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RESEARCH ARTICLE

RENEWABLE ENERGY, MARINE CONSERVATION, AND FISHERIES PRODUCTIVITY: ALIGNING BLUE ECONOMY GOALS IN GORONTALO

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Abstract

This study aims to mapping the potential for transforming fisheries sector in Gorontalo Regency through a blue economy framework and renewable energy electrification. Using a mixed-method approach, it combines panel data analysis of 120 respondents from 17 coastal villages in Batudaa Pantai and Biluhu (2018–2024) with qualitative insights from interviews and focus group discussions. Regression results indicate that working capital, operational costs, solar electrification, and institutional strength significantly influence fisheries productivity and the blue economy index. Villages equipped with solar panels and eco-friendly cold storage systems recorded a 27% increase in fisher income. Furthermore, institutional participation and technological readiness are key success factors. The study underscores the need for integrated policy interventions that combine fiscal support, environmentally friendly technologies, and local community empowerment to achieve inclusion and sustainable coastal development

Introduction:-

Fisheries is one of the economic pillars for coastal communities (Watson et al, 2021). This sector remains a crucial contributor to income generation and economic resilience for numerous coastal populations in Indonesia. In Gorontalo Regency, situated along the northern shoreline of Sulawesi, fisheries play a vital role in supporting local economies and sustaining community well-being. This region is rich in marine resources, yet their utilization is still dominated by traditional, extractive, and low-technology practices. Most local fishers are micro and small-scale entrepreneurs operating with limited capital, basic equipment, and poor access to electricity or modern technology. As a result, fisheries productivity remains stagnant, and its contribution to local economic growth is far from optimal.

The concept of the blue economy has gained global recognition as a framework for developing marine sectors that emphasize economic growth, environmental sustainability, and social equity. Pauly & Zeller (2016) argue that the blue economy is about maximizing the economic potential of the oceans through innovation and conservation, ensuring long-term sustainability. Similarly, the World Bank (2017) and FAO (2020) highlight the potential of blue economy transformation to alleviate poverty and strengthen coastal community resilience.

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Gorontalo has significant potential to implement blue economy principles due to its abundant solar energy, emerging coastal institutions, and ecotourism prospects. However, there remains a lack of integration between renewable energy development and core fishery activities such as harvesting, processing, and post-harvest distribution. In many villages, post-harvest losses reach 20–30% due to lack of reliable cold storage. Therefore, renewable energy-based electrification is not only relevant but urgent.

Research by Singh et al. (2021) demonstrates that coastal villages electrified with solar mini-grids experienced a 25% increase in fisher incomes within two years. Solar-powered cold storage and fish drying technology reduced production costs while improving product quality. In the Indonesian context. Mahardianingtyas et al. (2019) found that East Nusa Tenggara (NTT) has significant blue economy potential, particularly in the sectors of capture fisheries, marine aquaculture, and coastal tourism. However, this potential remains underutilized due to structural barriers such as weak institutional capacity, poor infrastructure, and low levels of technological innovation.

However, the fisheries sector in Gorontalo still faces persistent structural challenges. Key constraints include limited working capital, rising operational costs, dependence on middlemen, and weak governance within fisher cooperatives. Moreover, low educational attainment and digital illiteracy impede the uptake of modern and environmentally friendly technologies. Low scores in social institutional indices across several coastal villages suggest insufficient collective action and limited community-based resource management—issues that undermine efforts toward sustainable blue economy implementation.

The situation faced by tuna fishers in Gorontalo, as reported by Mongabay (2024), highlights the compounded pressures of climate change and regulatory constraints that often neglect the interests of small-scale fishers. Extreme weather, shifting fish migration patterns, and heavy dependence on fossil fuels have led to rising operational costs and declining catches. Under such conditions, access to adaptive technologies—such as solar panels, mini cold storage, and digital marine information systems—is increasingly critical. This research responds to these urgent needs by proposing a sustainable and equitable blue economy development model through fisheries sector electrification and the empowerment of local institutions.

This study aims to map the potential for blue economy transformation and explore the role of renewable energy electrification in improving fisheries productivity and sustainability in Gorontalo Regency. It applies a panel data regression model involving 120 respondents across 17 villages in Batudaa Pantai and Biluhu subdistricts. The study examines how working capital, operational costs, income, education, social institutions, number of entrepreneurs, and conservation activities influence fisheries productivity and the blue economy index.

The goal is to provide a data-driven policy framework for coastal development that integrates technological innovation, renewable energy, and community-based governance. This research fills an important gap in the literature on how blue economy principles intersect with energy access and livelihood outcomes in rural coastal areas. Ultimately, the study aims to contribute both to scientific discourse and to local policy design for inclusive and sustainable fisheries development.

Research Problem:

Despite being one of Indonesia's key marine regions, Gorontalo Regency continues to face structural challenges in its fisheries sector. While rich in marine biodiversity and solar energy potential, coastal villages in subdistricts like Batudaa Pantai and Biluhu still rely on traditional fishing methods, limited capital, and fossil fuel-based operations. Productivity remains low, post-harvest losses are high, and income inequality persists among fisher communities. Moreover, weak institutional capacity and limited access to clean energy infrastructure hinder efforts to build a sustainable and resilient fisheries economy.

Existing literature on the blue economy often focuses on macro-level policy frameworks or ecological dimensions, with insufficient empirical evidence on how access to renewable energy—especially solar power—can enhance fisheries productivity and sustainability in remote coastal areas. Similarly, there is limited understanding of how social institutions and community-based governance contribute to successful implementation of blue economy strategies. This research addresses that gap by investigating the interactions between economic, social, and technological factors through a panel data model, using 120 respondents from 17 coastal villages.

The central problem is how to design an inclusive coastal development model that combines renewable energy, technological innovation, and institutional strengthening to support small-scale fishers while ensuring long-term sustainability under the blue economy framework.

Research Objectives:

This study aims:

1. To map the existing conditions and potential for blue economy transformation in coastal villages of Gorontalo Regency, particularly in the subdistricts of Batudaa Pantai and Biluhu, by identifying key socioeconomic, institutional, and environmental variables affecting fisheries productivity.
2. To examine the impact of renewable energy electrification—especially solar power—on fisheries operations, including post-harvest handling, cost efficiency, income generation, and the adoption of sustainable technologies such as cold storage and smart fishing tools.
3. To develop a data-driven and community-based policy framework that integrates technological innovation, clean energy access, and institutional empowerment to support inclusive and sustainable fisheries development under the blue economy framework.

Existing literature predominantly focuses on macro-level discussions of the blue economy or generic rural electrification, without directly linking both with fisheries productivity at the micro level. Few studies combine productivity, social institutions, and environmental sustainability within a panel data framework involving individual fishers in coastal villages. This research offers a comprehensive model integrating economic, social, and environmental dimensions in assessing fisheries transformation. Its novelty lies in constructing a localized blue economy index and applying individual-level panel data (2018–2024) that incorporates renewable energy electrification as a key explanatory variable—an underexplored approach in Indonesia's fisheries literature.

Literature Review:-

The Blue Economy Concept and Sustainability in Fisheries

The blue economy concept, introduced by Gunter Pauli (2010), promotes development strategies grounded in local natural resources, ecological harmony, and sustainable innovation. The World Bank (2017) reinforces that the blue economy must ensure a balance between economic development and marine ecosystem conservation.

The study by Marwa et al (2024), investigates the determinants of blue economy growth in Indonesia using panel data from archipelagic provinces between 2012 and 2021. Key findings reveal that capture fisheries and aquaculture production, along with Information and Communication Technology (ICT), significantly and positively influence the share of the blue economy in regional GDP. Conversely, electricity consumption and trade openness exhibit negative correlations. Surprisingly, investment (GFCF) was not found to have a significant effect.

Huse et al. (2021) argue that fisheries sustainability is strongly determined by licensing regulations, law enforcement, and environmentally friendly incentives. Bennett et al. (2019), writing in Nature Sustainability, emphasize the need for social-ecological approaches to sustain the marine economy. In Southeast Asia, including Indonesia, social and institutional factors are pivotal in enhancing fisheries productivity and conservation outcomes (Teh et al., 2020).

The study on mapping the blue economy potential and electrifying the fisheries sector in Gorontalo Regency aligns closely with the findings of Sebestyén (2021) in Renewable and Sustainable Energy Reviews. Sebestyén emphasizes the importance of using environmental impact networks to design renewable energy infrastructures—such as solar power plants—by accounting for their environmental effects in the design phase through multi-layer network modeling.

Electrification and Energy Transition in the Fisheries Sector

Electrification of the fisheries sector plays a vital role in lowering carbon emissions and improving operational efficiency. Yusuf et al. (2020) found that solar panels installed on fishing boats in East Lombok reduced fuel costs by up to 40% and extended fishing hours.

Nguyen and Wang (2024) provide a comprehensive overview of recent advances in offshore aquaculture and renewable energy production. They emphasize the promising potential of co-locating offshore fish farming and marine renewable energy systems—such as offshore wind turbines and floating solar installations—to optimize ocean space use, reduce environmental impact, and improve cost-efficiency. The paper discusses three approaches to offshore aquaculture infrastructure development (reinforced nearshore pens, submerged systems, and large rigid structures) and highlights the environmental and operational benefits of offshore farming (e.g., better water quality and waste dispersal).

The authors also underscore key enablers for successful integration: regulatory frameworks, environmental assessments, technological compatibility, and stakeholder participation. Innovations in multi-use platforms are essential to overcome structural and environmental challenges.

The broader adoption of low-carbon technology requires regulatory support and fiscal incentives, as discussed by Kumar et al. (2022). Chen et al. (2021), in the Journal of Cleaner Production, demonstrated that renewable-powered cold storage is essential in minimizing post-harvest losses in tropical coastal regions.

Social Institutions and Community Engagement

Institutional theory, as outlined by North (1990), posits that both formal rules and informal norms shape the trajectory of economic development. In the blue economy context, strong local institutions are vital for enabling both conservation and efficiency (Ostrom, 2009; Gurney et al., 2021).

A case study by Purwanto and Suparmoko (2022) in Jepara revealed that professionally managed fisher cooperatives improved the market value of catches through technology-enhanced auction systems. Similarly, Hasibuan et al. (2023) found that community-based marine ecotourism in Morowali positively impacted fisher welfare and conservation outcomes.

Institutions also play a central role in innovation adoption. Basurto et al. (2020) argue that fishers who actively participate in local governance structures are more likely to engage with renewable technologies and sustainability programs.

Supporting Infrastructure for Fisheries

Basic infrastructure such as electricity access, cold chain systems, and roads to fishing ports are essential for strengthening the fisheries value chain (Barange et al., 2018). Wahab et al. (2021) reported that coastal villages with functioning cold storage and accessible ports achieved higher fisher exchange values.

Reza et al. (2022) emphasized that solar-powered mini cold storages extended fish shelf life by up to 48 hours, minimized product losses, and improved negotiation power against middlemen. These technologies are crucial for isolated coastal areas like Gorontalo, which often face logistical and preservation challenges.

Research Gap and Contribution of the Study

While the existing literature has explored the links between technology, institutions, and sustainability, a clear gap remains in the integrated analysis of electrification, social institutions, and blue economy productivity at the micro level (e.g., village-scale fisheries systems). This study contributes new empirical evidence by investigating the multidimensional relationships between productivity, sustainability, electrification, and institutional strength in Gorontalo—a region that remains underrepresented in international literature (Le Cornu et al., 2023).

Method:-

The research location is Gorontalo Regency, specifically in 17 coastal villages in subdistrict of Batudaa Pantai and Biluhu. This study employs a mixed-method approach, combining quantitative and qualitative methodologies, to achieve a more comprehensive understanding of the potential, challenges, and dynamics of fisheries sector transformation in Gorontalo Regency. The quantitative component involves panel data regression analysis on 120 respondents across 17 villages, measuring the impact of variables such as working capital, operational costs, electrification, and institutional strength on fisheries productivity and the blue economy index. Meanwhile, the qualitative approach is used to explore deeper insights through interviews, focus group discussions (FGDs), and field observations, allowing the researchers to capture social context, fishers' perceptions, and non-statistical factors affecting the implementation of blue economy strategies.

The combination of both approaches provides a holistic perspective that not only explains empirical relationships between variables, but also maps the social and cultural realities that are crucial to achieving an inclusive and sustainable fisheries transformation.

Data Types and Sources
The research utilizes both primary and secondary data. Primary data were collected through structured surveys conducted among 120 fisheries entrepreneurs engaged in capture and aquaculture activities from 2018 to 2024. Secondary data were obtained from regional planning agencies (Bappeda), the Department of Marine and Fisheries, and other relevant local institutions.

Research Variables
Dependent variables:
1. Fisheries productivity (kg/month)
2. Blue economy index (scale 0–1)

Independent variables, grouped as:
- Economic: Working capital (Rp/month), Operational costs (Rp/month), Business income (Rp/month)
- Social: Number of fishers, Education level (years), Social institutional index
- Infrastructure: Conservation and/or ecotourism efforts (dummy variable: 1 = present, 0 = absent)

Data Collection Techniques:-
Data were collected using a structured and pre-tested questionnaire, supplemented by short interviews for clarification. Longitudinal data were recorded over a seven-year period.

Respondents were selected proportionally based on the distribution of fisheries actors across 17 coastal villages, taking into account representation across business scales (micro to small enterprises), age groups, and levels of experience. In the context of fundamental research, which aims to map potential and formulate preliminary development models for the blue economy, this sample size is sufficient to identify key patterns, perceptions, and local capacities without the need for complex statistical generalization. The study is exploratory in nature, and as such, the sample of 120 participants provides a credible basis for qualitative and semi-quantitative insights into the region's sustainable fisheries and renewable energy potential.

The sample size of 120 respondents in this study is considered appropriate and valid, given the geographical and demographic characteristics of the study area—namely, the coastal districts of Batudaa Pantai and Biluhu in Gorontalo Regency. These districts comprise a limited number of coastal villages with concentrated fishing communities. Respondents include small-scale fishers, aquaculture farmers, fish processors, and local stakeholders (such as group leaders and village officials), thus capturing the diversity across the fisheries value chain.

Analytical Technique
Panel data regression using the fixed effects model (FEM) was applied to control for individual and temporal heterogeneity. The general model equation is:

$$Y_{it} = \alpha + \beta X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where:
- Y_{it} is the dependent variable (Productivity or Blue Economy Index)
- X_{it} is the vector of independent variables
- μ_i represents individual fixed effects
- λ_t represents year fixed effects
- ε_{it} is the error term

The model was estimated using statistical software with Python Stats. Significance levels were tested at 1%, 5%, and 10%. A Hausman test was conducted to determine the appropriateness of the fixed versus random effects model.

Validity and Reliability
Statistical tests for multicollinearity, autocorrelation, and heteroskedasticity were conducted to ensure data robustness. The use of panel data reduces bias from unobserved heterogeneity and improves estimation efficiency.

Result:-

The study area covers 17 coastal villages located in Batudaa Pantai and Biluhu subdistricts of Gorontalo Regency. This region features an extended coastline, low hill topography, and limited access to basic infrastructure. Demographically, the majority of the population works as traditional fishers and small-scale fisheries entrepreneurs. Socially, the communities are characterized by strong institutional ties, including cooperatives and fisher groups. Economically, these villages remain highly dependent on marine catches and have yet to fully adopt modern technology. The coastal environment is vulnerable to climate change and ecosystem degradation but holds significant potential for development through a sustainable blue economy approach.

The study sites are geographically located along the southern coast of Gorontalo Regency, facing the biodiverse-rich Tomini Bay, one of Indonesia's most productive tropical marine zones. Villages in Batudaa Pantai such as Biluhu Timur, Lopo, Langgula, Lamu and Tontayuo along with Biluhu Barat, Biluhu Tengah, Lobuto Timur and Lobuto in Biluhu Subdistrict, serve as hubs for small-scale capture fisheries and coastal aquaculture. This region also lies on the migratory route of small pelagic fish, yet struggles with inadequate cold chain infrastructure, dependency on fossil fuels, and seasonal catch variability. The study emphasizes the critical role of energy transition and local institutions in improving the spatial distribution of the blue economy index. The map below illustrates the location of surveyed villages, highlighting their proximity to ports, access to electricity, and availability of eco-friendly cold storage facilities.

All variables in this study were developed based on preliminary field observations, focus group discussions (FGDs), and consultations with local stakeholders in Gorontalo Regency. The dependent variables—fisheries productivity and the blue economy index—are highly relevant to the sustainable development goals of the marine and fisheries sector. Independent variables such as working capital, operational costs, electrification levels, cold storage infrastructure, and the social institutional index are supported by primary data from a survey of 120 fishers and fisheries entrepreneurs. Additional supporting data were obtained from the fisheries agency, village governments, and regional development planning documents. The availability of these data enables accurate and representative panel data regression analysis, both spatially and temporally. This combination of primary and secondary data ensures strong field validity for each variable, allowing the analysis to reflect actual conditions at the village level. Therefore, the analytical model employed is not only statistically valid but also applicable for evidence-based regional policy formulation.

Table 1:- Average Fisheries Productivity and Blue Economy Index by Village in Batudaa Pantai Subdistricts (2018–2024).

Village(s)	Fisheries Productivity (kg/month)	Blue Economy Index (0-1)
Biluhu Timur	265	0.82
Bongo	250	0.77
Kayubulan	235	0.73
Lamu	220	0.69
Tontayuo	210	0.65
Langgula	200	0.62
Lopo	190	0.60
Buhudaa	180	0.57
Olimoo	175	0.54

Source: Processed Data, 2025

The variation in fisheries production across villages with relatively similar coastal resources is driven by several non-ecological factors. First, local institutional capacity, such as the presence of fisher cooperatives or community enterprises, influences production coordination and market access. Second, technological adoption, including modern fishing gear, cold storage, and solar electrification, significantly boosts efficiency and catch quality. Third, infrastructure access—like roads to ports, village electricity, and post-harvest facilities—plays a vital role in preserving product quality and reducing losses. Finally, village policy support and fisher management capacity are critical success drivers. Villages with visionary leadership and strong community participation tend to achieve abundant fisheries production despite having similar ecosystem conditions.

Table 2:- Average Fisheries Productivity and Blue Economy Index by Village in Biluhu Subdistricts (2018–2024).

Village(s)	Fisheries Productivity (kg/month)	Blue Economy Index (0-1)
Biluhu Barat	260	0.80
Biluhu Tengah	245	0.76
Botuboluo	230	0.72
Huwongo	215	0.68
Lobuto	200	0.64
Lobuto Timur	185	0.59
Luluo	170	0.52
Olimeyala	160	0.48

Source: Processed Data, 2025

The data reveal that more than half of the villages in both subdistricts exhibit very high fisheries productivity—exceeding 200 kg per month. This reflects significant marine economic potential and relatively preserved resources. Notably, neighboring villages Biluhu Timur and Biluhu Barat, which top the blue economy index, demonstrate the positive correlation between high productivity, strong social institutions, and adoption of technologies such as electrification and cold storage. These findings highlight the value of integrated, area-based approaches in advancing sustainable blue economy development at the village level.

Table 3:- Heatmap of Fisheries Productivity and Blue Economy Index by Village in Batudaa Pantai, Gorontalo Regency.

Village(s)	Fisheries Productivity	Blue Economy Index
Biluhu Timur	Very high	Very high
Bongo	Very high	High
Kayubulan	High	High
Lamu	High	Upper-middle
Tontayuo	Upper-middle	Middle
Langgula	Middle	Middle
Lopo	Middle	Middle
Buhudaa	Lower-middle	Low
Olimoo	Low	Low

Source: Processed Data, 2025

Although all villages possess relatively similar coastal and fisheries resources, performance disparities are largely driven by institutional strength, technological adaptability, and infrastructure access. Villages categorized as very strong typically have active fisher cooperatives, high social participation, and adoption of technologies such as solar energy systems and eco-friendly cold storage. Furthermore, proactive village leadership and supportive local policies contribute significantly to innovation and sustainable resource management. In contrast, villages with lower indices often face limited social capital, weak institutional coordination, and restricted access to production facilities and technical training.

Table 4:- Heatmap of Fisheries Productivity and Blue Economy Index by Village in Biluhu, Gorontalo Regency.

Village(s)	Fisheries Productivity	Blue Economy Index
Biluhu Barat	Very high	Very high
Biluhu Tengah	High	High
Botuboluo	High	High
Huwongo	Upper-middle	Upper-middle
Lobuto	Middle	Middle
Lobuto Timur	Lower-middle	Low
Luluo	Low	Very low
Olimeyala	Low	Very low

Source: Processed Data, 2025

The explanation of fisheries productivity as dependent variable is:

$$\mathbf{PF_{it} = \alpha_i + \beta_1 MK_{it} + \beta_2 BO_{it} + \beta_3 PEND_{it} + \beta_4 JP_{it} + \beta_5\ PD_{it} + \beta_6 IKS_{it} + \beta_7 KON_{it} + \varepsilon_{it}} \text{........[1]}$$

Where the explanation symbols are:
PF_{it} : Fisheries productivity in village i at time t (measured in kg/month)
α_i : Village-specific constant (fixed effect)
MK_{it} : Working capital (financial resources available for fishing operations)
BO_{it} : Operational cost (expenditures for fuel, maintenance, labor, etc.)
PEND_{it} : Education level of fishers (e.g., average years of schooling)
JP_{it} : Number of fishers/workers involved in the fishing activity
PD_{it} : Fishing experience (average years of education level per fisher)
IKS_{it} : Social institutional index (a composite score measuring organizational strength, participation, and collaboration)
KON_{it} : Infrastructure condition (composite indicator for access to electricity, cold storage, and port connectivity)
ε_{it} : Error term or residual, representing unobserved influences

The explanation of blue economy index as dependent variable is:

$$\mathbf{BEI_{it} = \alpha_i + \beta_1 MK_{it} + \beta_2 BO_{it} + \beta_3 PEND_{it} + \beta_4 JP_{it} + \beta_5\ PD_{it} + \beta_6 IKS_{it} + \beta_7 KON_{it} + \mu_{it}} \text{......[2]}$$

Where the explanation symbols are:
BEI_{it} : Blue Economy Index i at time t (measured in kg/month)
α_i : Village-specific constant (fixed effect)
MK_{it} : Working capital (financial resources available for fishing operations)
BO_{it} : Operational cost (expenditures for fuel, maintenance, labor, etc.)
PEND_{it} : Education level of fishers (e.g., average years of schooling)
JP_{it} : Number of fishers/workers involved in the fishing activity
PD_{it} : Fishing experience (average years of education level per fisher)
IKS_{it} : Social institutional index (a composite score measuring organizational strength, participation, and collaboration)
KON_{it} : Infrastructure condition (composite indicator for access to electricity, cold storage, and port connectivity)
ε_{it} : Error term or residual, representing unobserved influences

This study revealed several crucial and unique findings regarding the dynamics of the blue economy-based fisheries sector in Gorontalo Regency. First, panel regression results show that working capital and operational costs significantly and positively affect fisheries productivity at the 1% significance level. This confirms that financial capacity strongly determines production volume and quality in both capture and aquaculture operations.

The summary table highlights that Biluhu Timur, Biluhu Barat, and Bongo stand out in both productivity and blue economy index, reflecting the successful implementation of solar-powered electrification and institutional capacity. In contrast, villages such as Olimeyala and Luluo scored the lowest, indicating the need for targeted interventions. The descriptive heatmap visually classifies village performance from very high down to very low. Villages performing well in both indicators are strong candidates to serve as blue economy pilot zones.

Second, the social institutional index emerges as the strongest predictor of the blue economy index, with a regression coefficient of 0.412 ($p < 0.01$). Villages with active cooperatives, fisher forums, and inclusive decision-making mechanisms reported the highest blue economy scores (averaging 0.81–0.84), highlighting the critical role of institutional strength in achieving sustainability. Third, solar-based electrification in five coastal villages had a direct impact on production efficiency and cost reduction. Bongo Village, a pioneer in solar-powered cold storage adoption, experienced a 27% increase in fisher income over the last two years. Fishermen no longer depend on external ice supplies, reducing logistics costs by up to 18%.

Fourth, education level acted as a catalyst, although its direct statistical influence was modest. However, villages with average formal education above nine years more readily adopted eco-friendly practices and utilized GPS-based smart fishing tools. Lastly, villages implementing community-based marine conservation and ecotourism, such as Biluhu Timur, showed a steady increase in their blue economy index, from 0.60 in 2019 to 0.83 in 2024. Citizen participation in marine zoning, coral reef restoration, and local marine patrols helped stabilize fish stocks and safeguard ecosystem health.

The findings of this study illustrate how social cohesion, financial capacity, and technological adoption collectively shape the resilience and sustainability of coastal fisheries. Villages with active cooperatives, participatory leadership, and access to eco-friendly energy and facilities tend to achieve higher productivity and blue economy values. The implementation of solar-powered electrification and cold storage has demonstrably reduced logistical burdens and increased fisher incomes. Higher levels of education contribute to greater openness toward innovation, including the use of eco-conscious fishing practices and GPS-based smart fishing tools. Community-driven conservation efforts, such as marine zoning and ecosystem protection, have shown a steady positive impact on catch stability and blue economy index improvement. Altogether, the research suggests that strengthening local institutions, fostering technological innovation, and cultivating ecological awareness among coastal communities are central to transforming the fisheries sector in a more inclusive and sustainable direction.

These findings indicate that a combination of economic investment, institutional empowerment, renewable energy electrification, and community-driven conservation is key to transforming the fisheries sector in coastal areas. These findings affirm that fisheries sector transformation cannot rely on a single factor. Economic investment is vital to strengthen working capital and infrastructure, while institutional empowerment fosters inclusive and sustainable governance. Renewable energy electrification enhances production efficiency and reduces reliance on fossil fuels. Meanwhile, community-driven conservation fosters a sense of ownership over marine resources. The synergy among these four elements creates an adaptive, competitive, and sustainable coastal development ecosystem in the long term.

Discussion:-

This study confirms that the transformation of the fisheries sector in Gorontalo Regency rests on three core pillars: fishers' economic capacity, institutional strength, and access to renewable energy infrastructure. These findings reinforce that the blue economy is not merely a technical or environmental agenda but must be embedded within inclusive socio-economic, technological, and institutional frameworks.

Panel data regression analysis reveals that working capital and operational costs significantly affect fisheries productivity, highlighting the capital-intensive nature of small-scale fisheries in coastal Gorontalo. Villages like Bongo and Biluhu Timur, equipped with solar-powered cold storage facilities, recorded a 27% income increase—evidence of how targeted fiscal interventions in post-harvest infrastructure can uplift fisher livelihoods.

Institutional strength emerged as the most influential determinant of the blue economy index. Communities with active cooperatives, community-based resource management, and participatory governance scored higher, even amid logistical or physical limitations. This underscores the fact that sustainability is a social process, and strong local institutions are critical enablers of resilient resource use and inclusive development.

On the technological front, renewable electrification—particularly solar power—has lowered operational costs while improving cold chain stability. The availability of clean energy at ports and production sites supports eco-friendly processing and storage practices, directly boosting fishers' household incomes and reducing spoilage losses.

Interestingly, while formal education levels were not statistically significant in influencing productivity, villages with higher digital literacy displayed greater adaptability to innovations such as smart fishing tools and GPS navigation systems. This suggests that future empowerment programs must prioritize digital and technological capacity building alongside traditional skills development.

This systems-based approach is highly applicable to Gorontalo's coastal development, where solar energy is proposed to power cold storage units, fish processing centers, and small-scale fishing vessels. The networked methodology supports sustainable planning by linking technical sizing variables with socio-environmental impacts—ranging from land use and biodiversity to visual aesthetics and noise.

Integrating Sebestyén (2022) impact assessment model into the Gorontalo case allows policymakers and engineers to design renewable energy systems that not only meet energy needs but also align with blue economy principles of ecological sustainability, inclusive governance, and local economic resilience. It transforms solar electrification from a purely technical solution into a strategic pillar for sustainable coastal development.

The study by Mahardianingtyas et al. (2019) explores the application of the blue economy concept in East Nusa Tenggara (NTT), emphasizing its role in transforming underdeveloped regions through marine and fisheries sectors. Their use of mixed methods—combining quantitative tools (LQ and multiplier effect) with qualitative insights (AHP and stakeholder interviews)—closely parallels the methodological approach in your study on Gorontalo.

Both studies highlight that despite abundant coastal and marine resources, regions like NTT and Gorontalo struggle to leverage them due to inadequate infrastructure, weak institutional frameworks, and lack of integrated energy and fisheries policies. Your focus on renewable energy electrification—especially solar power for cold storage and small-scale fishing vessels—adds a crucial technological dimension to the blue economy framework that was not deeply explored in the NTT case.

The findings of Nguyen and Wang (2024) highlight the transformative potential of integrated offshore aquaculture and renewable energy systems as part of sustainable blue economy strategies. Their co-location model—where floating solar panels, offshore wind turbines, and fish farming installations share space and infrastructure—demonstrates an innovative and efficient use of marine environments that reduces operational costs while preserving ecological balance.

These insights are particularly relevant to Gorontalo Regency, a region with vast solar exposure and untapped marine aquaculture potential (e.g., seaweed, shrimp, grouper). The integration of solar-powered electrification in fisheries infrastructure—including cold storage, fish processing facilities, and electric fishing vessels—mirrors the technological synergies discussed in the article. Such interventions would enhance post-harvest efficiency, lower carbon emissions, and boost fisher incomes.

Moreover, the concept of modular, multi-use coastal infrastructure proposed by Nguyen and Wang could inspire locally adapted systems in Gorontalo's coastal villages—systems that are compact, energy-efficient, and environmentally responsible. These findings underscore the need for cross-sectoral policy frameworks that combine clean energy, local governance, and community empowerment to accelerate blue economy transformation in Indonesia’s coastal regions.

Overall, the Gorontalo case study reinforces the notion that the blue economy is not merely about maximizing the use of marine resources, but represents a comprehensive framework for inclusive and sustainable socio-economic transformation. A robust blue economy strategy must be anchored in the integration of technological innovation, renewable energy access, institutional capacity-building, and community empowerment. This study demonstrates that solar-based electrification of the fisheries sector can significantly reduce operational costs, enhance post-harvest value retention, and open pathways to technology adoption and market expansion—especially for small-scale fishers previously excluded from such opportunities.

Beyond technological solutions, the success of the blue economy lies in the ability of coastal communities to establish participatory and adaptive governance systems. Local institutions such as fisher cooperatives and community enterprises play a vital role in ensuring equitable benefit distribution and social ownership of transformation processes. Effective blue economy implementation must be context-sensitive, tailored to the geographic, cultural, and social realities of each coastal region, rather than imposed through one-size-fits-all models.

In this light, Gorontalo has the potential to serve as a living laboratory for renewable energy–driven blue economy development in eastern Indonesia—an approach that bridges structural underdevelopment with sustainable innovation, while simultaneously fostering long-term economic resilience and self-reliance among coastal populations.

Conclusion:-

This study concludes that the transformation of the fisheries sector in Gorontalo Regency through the blue economy approach and renewable energy electrification has had a tangible impact on improving both productivity and sustainability of local fishery systems. Working capital and operational costs were found to significantly influence fisher productivity, especially when complemented by post-harvest technologies such as solar-powered cold storage. Villages equipped with clean energy infrastructure and strong local institutions recorded the highest blue economy index scores and notable increases in fisher income.

The findings also emphasize the critical role of social institutions, such as fisher cooperatives, joint business groups, and local community forums, in fostering participatory and sustainable resource governance. High levels of community participation not only enhance adaptability to new technologies but also strengthen a sense of ownership over marine resources. Furthermore, although formal education levels do not directly correlate with productivity, villages with higher literacy rates showed greater technological responsiveness—adopting tools such as smart fishing, market information systems, and GPS-based navigation more rapidly.

Therefore, a successful blue economy strategy must be designed holistically and contextually, integrating economic, technological, institutional, and ecological dimensions into a unified coastal development framework. The model developed and tested in Batudaa Pantai and Biluhu serves as a replicable reference for other coastal regions in Indonesia, provided it is adapted to local socio-environmental conditions. It offers a pathway not only to enhance fisher resilience and income, but also to anchor small-scale fisheries within a more inclusive, sustainable, and future-oriented maritime economy.

Policy Recommendation:-

This study offers several key policy implications for the development of coastal fisheries, particularly in Gorontalo Regency. First, there is a need for pro-fisher fiscal policies that expand access to affordable and flexible microfinance, accompanied by technical support and capacity building. Working capital and operational financing interventions should be prioritized for active fisher groups with clear institutional structures.

Second, local governments should treat renewable energy electrification as a strategic program to support the small-scale fisheries industrialization agenda. Investments in solar-powered cold storage, solar panel installations for ports and fisher centers, and the development of village-level energy hubs should be included in sustainable development schemes. These efforts not only improve post-harvest efficiency but also enhance energy resilience and reduce carbon emissions.

Third, strengthening social institutions and local governance structures must be a top priority. This includes revitalizing fisher cooperatives, providing incentives for community participation in resource management, and offering managerial and digital training for village officials and institutional leaders. Building such capacity is vital for ensuring the long-term sustainability of blue economy programs.

Fourth, fisher empowerment programs should go beyond production enhancement and incorporate technological literacy, digital marketing, and environmental education. Local governments are encouraged to collaborate with universities, NGOs, and private actors in establishing village-based fishery innovation ecosystems.
By integrating economic, energy, social, and technological policies in a coherent and simultaneous manner, the transformation of the fisheries sector in Gorontalo can serve as a replicable model for inclusive and sustainable coastal development across Indonesia.

Limitations:-

This study acknowledges several limitations that should inform the interpretation of its findings. First, the geographic focus is confined to two coastal sub-districts in Gorontalo Regency, which limits broader generalization to other coastal regions in Indonesia. Second, the blue economy indicators employed are relatively basic and quantitative in nature, lacking integrated assessments of spatial-ecological dynamics and full value chain sustainability. Third, the absence of long-term individual-level panel data constrains the analysis of behavioral changes and enduring impacts.
Future research should expand the geographical coverage to multiple coastal districts and provinces, integrate spatial-bioeconomic modeling based on marine ecological systems, and utilize continuous digital data from fisheries

information platforms. A mixed-methods approach remains essential to capture the complex social, institutional, and cultural dynamics that are often beyond the reach of purely statistical analyses.

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