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LIFE CYCLE ASSESSMENT AND COST OPTIMIZATION OF RENEWABLE ENERGY SYSTEMS: A MANAGEMENT ENGINEERING PERSPECTIVES

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ABSTRACT

This study investigates the profile, environmental impact, economic viability, and optimization strategies of Region 1, Philippines, renewable energy systems. Employing a mixed-methods approach, the research assessed commonly deployed technologies, distribution across municipalities, installed capacity, and supporting policy frameworks. Findings reveal that solar and hydropower are the most prevalent technologies, with deployment concentrated in municipalities such as Burgos, Bangui, San Fernando City, and Candon City. While renewable energy contributes significantly to the region's energy mix, fossil fuels still account for a substantial share. Environmental lifecycle analysis shows positive stakeholder perceptions, particularly in operational efficiency and emissions reduction, although gaps remain in decommissioning practices. Economically, high initial costs pose barriers, yet renewables are perceived as cost-competitive and financially viable in the long term. The study concludes that comprehensive strategies – including infrastructure development, regulatory reforms, local manufacturing promotion, and broader access to incentives – are essential to optimize renewable energy systems and promote sustainable energy development in Region 1.

KEYWORDS: *Energy Economics, Environmental Sustainability, Policy and Infrastructure Optimization, Region 1 Philippines, Renewable Energy Systems*

1. INTRODUCTION

Renewable energy systems (RES) are vital in fostering sustainable development, strengthening climate resilience, and boosting regional economies. Rapid technological advances have made these clean alternatives to fossil fuels more cost-effective. However, integrating them into local power systems—particularly within municipal grids—remains challenging. Life Cycle Assessment (LCA) is essential for evaluating RES's environmental and economic performance, enabling informed policy-making and deployment strategies.

Region 1, comprising Ilocos Norte, Ilocos Sur, La Union, and Pangasinan, is steadily positioning itself as a key renewable energy hub in northern Luzon. The region is at the forefront of solar, wind, hydro, and biomass energy development, benefiting from its favorable topography and abundant natural resources. Ilocos Norte, in particular, is notable for hosting Southeast Asia's first onshore wind facility—the 33 MW Bangui Wind Farm—and the 150 MW Burgos Wind Farm, which is currently the largest in the region. Other significant wind energy projects include the 81 MW Caparispisan Wind Farm and the ongoing Balaoi–Caunayan Wind Project, which is expected to generate 160 MW upon completion (Wikipedia, n.d.). In terms of solar energy, the recently operational Ilocos Norte Solar PV Park (83.3 MW) and the Garcia 2 Solar Project in Currimao (68 MW) represent major advancements in the region's solar power capacity (Power Technology, n.d.; Inquirer Business, n.d.).

However, implementation across Region 1 is uneven. Municipal infrastructure, policy, and technical capacity disparities have restricted broader adoption. Constraints such as weak grid integration, municipal-level regulatory inconsistencies, and high upfront costs persist despite national incentives like Feed-in Tariffs and the Green Energy Auction Program. Addressing these is critical to scaling renewables effectively.

Region 1 is also increasingly climate-sensitive, facing regular typhoons, droughts, and coastal risks. These conditions underscore the importance of decentralized and resilient renewable energy models. Local initiatives—such as solar water-pumping systems and barangay-level microgrids—exemplify viable decentralized solutions supported by partnerships among LGUs, private stakeholders, and NGOs.

Despite the promising growth and local resilience efforts, a significant knowledge gap remains regarding the full life cycle costs and environmental impacts of RES in Region 1. Each province—and its municipalities—exhibits unique resource profiles, socio-economic conditions, and vulnerability contexts. This study responds to this gap by conducting a comprehensive life cycle and cost assessment of RES in Region 1. It evaluates technology deployment, municipal distribution, financial viability, policy support, and ecological implications to support

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sustainable energy planning in alignment with local priorities and national climate goals.

2. OBJECTIVES

This study aims to evaluate and optimize renewable energy systems in Region 1, Philippines, through life cycle assessment and cost analysis from a management engineering perspective. Specifically, it seeks to profile these systems regarding technology types, geographic distribution, installed capacity, policy frameworks, and financing mechanisms. It also assesses the environmental impacts across various life cycle stages, including resource extraction, construction, operation, decommissioning, and reduction of greenhouse gas emissions. Furthermore, the study analyzes key economic factors such as capital investment, operational costs, return on investment, and cost competitiveness relative to traditional energy sources. It identifies the technical, regulatory, and financial challenges that hinder optimization and, ultimately, proposes integrated management strategies to improve the region's environmental and economic performance of renewable energy systems.

3. METHODOLOGY

Research Design

This study employed a descriptive-exploratory research design to examine the characteristics, challenges, and emerging patterns associated with renewable energy systems (RES) in Region 1, Philippines. This approach was deemed appropriate for systematically describing RES's technical and socio-economic dimensions while exploring the underlying factors influencing their implementation—particularly in provincial and rural settings where empirical studies are relatively limited (Creswell, 2014). Integrating descriptive and exploratory methods enabled the researcher to capture measurable performance indicators and contextual insights relevant to the region's unique geographic, economic, and social landscape.

4. SAMPLING DESIGN

A purposive sampling technique was utilized to identify and select information-rich respondents directly involved in renewable energy projects within Region 1. Two key participant groups were targeted: (1) engineers, technical personnel, and developers affiliated with active RES projects such as the Bangui Wind Farm, Burgos Wind Project, and solar farms in Ilocos Norte and La Union; and (2) local community members residing in areas directly impacted by these installations. The first group provided expert insights on project planning, implementation, operational challenges, and cost optimization strategies. The second group offered grassroots perspectives on energy accessibility, environmental and economic impacts, and community perceptions regarding the sustainability of these systems.

5. INSTRUMENTATION

The primary data collection tool was a structured questionnaire comprising closed-ended and open-ended questions. This mixed-method format enabled the collection of consistent quantitative data while also capturing qualitative narratives from respondents. The instrument was developed through a multi-phase process that included item drafting, expert panel validation (involving energy professionals from Region 1), pilot testing in Ilocos Norte, and subsequent refinement based on feedback. Ethical clearance and permissions were obtained from local authorities and institutional stakeholders to ensure compliance with regional protocols.

6. DATA COLLECTION PROCEDURE

Data were gathered over two months to accommodate the dispersed geographical coverage of the selected RES sites in Region 1. Questionnaires were distributed electronically to respondents in urban centers or working in energy facilities. Face-to-face administration was conducted for rural and off-grid communities—especially in the municipalities of Burgos, Bangui, Pagudpud, and parts of La Union—to ensure inclusivity despite connectivity challenges. This dual-mode approach ensured balanced representation across technologically advanced and underserved regional locations.

7. GEOGRAPHICAL SCOPE

The research focused exclusively on municipalities in Region 1 hosting operational renewable energy infrastructure. These include Ilocos Norte (notably Burgos, Bangui, and Pagudpud), where large-scale wind and solar projects are located, and La Union, which features smaller-scale solar and hydropower systems. Municipalities without active renewable installations were excluded to maintain contextual relevance and ensure that all respondents had direct or indirect exposure to renewable energy systems in their respective localities.

8. STATISTICAL AND QUALITATIVE ANALYSIS

Quantitative data were analyzed using descriptive statistics such as frequencies, percentages, means, and standard deviations. These tools facilitated the profiling of respondent groups and the assessment of perceived benefits, operational costs, and environmental performance of RES in Region 1.

For the qualitative component, thematic analysis was applied to open-ended responses. Responses were coded and categorized into major themes—such as perceptions of sustainability, socio-economic impact, and policy awareness—allowing for a deeper understanding of various stakeholders lived experiences and views. The themes were validated through peer debriefing and triangulated with secondary data to ensure credibility and depth.

10. RESULTS

3.1 Profile of Renewable Energy Systems in Region 1

3.1.1 Types of Renewable Energy Technologies Commonly Deployed

The study revealed that solar energy systems are the most widely deployed renewable energy technology in Region 1, comprising 28% of all identified systems. This trend reflects the region's strategic exploitation of its high solar irradiance, particularly in rural and off-grid areas (DOE Region 1, 2023). Hydropower follows at 24%, continuing its historical role as a mainstay in the regional energy mix. Biomass accounts for 16%, suggesting growing interest in waste-to-energy applications, although deployment is still limited. These findings imply a promising but uneven diversification of renewable energy technologies, emphasizing the need for municipality-specific deployment strategies (IRENA, 2023).

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The dominance of solar and hydro indicates a shift toward more sustainable energy sources but also underscores the importance of balanced development across renewable technologies to maximize energy security and equity across Region 1.

3.1.2 Municipal Distribution and Availability of Renewable Energy Resources in Region 1
In Region 1, the distribution of renewable energy resources varies among municipalities. It is influenced by geography, infrastructure, and local energy policies. Ilocos Norte leads with the highest concentration of renewable energy projects, particularly wind and solar farms in Burgos, Bangui, and Pagudpud. These municipalities benefit from favorable wind patterns and high solar irradiance. La Union follows, with several solar energy projects spread across the municipalities of Bauang, San Fernando City, and Agoo, supported by relatively well-developed infrastructure. Pangasinan contributes through biomass and hydropower projects in municipalities such as San Carlos City and Bayambang. Ilocos Sur, meanwhile, has emerging solar projects in municipalities like Narvacan and Candon City. This uneven distribution highlights municipal-level disparities in renewable energy deployment and infrastructure readiness (World Bank, 2022). Targeted local policies and investments are essential to unlock the renewable energy potential of underserved municipalities and achieve equitable energy development across Region 1.

3.1.3 Installed Capacity and Contribution to the Total Energy Mix Renewable energy contributes 30% to Region 1's total energy mix, led by geothermal, hydro, and solar. However, coal (27%) and natural gas (23%) remain significant, reflecting Region 1's continued reliance on fossil fuels despite climate commitments (IEA, 2023). While the contribution of renewables is notable, the continued dominance of fossil fuels suggests a need for accelerated transitions through more vigorous enforcement of renewable energy policies and incentives.

3.1.4 Policy Frameworks and Incentives Supporting Renewable Energy Adoption
The Feed-in Tariff (FiT) system is the most cited incentive mechanism at 35%, followed by the Renewable Energy Act of 2008 (31%) and the Net Metering Program (17%). The Green Energy Auction Program (14%) and other financial incentives (3%) reflect limited awareness or accessibility (DOE Region 1, 2023). The findings highlight the effectiveness of FiT and the RE Act but suggest the need for broader dissemination and implementation of other mechanisms to encourage more participation from developers and consumers alike.

3.1.5 Current Costs and Funding Mechanisms for Renewable Energy Projects
Public-private partnerships (34%) lead funding mechanisms, with government subsidies (25%) and international financial support (21%) following closely. Local investments (13%) and innovative mechanisms like green bonds (7%) are less utilized (ADB, 2022). While PPPs and government support remain central, expanding access to innovative financing tools is essential for scaling renewable projects and attracting more private sector participation.

3.2 Environmental Impacts Across the Renewable Energy Lifecycle
3.2.1 Material Extraction and Resource Utilization
Respondents generally agreed that renewable energy projects utilize resources efficiently (mean = 3.88). The highest-rated indicator was "resource utilization is optimized" (4.18), reinforcing the perception of sustainability in early lifecycle stages (IEA, 2022). Positive stakeholder perceptions support further investment in renewables but call for standardized lifecycle assessments to validate these perceptions across project types.

3.2.2 Manufacturing and Construction Processes This stage received favorable scores, with a grand mean of 4.12. The item "Construction processes use sustainable practices" scored 4.32, suggesting developers are increasingly adopting green construction protocols (UNEP, 2023). Encouraging sustainability in construction strengthens public support and can contribute to achieving broader environmental goals.

3.2.3 Operation and Maintenance Requirements The operational phase was viewed favorably, with a grand mean 4.29. The statement "Renewables require minimal environmental intervention" scored 4.40 (IRENA, 2023). High operational efficiency and minimal impact can be key selling points in policy advocacy and consumer education efforts.

3.2.4 Decommissioning and Waste Management Practices
This phase received lower agreement (mean = 3.10), with environmental restoration post-decommissioning rated 3.70. The result implies underdeveloped protocols for system end-of-life management (IEA, 2022). Policymakers must prioritize establishing clear guidelines for decommissioning and waste handling to ensure full lifecycle sustainability.

3.2.5 Carbon Footprint and Greenhouse Gas Emissions Reduction Strong agreement was expressed on emissions reduction benefits (mean = 4.17). The highest score (4.48) was given to the statement about carbon reduction (UNFCCC, 2022). These results affirm the role of renewables in climate mitigation, reinforcing the need for national policies that prioritize clean energy in emissions reduction plans.

3.3 Economic Factors Influencing Adoption and Sustainability
3.3.1 Initial Investment Costs Respondents acknowledged high upfront costs (mean = 3.06), indicating cautious optimism regarding long-term benefits (ADB, 2022). Government subsidies, tax incentives, and financing options must be strengthened to overcome initial cost barriers.

3.3.2 Operational and Maintenance Costs Operational costs were rated modestly (mean = 2.90), though the importance of regular maintenance was recognized (3.22). Investment in local technical capacity and maintenance support systems is necessary for project sustainability.

3.3.3 Return on Investment and Payback Periods This dimension scored highly (mean = 4.12), indicating strong confidence in the financial viability of renewable energy.

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Positive ROI perceptions are critical for attracting long-term private and institutional investors.

3.3.4 Cost Competitiveness Compared to Traditional Energy Sources Respondents overwhelmingly supported the cost competitiveness of renewables (mean = 4.78). With renewables now seen as economically superior, policy shifts must reflect this reality by phasing out fossil fuel subsidies.

3.3.5 Role of Subsidies, Tax Incentives, and Financing Options A moderate mean 3.20 was recorded. While the role of fiscal tools is acknowledged, implementation gaps remain. A re-evaluation of existing fiscal frameworks is essential to ensure equitable and timely access to funding.

3.4 Key Challenges and Barriers to Optimization High initial costs were the most cited barrier (28%), followed by regulatory delays, limited grid capacity, and lack of technical expertise. These findings mirror national and global studies on renewable energy hurdles (World Bank, 2022). Coordinated multi-stakeholder strategies are needed, combining infrastructure development, policy streamlining, and workforce training.

3.5 Strategies to Optimize Life Cycle Costs and Environmental Impacts The top strategies proposed include enforcing stricter environmental regulations (27%), promoting local manufacturing of components (23%), and increasing financial incentives (22%). Others emphasized PPPs (17%) and investment in R&D (13%). A holistic optimization approach integrating regulatory, industrial, and financial interventions is key to enhancing the performance and sustainability of renewable energy systems in Region 1.

11. SUGGESTIONS

Future studies may conduct a comparative life cycle assessment (LCA) of specific renewable energy technologies—such as solar, wind, hydropower, and biomass—to identify the most efficient systems under Region 1's conditions (IRENA, 2023). Research on post-decommissioning impacts is also recommended to address gaps in waste management and environmental restoration (IEA, 2022).

Further inquiry into the socioeconomic effects of renewable energy at the community level could inform inclusive development strategies (World Bank, 2022). Applying optimization models from management engineering, such as cost-benefit analysis and simulations, may enhance deployment efficiency (ADB, 2022).

Assessing the effectiveness of policy implementation and identifying local barriers would help align national frameworks with regional realities (DOE Region 1, 2023). Additionally, exploring the feasibility of local manufacturing hubs for renewable components could support job creation and reduce reliance on imports (UNEP, 2023).

Research on grid integration, storage solutions, and consumer adoption behaviors is essential to support long-term sustainability (IEA, 2023; ADB, 2022). Lastly, cross-regional comparative studies could offer broader insights into renewable energy development across the Philippines (World Bank, 2022).

12. CONCLUSION

The study concludes that renewable energy systems in Region 1 are undergoing significant growth, with solar and hydropower emerging as the dominant technologies due to the region's favorable geographic and climatic conditions. However, this dominance also reflects an uneven diversification of renewable energy sources, as biomass and wind remain underutilized. The distribution of renewable energy projects varies considerably among municipalities, revealing infrastructural and policy disparities that must be addressed to ensure equitable access and energy development across the region.

Despite contributing 30% to the regional energy mix, renewable energy is still overshadowed by fossil fuels such as coal and natural gas. This indicates that while progress is evident, a more aggressive transition is necessary to meet national climate goals. The study also found that while policies like the Feed-in Tariff and Renewable Energy Act are widely recognized and utilized, other mechanisms—such as the Green Energy Auction Program and Net Metering—suffer from limited awareness and accessibility, highlighting the need for broader dissemination and simplified implementation procedures.

From an environmental perspective, renewable energy projects are generally perceived as sustainable throughout most life cycle stages, particularly during construction and operation. However, the study identifies a critical gap in decommissioning and waste management practices, underscoring the need for clear environmental protocols to ensure long-term sustainability. Economic analyses reveal that high initial costs remain a barrier to adoption, though strong perceptions of return on investment and cost competitiveness suggest increasing market confidence in renewable technologies.

Furthermore, the study identifies key barriers to optimization, including regulatory delays, grid limitations, and the lack of technical expertise. Nonetheless, respondents propose various viable strategies, such as stricter environmental regulations, increased financial incentives, and the promotion of local manufacturing to improve the performance and scalability of renewable energy systems. Overall, the findings underscore the importance of integrated policy, financial, and technical interventions in advancing a sustainable, inclusive, and efficient renewable energy transition in Region 1.

13. AREA FOR FURTHER RESEARCH

To enhance the sustainability and efficiency of renewable energy systems in Region 1, several strategic actions are recommended. First, investments in underutilized sources such as biomass and wind should be encouraged to complement the current dominance of solar and hydropower, with deployment guided by localized resource assessments. Addressing regional disparities is also crucial; municipalities with limited renewable energy uptake, particularly in Ilocos Sur and Pangasinan, should be supported through targeted technical and financial

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assistance. In parallel, accelerating the phase-out of fossil fuels requires the enforcement of clean energy targets, reduction of fossil fuel subsidies, and the strengthening of pro-renewable policies. Expanding awareness and streamlining access to incentive mechanisms—such as the Net Metering Program and the Green Energy Auction—will foster broader stakeholder participation. Financing must also be diversified through instruments like green bonds, community investments, and microfinancing to attract both public and private investors. Environmental oversight should be reinforced by establishing clear protocols for decommissioning and waste management to ensure lifecycle sustainability. Developing local technical expertise through training programs and institutional partnerships will further support reliable operations and maintenance. Additionally, promoting successful renewable energy projects and reinforcing the confidence in return on investment (ROI) can attract more private investment and increase market trust. Reviewing and improving existing fiscal frameworks will help ensure more equitable, transparent, and accessible subsidy programs. Lastly, a multi-sectoral, integrated optimization strategy—combining regulatory reforms, local manufacturing support, research and development, and robust public-private partnerships—is essential for advancing renewable energy development in the region.

13. FIGURES AND REFERENCES

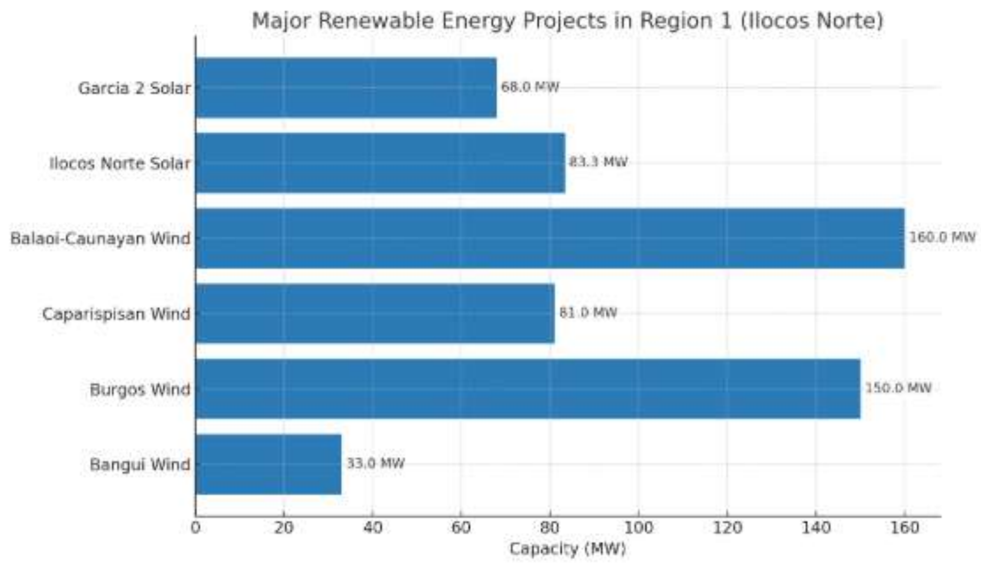

Figure 1. ***Major Renewable Energy Projects in Region 1 by Capacity (in MW)***

REFERENCES

1. *ACEN Corporation. (2023). Project portfolio. https://www.acenrenewables.com*
2. *Asian Development Bank (ADB). (2022). Renewable energy investment opportunities in Southeast Asia: Country highlights for the Philippines. Mandaluyong City: ADB.*
3. *Asian Development Bank. (2022). Renewable energy investment opportunities in the Philippines. https://www.adb.org*
4. *Ayala Group. (2023). Renewable energy investments in the Philippines. https://www.ayala.com.ph*
5. *Bangui Wind Farm. (n.d.). Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Bangui_Wind_Farm*
6. *Balaoi and Caunayan Wind Farm. (n.d.). Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Balaoi_and_Caunayan_Wind_Farm*
7. *BusinessWorld. (2021, May 20). AC Energy starts building 160-MW Pagudpud wind farm. https://www.bworldonline.com*
8. *Caparispisan Wind Farm. (n.d.). Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Caparispisan_Wind_Farm*
9. *Department of Energy (DOE). (2023). Energy situationer and outlook for Regionhttps://www.doe.gov.ph*
10. *Department of Energy (DOE). (2023). Philippine energy situationer and outlook. https://www.doe.gov.ph*
11. *Energy Development Corporation (EDC). (2023). Burgos Wind Farm profile. Power-Technology. Retrieved from global Power-Technology database*
12. *First Gen Corporation. (2023). Clean energy solutions. https://www.firstgen.com.ph*
13. *Global Energy Monitor. (2023). Garcia 2 solar farm. https://www.gem.wiki/Garcia_2_solar_farm*
14. *GlobalData. (2024, October 21). Ilocos Norte Solar PV Park. Power-Technology Data Insights.*
15. *International Energy Agency (IEA). (2022). Southeast Asia energy outlook. Paris: IEA.*
16. *International Energy Agency (IEA). (2022, 2023). Renewable energy market updates. https://www.iea.org*
17. *International Energy Agency (IEA). (2023). Tracking clean energy progress: Renewable energy in the Philippines. Retrieved from https://www.iea.org*
18. *International Renewable Energy Agency (IRENA). (2023). Renewable capacity statistics. https://www.irena.org*
19. *International Renewable Energy Agency (IRENA). (2023). Renewable capacity statistics by region and country. Abu Dhabi: IRENA.*
20. *Koons, E. (2022). Wind energy in the Philippines. EnergyTracker Asia.*

ISSN (Online): 2455-3662
EPRA International Journal of Multidisciplinary Research (IJMR) - Peer Reviewed Journal
Volume: 11| Issue: 6| June 2025|| Journal DOI: 10.36713/epra2013 || SJIF Impact Factor 2025: 8.691 || ISI Value: 1.188

21. *Philippine Daily Inquirer. (2023, March 31). NSEC opens 68-MW Garcia 2 solar project in Ilocos Norte. Retrieved from https://www.inquirer.net*
22. *United Nations Environment Programme (UNEP). (2023). Guidelines for sustainable infrastructure in Asia. Nairobi: UNEP.*
23. *United Nations Environment Programme (UNEP). (2023). Sustainable infrastructure and construction. https://www.unep.org*
24. *United Nations Framework Convention on Climate Change (UNFCCC). (2022). Nationally determined contributions synthesis report: Philippines update. Bonn: UNFCCC.*
25. *United Nations Framework Convention on Climate Change (UNFCCC). (2022). Nationally determined contributions synthesis report. https://unfccc.int*
26. *World Bank. (2022). Achieving sustainable energy for all in Philippine regions: Focus on Luzon and Region 1. Washington, D.C.: World Bank.*
27. *World Bank. (2022). Achieving sustainable energy for all in the Philippines. https://www.worldbank.org*
28. *World Bank. (2023). Decentralized energy systems and municipal renewable energy planning in Southeast Asia. Retrieved from https://www.worldbank.org*