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Integrating Renewable Energy, Institutional Empowerment, Post-Harvest Efficiency in Sustainable Blue Economy Models

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ABSTRACT

This study explores how the integration of renewable energy, institutional empowerment, and post-harvest efficiency can enhance sustainable blue economy models. A mixed-method design combines quantitative and qualitative data from coastal fisheries to examine the relationships between energy access, institutional strength, and operational efficiency. The results show that working capital, cooperative governance, and solar-based electrification improve fisheries productivity, while greater post-harvest losses reduce both efficiency and sustainability outcomes. Communities adopting renewable energy and participatory institutions achieve higher income growth, stronger resource resilience, and broader social inclusion. The findings emphasize that technological innovation must operate alongside institutional capacity and equitable management systems. By introducing post-harvest loss as a measurable indicator of efficiency, this research expands the analytical framework of the blue economy and offers a replicable model for sustainable coastal development aligned with global sustainability goals.

Keywords: Blue Economy, Institutional Empowerment, Renewable Energy, Sustainable Fisheries, Post-Harvest Efficiency
JEL Classifications: Q220; Q430; Q520; Q530

1. INTRODUCTION

The blue economy has emerged as a multidimensional development paradigm emphasizing the balance between economic growth, environmental sustainability, and social inclusion (World Bank, 2017; FAO, 2022). Coastal regions in developing countries face structural challenges that limit their ability to harness marine resources sustainably. Gorontalo Regency, located in northern Sulawesi, Indonesia, is one such region where the fisheries sector plays a pivotal role in local livelihoods but remains constrained by low productivity, limited access to technology, and dependence on fossil fuels.

Despite its abundant solar potential and rich marine biodiversity, coastal Gorontalo continues to operate under traditional, extractive, and energy-inefficient systems. Small-scale fishers dominate the sector, often relying on outdated tools, high fuel costs, and unstable electricity supply. Consequently, post-harvest losses remain high, reaching up to 30% and income levels among fishers remain below regional averages (Mongabay, 2024). This persistent inefficiency in post-harvest handling, represented by the post-harvest loss rate (PHL), reflects both technological and institutional weaknesses that reduce effective fisheries productivity and profitability.

Electrification through renewable energy, particularly solar power, represents a promising opportunity to transform fisheries operations while advancing sustainability goals (Singh et al., 2021; Chen et al., 2021). Solar-powered cold storage and ice-making systems can directly reduce the PHL by improving preservation capacity and extending the shelf life of marine products. The integration of renewable energy into fisheries value chains, therefore, has dual impacts: lowering operational costs and minimizing losses, which together enhance the efficiency component of the blue economy index (Bennett et al, 2019).

At the same time, the role of local institutions like cooperatives, village enterprises, and community-based organizations, has become increasingly critical. Strong institutional frameworks are necessary to ensure equitable access to technology, collective decision-making, and sustainable resource governance (North, 1990; Ostrom, 2009). Institutional empowerment not only fosters adaptive governance but also enhances fishers' capacity to manage energy transition, reduce post-harvest inefficiencies, and respond to market volatility.

However, empirical evidence linking renewable energy adoption, post-harvest loss reduction, and institutional strength with measurable outcomes in fisheries productivity and blue economy transformation remains limited. Most previous studies focus either on macro-level blue economy frameworks (Marwa et al., 2024) or technical electrification impacts (Sebestyén, 2021), without integrating socio-institutional and operational efficiency dimensions such as PHL. This study addresses that gap by assessing the combined effects of renewable energy electrification, post-harvest loss reduction, and institutional empowerment on fisheries productivity and the blue economy index in Gorontalo's coastal villages.

2. LITERATURE REVIEW

2.1. The Blue Economy and Sustainable Fisheries Development

The blue economy, initially conceptualized by Pauli (2010), emphasizes innovation that ensures economic prosperity, environmental sustainability, and social inclusiveness. It seeks to maximize the value of marine resources while preserving ecological balance. According to FAO (2022) and UNEP (2023), sustainable fisheries are fundamental pillars of the blue economy because they support livelihoods, food security, and climate resilience.

In the Indonesian context, the blue economy is recognized as a strategic framework for inclusive coastal development (World Bank, 2017). However, challenges such as resource degradation, weak institutional capacity, and inefficient value chains have constrained its implementation (Mahardianingtyas et al., 2019). A critical but often overlooked aspect is the post-harvest loss rate (PHL), the proportion of fish lost during handling, processing, and storage. High PHL reduces the effective yield of fisheries and weakens the contribution of marine resources to economic welfare. Kumar et al. (2022) found that in tropical small-scale fisheries, reducing PHL by 10–15% could increase local income equivalently to a 5% rise in total catch without additional ecological pressure.

Therefore, addressing post-harvest inefficiency represents a core element of blue economy implementation, linking environmental stewardship to economic efficiency. Integrating the PHL dimension into blue economy frameworks enhances understanding of how renewable energy and institutional innovation translate into tangible welfare improvements.

2.2. Renewable Energy and Electrification in the Fisheries Sector

Electrification is central to sustainable fisheries modernization. Renewable energy, particularly solar-based systems, improves operational efficiency, reduces dependency on fossil fuels, and lowers carbon emissions (Yusuf et al., 2020). Empirical studies demonstrate that renewable-powered cold storage and ice-making facilities can significantly reduce post-harvest loss rates (PHL) and improve product quality and safety (Chen et al., 2021; Singh et al., 2021). These interventions extend the shelf life of fish products, stabilize prices, and enhance export readiness.

In Gorontalo, pilot solar-electrification programs introduced by local universities and the provincial government have proven effective in reducing spoilage and energy costs. However, their reach remains limited due to fragmented coordination and the absence of institutional frameworks for long-term management. As Sebestyén (2021) and Nguyen and Wang (2024) argue, technological adoption alone cannot ensure sustainability; it must be complemented by social mechanisms that guarantee equitable access and maintenance.

From a systems perspective, integrating renewable energy with cold chain facilities directly influences PHL reduction, which in turn enhances fisheries productivity. This interrelationship makes PHL a crucial variable in evaluating the effectiveness of energy transition programs in coastal areas.

2.3. Institutional Empowerment and Community-Based Governance

Institutional empowerment forms the social backbone of the blue economy. As theorized by North (1990) and Ostrom (2009), institutions both formal rules and informal norms, shape economic behavior and collective outcomes. In the fisheries sector, empowered local institutions foster resource stewardship, financial inclusion, and cooperative investment (Pomeroy and Andrew, 2011).

Recent Southeast Asian studies reinforce this argument. Purwanto and Suparmoko (2022) found that digitalized cooperatives improved transparency in fish trading, while Hasibuan et al. (2023) highlighted that community-based marine tourism in Morowali strengthened governance and welfare outcomes. Institutional strength thus acts as both a catalyst and regulator, enabling equitable access to technologies that lower operational costs and post-harvest losses.

In the context of Gorontalo, cooperative-led management of solar cold storage exemplifies how institutional capacity mediates the relationship between technology adoption and reduced PHL. The synergy between institutional empowerment and technological efficiency underscores the dual role of governance: ensuring participation and achieving measurable economic benefits.

2.4. Research Gap and Conceptual Framework

Although extensive research exists on the blue economy, renewable energy, and fisheries management, few studies integrate these with post-harvest efficiency indicators such as the Post-Harvest Loss Rate (PHL) at the micro (village) level (Le Cornu et al., 2023). Most existing literature either focuses on macroeconomic analysis or technological feasibility, overlooking how institutional strength and operational efficiency co-evolve in shaping sustainable fisheries.

This study fills that gap by proposing an interdisciplinary framework that connects:

1. Economic Empowerment, access to capital, cost efficiency, and livelihood improvement;
2. Energy Transition, renewable energy adoption and electrification of fisheries operations;
3. Institutional Empowerment, governance capacity and cooperative participation; and
4. Operational Efficiency (PHL Reduction), minimizing fish spoilage and maximizing the value chain outcome.

Incorporating PHL provides a measurable bridge between energy and institutional variables, offering empirical evidence of how cleaner energy and stronger institutions translate into higher fisheries productivity and sustainability. The conceptual framework positions PHL as both a mediating variable (linking renewable energy adoption to productivity) and a performance indicator of the blue economy's efficiency dimension.

3. METHODOLOGY

3.1. Study Area

The research was conducted in Gorontalo Regency, situated along the southern coastline of Tomini Bay, Sulawesi, Indonesia. The study covers 17 coastal villages across the sub-districts of Batudaa Pantai and Biluhu, representing varying degrees of institutional development, electrification access, and fisheries productivity. These villages exhibit distinct energy and post-harvest characteristics, ranging from communities with established solar-powered cold-storage units to those still dependent on ice supply from urban centers. Such variation allows comparative analysis of how renewable energy adoption, institutional capacity, and post-harvest loss rate (PHL) interact to influence fisheries outcomes.

The region's climate is tropical with a bimodal rainfall pattern, and fishing activities are dominated by artisanal fishers targeting pelagic species such as tuna and skipjack. Economic activities revolve around small-scale capture fisheries, fish processing, and trading, all of which are highly sensitive to energy access and post-harvest efficiency.

3.2. Research Design

This study applies a mixed-methods approach, combining quantitative panel-data analysis with qualitative insights from community interviews and focus-group discussions. The design enables triangulation between statistical results and field-based observations of behavioral and institutional dynamics.

Quantitatively, the research covers the period 2018-2024, using annual observations at the village level (N = 17, T = 7). The inclusion of PHL as an operational-efficiency variable strengthens the analytical bridge between energy transition and productivity performance.

Qualitatively, participatory observations were conducted with fisher groups, cooperative managers, and local government officers to contextualize variations in PHL, energy use, and institutional functioning. This dual-track design ensures that both measurable outcomes and socio-institutional mechanisms are captured.

3.3. Data and Variables

3.3.1. Dependent variables

1. Fisheries Productivity (PF), annual average catch per fisher (kg/month) or value added (IDR).
2. Blue Economy Index (BEI), composite indicator derived from economic, social, and environmental sub-indices standardized to a 0–1 scale.

3.3.2. Independent variables

1. Working Capital (MK), average capital available per fisher (million IDR)
2. Operational Costs (BO), monthly expenditure on fuel, ice, and maintenance
3. Institutional Strength (IKS), index (0–1) measuring participation, transparency, and leadership capacity within local cooperatives
4. Renewable Energy Electrification (KON), dummy or proportion variable capturing solar-power utilization in fisheries operations
5. Education Level (PEND), average years of schooling among active fishers
6. Post-Harvest Loss Rate (PHL), newly introduced variable, defined as:

$$PHL_{it} = \frac{\text{Fish landed}_{it} - \text{Fish sold / consumed fresh}_{it}}{\text{Fish landed}_{it}} \times 100$$

It represents the monthly percentage of fish lost due to spoilage, improper handling, or storage limitations. A lower PHL indicates higher operational efficiency. The data were derived from cooperative sales logs, local fish markets, and cold-storage records. Where detailed logs were unavailable, estimations were validated through interviews with fish-processing groups.

Expected Relationships

- KON (+) → PF/BEI (+): solar electrification improves productivity.
- IKS (+) → PF/BEI (+): institutional strength enhances coordination.
- PHL (–) → PF/BEI (+): lower losses raise effective yield and sustainability.
- KON → PHL (–): energy access mediates the reduction of post-harvest losses.

Control variables include village population size, fishing-days per month, and access to markets or ports.

3.4. Analytical Model

Panel-data estimation techniques were employed to test both direct and mediating effects of the variables. The primary econometric specification is:

$$Y_{it} = \alpha + \beta_1 MKit + \beta_2 BO_{it} + \beta_3 IKS_{it} + \beta_4 KON_{it} + \beta_5 PEND_{it} + \beta_6 PHL_{it} + \mu_i + \varepsilon_{it}$$

where Y_{it} denotes either PF or BEI, *i* is village, and *t* is year. A Fixed-Effects Model (FEM) was selected based on the Hausman test ($P < 0.05$), controlling for unobserved village-specific heterogeneity. Robust standard errors were applied to address heteroskedasticity.

To explore PHL's mediating role, an additional path was estimated:

$$PHL_{it} = \gamma_0 + \gamma_1 KON_{it} + \gamma_2 IKS_{it} + \gamma 3BO_{it} + \nu_i + ή_{it}$$

Comparing the coefficients of KON on PF/BEI with and without PHL reveals the extent to which energy access improves productivity via loss reduction. This mediation approach strengthens causal interpretation between electrification, efficiency, and economic outcomes.

3.5. Data Collection and Validation

Primary data were gathered through structured questionnaires administered to 120 respondents (fishers, cooperative leaders, traders) between 2022 and 2024. Secondary data on catch, sales, energy consumption, and cold-storage operation were obtained from the Gorontalo Fisheries Office, BPS Gorontalo, and village cooperative records.

For PHL, triangulation was performed using three independent sources:
1. Cooperative ledgers recording daily landings and sales;
2. Local market monitoring for spoilage and unsold fish; and
3. FGD-based validation with fisher groups to cross-check monthly average losses.

Data consistency was verified through ratio-analysis and cross-year comparisons. Outliers exceeding ±3 SD were winsorized to ensure stability. All quantitative data were processed using STATA 18.

3.6. Ethical Considerations

All research activities complied with ethical standards set by the Research and Community Service Institute of the State University of Gorontalo (LPPM-UNG). Participants were informed about the study's objectives, data usage, and confidentiality protocols before giving consent.

Special attention was given to handling economic data such as income, capital, and post-harvest loss values, which were anonymized at the village level to protect respondents' privacy. FGDs were designed to encourage inclusive participation, ensuring representation of women and young fishers in discussing post-harvest management and cooperative governance.

4. RESULTS

4.1. Overview of the Study Area and Respondent Characteristics

The study was conducted across 17 coastal villages within Batudaa Pantai and Biluhu subdistricts of Gorontalo Regency, areas with high marine potential but limited energy access and infrastructure. A total of 120 respondents participated, consisting of small-scale fishers (82%), aquaculture farmers, fish processors, and cooperative leaders.

The average fisher age was 41 years, with mean education of 8.7 years (junior secondary). About 63% were cooperative members, while 29% had access to solar-based systems, mainly for household lighting and ice-making.

An important descriptive finding is the average post-harvest loss rate (PHL), which reached 22.6% across all villages. Electrified villages (e.g., Biluhu Timur, Bongo, and Kayubulan) showed lower PHL levels, ranging 12–15%, compared to 30–35% in non-electrified areas (e.g., Olimoo, Olimeyala, and Lopo). These variations provide the empirical basis for exploring PHL as an operational-efficiency indicator within the blue economy framework.

4.2. Fisheries Productivity, Blue Economy Index, and Post-Harvest Loss Rate

Tables 1 and 2 summarize the average fisheries productivity, Blue Economy Index (BEI), and PHL across study villages (2018-2024).

The table illustrates variations in fisheries productivity, blue economy index (BEI), and post-harvest loss (PHL) across nine coastal villages. A clear pattern emerges: higher productivity is associated with higher BEI values and lower PHL levels. Villages such as Biluhu Timur and Bongo demonstrate greater efficiency due to the use of solar-powered cold storage, while Buhudaa and Olimoo record the highest PHL (over 30 percent) mainly due to limited preservation and distribution capacity. These results highlight that post-harvest efficiency is a critical determinant of blue economy performance and sustainability.

Table 1: Average fisheries productivity, BEI, and PHL (Batudaa Pantai, 2018-2024)

Village	Productivity (kg/month)	BEI (0–1)	PHL (%)
Biluhu Timur	265	0.82	13.4
Bongo	250	0.77	14.1
Kayubulan	235	0.73	15.6
Lamu	220	0.69	18.2
Tontayuo	210	0.65	21.8
Langgula	200	0.62	23.0
Lopo	190	0.60	27.5
Buhudaa	180	0.57	30.3
Olimoo	175	0.54	32.1

Source: Processed Field Data, 2025

Table 2: Average fisheries productivity, BEI, and PHL (Biluhu, 2018-2024)

Village	Productivity (kg/month)	BEI (0–1)	PHL (%)
Biluhu Barat	260	0.80	14.7
Biluhu Tengah	245	0.76	16.2
Botuboluo	230	0.72	18.4
Huwongo	215	0.68	21.0
Lobuto	200	0.64	23.6
Lobuto Timur	185	0.59	28.1
Luluo	170	0.52	31.8
Olimeyala	160	0.48	34.6

Source: Processed Field Data, 2025

Table 3: Panel regression summary (Fixed effects, 2018–2024)

Variable	Fisheries Productivity (*β*)	Blue Economy Index (*β*)	Significance
Working Capital (MK)	0.273***	0.108**	P<0.01
Operational Cost (BO)	0.239***	0.091*	P<0.01
Institutional Index (IKS)	0.312***	0.401***	P<0.01
Electrification (KON)	0.221**	0.342***	P<0.05
Education (PEND)	0.084	0.069	n.s.
Post-Harvest Loss Rate (PHL)	–0.197*	–0.166*	P<0.01
Constant	0.407	0.281	—
R^2 (within)	0.71	0.74	—

***P<0.01; **P<0.05; *P<0.10

Villages that integrated solar-powered cold storage exhibited not only higher productivity and BEI but also significantly lower PHL. These patterns strengthen the hypothesis that renewable energy and institutional capacity jointly drive efficiency and sustainability within the coastal blue economy system.

4.3. Regression Results

Panel data regression was performed using the fixed effects model (FEM) to account for unobserved heterogeneity across villages and years. Two core models were estimated, Model 1 for fisheries productivity (PF) and Model 2 for blue economy index (BEI), with PHL included as an independent and mediating variable.

4.4. Model Specification

$$PF_{it} = \alpha + \beta_1 MK_{it} + \beta_2 BO_{it} + \beta_3 IKS_{it} + \beta_4 KON_{it} + \beta_5 PEND_{it} + \beta_6 PHL_{it} + \varepsilon_{it}$$

$$BEI_{it} = \alpha + \beta_1 MK_{it} + \beta_2 BO_{it} + \beta_3 IKS_{it} + \beta_4 KON_{it} + \beta_5 PEND_{it} + \beta_6 PHL_{it} + \varepsilon_{it}$$

The regression results are presented in Table 3 indicate that a decrease in the Post-Harvest Loss Rate (PHL) is associated with higher fisheries productivity and a higher Blue Economy Index. Specifically, the negative and statistically significant coefficients of PHL suggest that reductions in post-harvest losses improve operational efficiency and sustainability outcomes, holding other factors constant.

This evidence underscores the efficiency channel through which renewable energy translates into blue economy gains, by reducing losses rather than merely boosting gross output.

4.5. Qualitative Findings

Field interviews and focus group discussions corroborate the quantitative findings and contextualize PHL reduction as a transformative mechanism in fisheries sustainability:

- Reduced post-harvest losses**:** Fisher groups using solar-powered cold storage reported 20-25% reductions in fish spoilage, extending product freshness from 6 h to 24 h, and enabling participation in higher-value markets in Gorontalo City and Manado
- Institutional Management**:** Active cooperatives managed cold-storage scheduling and fee-sharing systems transparently, preventing elite capture and ensuring inclusive benefits
- Behavioral changes**:** Fishers in low-PHL villages displayed improved sorting, icing, and handling practices, reflecting adaptive learning stimulated by electrification and training
- Technology–institution synergy**:** Villages with weak institutions often experienced neglect of solar units or misuse for non-productive activities, whereas strong institutions maintain performance and reduced technical downtime
- Gender participation**:** Women's groups engaged in fish processing and marketing reported reduced raw-material waste, highlighting PHL reduction as an empowerment dimension as well.

Collectively, these findings demonstrate that PHL functions as a key operational indicator linking technological and institutional interventions to sustainable blue economy outcomes.

5. DISCUSSION

5.1. Integrating Renewable Energy into Blue Economy Transformation

This study reinforces the view that renewable energy adoption, particularly solar-based electrification, plays a transformative role in the blue economy by improving efficiency and sustainability across the fisheries value chain. The results show that villages with solar-powered cold storage and processing facilities achieved higher productivity, lower post-harvest loss rates (PHL), and consequently higher blue economy index (BEI) scores.

The decline in PHL, averaging 8–12% points lower in electrified communities, indicates that renewable energy does more than just supply power—it creates an enabling environment for post-harvest management, cold chain continuity, and market stability. This aligns with findings by Chen et al. (2021) and Singh et al. (2021), who noted that renewable-powered preservation systems significantly reduce spoilage and enhance income retention among small-scale fishers.

By integrating PHL into the analysis, this study provides empirical evidence that energy transition enhances fisheries sustainability through efficiency gains, not merely through increased gross output. In other words, clean energy indirectly drives economic productivity by minimizing losses, a channel often overlooked in blue economy literature. This efficiency mechanism links the ecological, economic, and social pillars of the blue economy: less waste implies fewer emissions, higher net income, and more equitable benefit distribution.

Beyond energy provision, the adoption of renewable technologies has stimulated behavioral and organizational change within fishing communities. The presence of reliable, decentralized power supply encourages cooperatives to adopt collective management of cold storage facilities and financial pooling mechanisms to cover maintenance costs. These cooperative-based arrangements not only reduce operational risks but also foster trust, accountability, and information sharing. Such institutional strengthening magnifies the long-term benefits of electrification, transforming energy access into an entry point for broader socioeconomic empowerment and sustainable governance of marine resources.

Furthermore, integrating renewable energy with efficient post-harvest systems supports the transition toward a circular blue economy model. Reduced spoilage and waste lower carbon intensity per kilogram of fish marketed, while stable energy supply enables diversification into value-added products such as processed and packaged seafood. This synergy between clean energy, institutional collaboration, and value chain efficiency demonstrates how blue economy transformation can align environmental performance with inclusive economic growth. It also highlights that sustainability in fisheries is achieved not only by increasing production, but by optimizing every link in the energy–efficiency–equity chain.

Furthermore, the fixed-effects regression confirms that PHL mediates the relationship between electrification and productivity. Electrified villages with organized cooperative management recorded both higher operational stability and lower volatility in income. This suggests that the renewable energy transition in coastal regions has begun to decarbonize not only energy systems but also inefficiencies in the value chain, offering a replicable model for sustainable fisheries modernization in other developing regions.

5.2. The Role of Institutional Empowerment in Energy Transition and Loss Reduction

Institutional empowerment remains the social foundation upon which technological transformation stands. Strong local institutions like cooperatives, village-owned enterprises (BUMDesa), and fisher associations proved essential in sustaining both energy infrastructure and loss-reduction practices. Villages with high institutional indices (IKS > 0.7) showed a consistent correlation with lower PHL levels (<18%), demonstrating that governance and social capital directly influence efficiency outcomes.

These results echo the principles of Ostrom (2009), emphasizing that collective action and rule enforcement reduce the tragedy of the commons, including post-harvest inefficiencies. Empowered institutions manage solar cold storage scheduling, coordinate training on fish handling, and ensure equitable cost-sharing, thus embedding technological innovation within a framework of local accountability.

This synergy between institutional empowerment and PHL reduction highlights the co-evolutionary nature of social and technological systems. In practical terms, empowered communities exhibit greater technological discipline: they maintain solar systems properly, monitor cold storage usage, and reinvest savings from reduced losses into productive assets. Conversely, weak institutions often experience system neglect and relapse into high PHL conditions despite having access to the same infrastructure.

Beyond these direct impacts, institutional empowerment also facilitates the diffusion of technological knowledge within communities. Training and peer-to-peer learning conducted through cooperatives create a feedback mechanism that ensures operational standards and maintenance protocols are consistently followed. This continuous learning environment not only improves the efficiency of renewable energy utilization but also nurtures a culture of accountability and innovation that strengthens community resilience in the long term.

Furthermore, the institutional framework functions as a bridge between government policy and local implementation. Strong institutions enable the effective use of public subsidies, manage revolving funds for energy maintenance, and align local initiatives with regional sustainability programs. In this way, institutional empowerment becomes a governance mechanism that translates national energy and blue economy strategies into tangible community-level outcomes, ensuring that the benefits of technological advancement are equitably distributed.

Therefore, institutional empowerment serves as a critical mediator that translates technological access into measurable sustainability performance. Without organizational capability and participatory governance, renewable energy systems risk underperformance and social inequality. In many cases, cooperative-led energy governance has successfully minimized spoilage, stabilized fish prices, and strengthened local resilience to fuel price fluctuations and market shocks.

5.3. Operational Efficiency and Post-Harvest Losses as Drivers of Sustainability

The inclusion of post-harvest loss rate (PHL) adds a crucial analytical dimension to blue economy discussions: operational efficiency. While previous research predominantly measured fisheries sustainability through ecological and income-based indicators, this study identifies PHL as a measurable proxy for efficiency and welfare retention.

PHL captures how much of the natural capital extracted from the sea is effectively utilized within the human economy. Reducing losses not only increases profitability but also enhances ecological performance by lowering the need for additional extraction. This dual benefit aligns with the sustainable yield principle in fisheries economics (Béné et al., 2010; FAO, 2022).

Empirically, a 1% decline in PHL leads to a 0.19-unit increase in productivity and a 0.17-unit rise in BEI, controlling for other factors. These elasticities confirm that waste reduction delivers economic impacts comparable to capital expansion, yet with lower environmental cost. In practical terms, reducing spoilage from 30% to 15% across 17 coastal villages could generate income equivalent to expanding the total annual catch by 20-25%, without increasing fishing pressure on marine ecosystems.

This finding reframes blue economy transformation as not merely about “catch more, sell more,” but “waste less, earn more.” Integrating PHL as a policy target encourages eco-efficiency, the optimization of production, energy, and resource use for maximum societal return with minimal environmental impact.

Beyond the direct economic benefits, reducing PHL also enhances carbon efficiency and mitigates the environmental footprint of fisheries operations. Less spoilage means reduced energy consumption in storage, transport, and waste disposal, resulting in lower greenhouse gas emissions per unit of output. Consequently, PHL reduction contributes not only to profitability but also to climate adaptation and mitigation efforts within the blue economy framework. By positioning PHL as a bridge variable between productivity and sustainability, this study highlights its strategic role in aligning local fisheries practices with national low-carbon development agendas.

Moreover, operational efficiency achieved through PHL management creates multiplier effects in the local economy. Savings from reduced spoilage are often reinvested into equipment maintenance, capacity building, and diversification of value-added products such as dried, smoked, or packaged fish. These reinvestments strengthen household income stability, promote gender-inclusive economic participation, and encourage innovation at the community level. Thus, reducing post-harvest losses functions as both an economic catalyst and a sustainability mechanism, ensuring that the gains from marine resource utilization are maximized and equitably distributed across generations.

5.4. Policy Implications

The results offer several actionable implications for policy and regional development:

1. Incorporate PHL reduction into fisheries and energy planning. Local governments should treat post-harvest efficiency as a performance metric in evaluating blue economy initiatives and renewable energy investments. Integrating PHL reduction targets into regional development plans and performance-based budgeting ensures that efficiency gains are institutionalized rather than incidental. This approach also aligns local fisheries management with broader national goals of food security and energy transition
2. Prioritize cooperative-led solar infrastructure. Strengthening cooperatives as operational managers ensures long-term maintenance and equitable access to cold storage, lowering PHL sustainably. Cooperative-led models foster shared responsibility, transparency, and reinvestment of collective savings, which are essential for sustaining the financial viability of renewable energy assets in small-scale fisheries
3. Link renewable energy subsidies to measurable outcomes. Public incentives should reward communities achieving significant reductions in PHL or energy consumption per unit of production. Outcome-based subsidy mechanisms can accelerate behavioral change, encourage data-driven management, and reduce dependence on perpetual grants. This performance-oriented framework promotes fiscal efficiency and accountability in the use of renewable energy funds
4. Promote digital monitoring of PHL. Introducing simple digital tools for recording fish landings, sales, and spoilage can help track efficiency improvements and guide adaptive policy. Integration with cloud-based data systems allows governments to analyze trends in real time, identify areas of inefficiency, and provide targeted technical assistance. The digitalization of PHL records also facilitates traceability, enhancing product credibility in export markets increasingly sensitive to sustainability certification
5. Integrate gender and youth inclusion. Empowering women and young fishers in value-added processing and logistics strengthens the social foundation of PHL reduction and enhances economic equity. Inclusive participation expands human capital in fisheries modernization and supports intergenerational knowledge transfer. Moreover, integrating women into cooperative management structures enhances transparency and innovation in decision-making, ensuring that the benefits of energy and efficiency investments reach all segments of society.

Together, these strategies frame PHL reduction as both a technological and institutional agenda, bridging clean energy, food security, and inclusive growth. They also reinforce the idea that energy transition is not solely a technical challenge but a governance reform, where institutional capacity, social equity, and digital transparency determine long-term sustainability. By embedding efficiency-oriented policies within cooperative structures and digital monitoring systems, governments can transform fisheries management into a model of low-carbon, data-informed, and socially inclusive blue economy development.

5.5. Synthesis

Overall, this study demonstrates that renewable energy and institutional empowerment jointly shape the efficiency frontier of the blue economy. By introducing post-harvest loss rate (PHL) into the analytical framework, the research captures the missing operational link between energy access and sustainability outcomes.

Reducing post-harvest losses is not a peripheral benefit but a central mechanism through which cleaner energy and stronger institutions deliver transformative impacts. In the context of Gorontalo, every percentage point reduction in PHL represents a tangible step toward an energy-efficient, inclusive, and ecologically balanced coastal economy.

Hence, the blue economy transformation must be understood not solely as a function of increased production or electrification, but as the collective achievement of efficient, low-waste, and socially governed marine systems, a model that holds relevance for coastal regions throughout Indonesia and the broader Global South.

Beyond the empirical findings, this synthesis underscores the importance of efficiency as a unifying pillar connecting environmental, economic, and social objectives within the blue economy paradigm. Efficiency here transcends technical optimization, it embodies institutional reliability, participatory governance, and adaptive learning processes that collectively sustain long-term productivity. By quantifying efficiency through PHL, this research provides policymakers with a concrete, measurable indicator that bridges abstract sustainability goals with operational realities in small-scale fisheries.

Furthermore, the integrative model presented in this study offers a scalable blueprint for policy innovation. Its principles, renewable energy integration, cooperative-based governance, and efficiency-driven planning, can be adapted to diverse coastal contexts where infrastructure gaps, energy insecurity, and market volatility persist. Embedding these components into national blue economy frameworks enables developing regions to achieve sustainability not by extraction expansion, but by resource optimization and social empowerment. In this sense, the study reframes energy transition and fisheries modernization as complementary pathways toward an inclusive, resilient, and low-carbon maritime future.

6. CONCLUSION

This study concludes that renewable energy integration, institutional empowerment, and post-harvest loss reduction (PHL) are mutually reinforcing pillars of sustainable blue economy transformation in Gorontalo's coastal communities. The empirical evidence demonstrates that:

1. Working capital and operational efficiency remain critical economic drivers of fisheries productivity.
2. Institutional strength, as measured through cooperative participation, transparency, and collective management, exerts the strongest influence on long-term sustainability outcomes ($\beta = 0.412$, $P < 0.01$).
3. Solar-based electrification significantly enhances production efficiency and income while reducing dependence on fossil fuels.
4. Post-harvest loss rate (PHL) has a statistically significant negative effect on both productivity and the blue economy index (BEI), highlighting that reducing spoilage is a major efficiency pathway toward sustainability.
5. Villages combining renewable energy, institutional governance, and loss-reduction practices (such as cold storage management, improved handling, and cooperative marketing) consistently achieve superior blue economy performance.

These findings expand the theoretical and empirical understanding of the blue economy by framing PHL reduction as a key operational variable linking technological innovation and institutional capacity. The study confirms that energy access alone does not guarantee sustainability; it must be embedded within participatory governance systems that ensure equitable benefit sharing, technical maintenance, and adaptive learning.

Consequently, Gorontalo's model illustrates how small-scale fisheries can achieve eco-efficiency and resilience through a triadic framework of clean energy adoption, institutional empowerment, and post-harvest optimization. This integrated approach offers a scalable and context-sensitive blueprint for inclusive and sustainable coastal development across Indonesia and other developing maritime regions.

Future research should extend this framework through spatial–bioeconomic modeling and digital PHL monitoring systems, enabling continuous assessment of sustainability progress in alignment with SDGs 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 13 (Climate Action), and 14 (Life Below Water).

In a broader perspective, these results reaffirm that sustainability in coastal economies depends on the synchronization of technology, governance, and efficiency rather than isolated interventions. When renewable energy adoption is reinforced by institutional integrity and operational discipline, it transforms traditional fisheries into adaptive, data-informed, and low-carbon systems. The conceptual and empirical framework presented here thus contributes not only to the literature on the blue economy but also to the evolving discourse on energy justice and equitable resource management in developing regions.

6.1. Policy Implications

The findings of this study offer clear and actionable policy directions for local and national governments, development partners, and community institutions seeking to accelerate blue economy transformation in coastal regions. The integration of renewable energy, institutional empowerment, and post-harvest loss reduction (PHL) generates a multidimensional policy framework that connects sustainability, inclusiveness, and efficiency.

Building on the empirical results, policymakers should recognize that post-harvest efficiency is not merely a technical goal but a strategic bridge between energy transition and economic inclusion. Reducing PHL enhances the return on public investment in renewable infrastructure, ensuring that subsidies and grants generate measurable welfare outcomes rather than temporary capacity expansion. Integrating efficiency indicators into local development plans allows governments to better target fiscal resources toward communities that demonstrate effective use of energy and institutional assets. In this way, performance-based governance becomes an essential instrument for accelerating both energy and fisheries transformation agendas.

Furthermore, the study underscores the need for cross-sectoral coordination among fisheries, energy, and cooperative agencies. Sustainable transformation requires aligning regulatory frameworks so that electrification programs explicitly account for value chain efficiency and social equity. Local governments can establish incentive schemes linking energy subsidies with institutional performance—rewarding cooperatives that maintain low PHL levels, ensure gender-inclusive participation, and reinvest profits in renewable systems maintenance. Such integrated governance not only amplifies the impact of renewable energy adoption but also builds community resilience, enhances data accountability, and supports long-term progress toward a circular and low-carbon blue economy model.

6.2. Integrating Energy Transition and Fisheries Modernization

Policymakers should treat renewable energy adoption not merely as an environmental agenda but as a productivity and welfare strategy.

- Scaling solar-based cold chain systems: Regional development plans (RPJMD) and *Rencana Zonasi Wilayah Pesisir* should allocate budget and incentives for community-managed solar cold storage facilities
- Performance-based support: Renewable energy grants and subsidies should be tied to measurable reductions in PHL and improvements in blue economy index (BEI) values, rather than solely on installation targets
- Hybrid energy models: Encourage public–private partnerships (PPP) to develop hybrid energy systems (solar + battery + biogas) to ensure 24 h preservation capacity and minimize spoilage
- By embedding energy transition within the broader framework of fisheries modernization, policymakers can create a synergistic pathway between technological innovation and socio-economic transformation. Renewable energy access not only enhances the physical infrastructure of production but also restructures governance and labor dynamics within fishing communities. When integrated effectively, hybrid energy systems can stabilize post-harvest handling, enable diversification into value-added processing, and reduce dependency on volatile fossil fuel markets. These systemic changes promote sustainable livelihoods, reduce environmental pressure, and ensure that the energy transition becomes a catalyst for inclusive and resilient coastal economic growth rather than an isolated technological intervention.

6.3. Institutional Strengthening for Sustainable Energy Governance

Institutional empowerment emerges as the foundation of sustainable energy transition and fisheries management.

- Cooperative-led governance: Local cooperatives or *BUMDesa* should be formally assigned as operators of cold storage and renewable facilities, supported by transparent financial reporting and participatory oversight
- Capacity building and technical training: Periodic training on energy maintenance, financial literacy, and data recording (including PHL monitoring) should be integrated into government extension programs
- Incentivizing collective action: Fiscal and non-fiscal incentives (e.g., profit-sharing schemes, tax reductions, or access to soft loans) should be provided to cooperatives demonstrating effective management and low PHL outcomes.

Sustainable energy governance depends not only on infrastructure investment but on institutional integrity and adaptive management capacity. Empowered cooperatives function as intermediaries that translate technical solutions into social and economic outcomes, ensuring that renewable systems remain operational and equitable over time. Embedding accountability through participatory governance mechanisms, such as transparent reporting, shared decision-making, and routine evaluation, enhances local ownership and trust. When these institutions are supported by consistent policy alignment and capacity development, they evolve from administrative entities into dynamic agents of transformation capable of maintaining low PHL levels, ensuring financial sustainability, and fostering innovation within the blue economy ecosystem.

6.4. Embedding PHL Reduction as a Policy Indicator

Reducing post-harvest losses is both an economic and environmental goal. The study's results show that each 1% reduction in PHL can increase fisheries productivity by 0.19 units and BEI by 0.17 units.

- National and regional targets: The Ministry of Marine Affairs and Fisheries (KKP) and provincial governments should incorporate PHL reduction indicators in their annual performance frameworks
- Digital monitoring systems: Encourage the use of mobile-based data systems for fish landing, sale, and spoilage tracking to provide real-time feedback and data-driven interventions
- Integration with food security programs: Link PHL reduction strategies to food supply stability and marine conservation efforts, recognizing loss reduction as a driver of sustainable production.

Embedding PHL reduction as a formal policy indicator ensures that efficiency gains are institutionalized within the governance architecture of the blue economy. By treating loss reduction as a quantifiable sustainability metric, policymakers can evaluate the effectiveness of investments in renewable energy, infrastructure, and community empowerment using consistent and evidence-based benchmarks. Moreover, connecting PHL metrics with fiscal incentives and inter-agency coordination mechanisms fosters policy coherence between the energy, fisheries, and environmental sectors. Over time, this approach transforms PHL reduction from a technical intervention into a strategic policy lever, capable of improving food system resilience, enhancing export competitiveness, and accelerating national progress toward low-carbon and resource-efficient economic growth.

6.5. Financial and Investment Policy Alignment

Financial institutions and public funds should prioritize investments in the "triple impact" sectors like energy, efficiency, and empowerment.

- Green financing schemes: Expand the role of *Green Sukuk* and microcredit facilities (KUR Hijau) to fund cooperative-owned renewable assets and cold chain modernization
- Risk mitigation instruments: Provide insurance or guarantee mechanisms to protect small fishers and cooperatives from revenue losses due to technical or climatic disruptions
- Results-based financing: Development partners and donors can design performance-linked grants tied to measurable improvements in PHL and institutional capacity indices.

6.6. Academic, Research, and Knowledge Transfer Roles

The university, government and industry nexus (*triple helix*) must continue to drive the evolution of blue economy knowledge.

- Applied research collaboration: Encourage universities to conduct ongoing evaluation of solar-cold chain effectiveness, energy efficiency, and institutional dynamics using updated PHL data
- Knowledge dissemination: Establish regional learning platforms for sharing best practices among coastal villages and across provinces
- Curriculum integration: Higher education institutions should embed the themes of renewable energy, institutional

governance, and PHL reduction into marine resource management programs.

6.7. Toward a Policy Blueprint for Blue Economy Transformation

Gorontalo's empirical experience offers a replicable blueprint for Indonesia's broader coastal development policy:

1. Technological pillar: Accelerate renewable energy access and hybrid cold chain systems
2. Institutional pillar: Strengthen community-based governance, transparency, and cooperative resilience
3. Efficiency pillar: Target post-harvest loss reduction as a measurable driver of economic growth and sustainability.

Through this integrated approach, the blue economy transitions from a conceptual framework into a practical governance model, anchored in clean energy, institutional participation, and efficient resource utilization. The inclusion of PHL as a policy performance metric ensures that economic progress does not come at the expense of environmental degradation, thus advancing Indonesia's commitment to sustainable, inclusive, and low-carbon coastal development.

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