefits between participating agents, highlighting the importance of incorporating benefit-sharing considerations into cooperative energy management strategies.

Sensitivity analyses indicated that approximately 54% household photovoltaic (PV) adoption enabled modeled electricity self-sufficiency, while approximately 74% supported consistent monthly electricity exports. An inter-agent electricity tariff of approximately USD 0.084/kWh provided a balance between community affordability and port financial viability when modeled carbon compliance costs were included. Carryover battery energy storage enhanced operational flexibility without substantially altering the relative economic performance of the pricing scenarios. Nevertheless, these findings depended on representative electricity demand profiles, assumed renewable generation and storage capacities, and simplified electricity market and carbon compliance mechanisms. Therefore, the results should be interpreted as scenario-based optimization outcomes rather than predictions of actual port operations. Future research should validate the MESECO framework using measured hourly electricity demand and renewable generation data, incorporate

investment costs and operational uncertainties, and evaluate the feasibility of regulatory arrangements and equitable benefit-sharing mechanisms to support the practical implementation of cooperative low-carbon energy systems.

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CONFLICT OF INTEREST

The authors declare that this study was conducted without any commercial or financial relationships that could be interpreted as a potential conflict of interest.

AUTHORS' CONTRIBUTIONS

I Gede Arei Banyupramesta: research conceptualization, methodology design, experiment execution, data collection, data analysis, manuscript drafting, and manuscript revision, research supervision, validation of research results, provision of scientific input, and manuscript review and revision. All authors have read and approved the final version of the manuscript.

STATEMENT ON THE USE OF GENERATIVE ARTIFICIAL INTELLIGENCE

The authors declare that generative artificial intelligence (AI) was used in the preparation of this manuscript to help improve linguistic clarity, correct grammar, and refine the writing structure. Generative AI was not used to generate, manipulate, or analyze research data. The entire content of the manuscript has been reviewed and verified by the author(s). The author(s) are fully responsible for the accuracy, integrity, and final content of the manuscript.

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