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The Philippines' Energy Transition: Assessing Emerging Technology Options Using OSeMOSYS (Open-Source Energy Modelling System)

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Abstract: The Philippines aspires for a clean energy future but has become increasingly reliant on imported fossil fuels due to rising energy demands. Despite renewable energy targets and a coal moratorium, emissions reductions have yet to materialize. This study evaluates the potential of offshore wind (floating and fixed), floating solar PV, in-stream tidal, and nuclear power to contribute to a Net-Zero energy plan for the Philippines, utilizing the Open-Source Energy Modelling System (OSeMOSYS). Seven scenarios were analyzed, including least-cost, renewable energy targets; Net-Zero emissions; and variations in offshore wind growth and nuclear power integration. Floating solar PV and offshore wind emerged as key decarbonization technologies, with uptake in all scenarios. Achieving Net-Zero CO_2 emissions by 2050 proved technically feasible but requires substantial capital, particularly after 2037. Current renewable energy targets are inadequate to induce emissions reductions; and a higher target of ~42% by 2035 was found to be more cost-effective. The addition of nuclear power showed limited cost and emissions benefits. Emissions reductions were projected to mainly occur after 2038, highlighting the need for more immediate policy action. Recommendations include setting a higher renewables target, offshore wind capacity goals, a roadmap for floating solar PV, and better incentives for private investment in renewables and electric transport.

Keywords: decarbonization pathways; renewable energy targets; Net Zero; floating solar PV; offshore wind; least-cost planning

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1. Introduction

This study examines the feasibility of reaching Net-Zero emissions in the Philippines through the integration of emerging low-carbon technologies into the national energy mix. It aims to comprehensively analyze the potential contributions of offshore wind, floating solar PV, in-stream tidal, and nuclear power.

1.1. Background

To limit global warming to below 2 degrees Celsius and mitigate the worst impacts of climate change, a substantial reduction in emissions from the energy sector, responsible for over 75% of global greenhouse gas emissions, is imperative [1]. In the Philippines, an archipelago nation in Southeast Asia, the decarbonization of the energy system is complicated by the necessity to meet increasing energy demand, driven by an expanding service sector [2]. As of June 2023, the total installed power generation capacity in the Philippines is 28.297 GW and is expected to need to quadruple by 2040 [3,4].

Figure 1 illustrates the breakdown of primary energy supply in the Philippines by technology type in 2021 [5]. CO_2 emissions were predominantly from the electricity sector (56.7%), followed by transport (24.1%), industry (9.6%), other sectors (9.3%), and non-energy use (0.3%) [5]. The sectoral contributions to the Philippines' total final energy consumption are summarized in Table 1 [5]. In recent years, the nation has become increasingly reliant on imported fossil fuels to meet rising demand, with these fuels making up 48.5% of the primary energy mix in 2021 [5]. As a result, the nation was among the top four coal importers globally in 2023 [6]. Furthermore, in contrast with its ASEAN counterparts, the Philippines lacks a national policy commitment to the Net-Zero target for the energy sector [7].

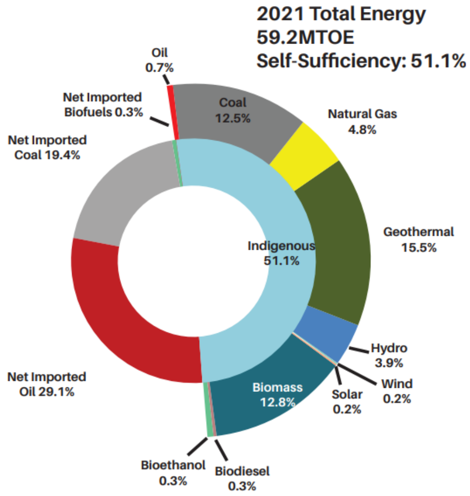

Figure 1. Breakdown of the Philippines' primary energy supply by technology type in the year 2020/21; 1 MTOE = 41.868 PJ [5].

Table 1. Breakdown of final energy consumption by sector in 2021 [5].

Sector	Final Energy Consumption (%)
Transport	31.3
Households	29.1
Industry	19.4
Services	13.7
Non-Energy Use	4.6
Agriculture	2

To transition towards cleaner energy sources and reduced import dependence, which leaves the country vulnerable to price shocks and supply disruption, the Philippines has established targets to enhance the adoption of renewable energy, aiming for a 35% share of the power generation mix by 2030 and 50% by 2040 [2,8]. Additionally, the Philippines' Nationally Determined Contribution (NDC) under the Paris Agreement aims for a 75% reduction in greenhouse gas (GHG) emissions by 2030, with 72.29% of this target contingent upon international support and 2.71% representing unconditional emissions reductions [9]. A moratorium on the issuance of new permits for coal power plants was implemented in 2020 [10]. These policies have yet to translate into a tangible decrease in fossil fuel dependence. The Philippines is investigating the incorporation of emerging low-carbon technologies into its energy mix to tackle these challenges and advance towards energy independence. This study evaluates the potential of offshore wind (both floating and fixed), floating solar PV, in-stream tidal, and nuclear power technologies to contribute to the future energy mix in the Philippines and examines the feasibility of achieving a Net-Zero target in the country.

This paper first presents the context and a literature review for the study (Section 1), followed by the methodology (Section 2), results (Section 3), and discussion (Section 4). Section 4 presents essential findings, policy implications, limitations, and directions for future research. The article concludes with final remarks in Section 5.

1.2. Literature Review

This literature review examines the extensive research on low-carbon energy transition pathways in the Philippines. It first examines prior studies, before diving deeper into emerging power technology options under consideration for integration into the country's energy mix.

1.2.1. Previous Studies

A growing body of research explores pathways for a low-carbon energy transition in the Philippines (Table 2). These studies highlight the potential for the country to achieve Net Zero, often emphasizing solar PV as a crucial technology, and pointing to potential co-benefits such as improved air quality and economic growth [11–15].

Table 2. Summary of key existing studies on energy transitions in the Philippines and their findings.

Study	**Scope**	**Relevant Findings**
Jacobson et al. (2018) [11]	Global study modelling pathways for 100% renewable energy by 2050.	Low-cost 100% renewable solution is possible globally and in the Philippines.
Teske (2019) [12]	Global study for achieving Net-Zero GHG emissions by 2050.	Zero GHG emissions possible across all sectors, potential challenges with interconnection in SE Asia.
Mondal et al. (2018) [13]	Assessment of low-carbon energy scenarios in the Philippines (2014–2040).	System cost increase of only 2.6% in renewable target scenario, diversification of supply improves security and decarbonization efforts.
Gulagi et al. (2021) [14]	Analysis of the Philippines' transition to 100% renewable energy (2015–2050).	Transition possible by 2050, solar PV and battery storage key technologies, possible to gain >50% efficiency with significant investment.
Alexander et al. (2023) [15]	Assessment of clean energy transition scenarios in the Philippines (2015–2070).	Phasing out coal crucial for emission reduction, solar PV identified as a key technology for transition.

This study builds on previous energy modelling studies, re-examining the technical feasibility of a Net-Zero target with the addition of technology options emerging before 2030. The integration of the new technologies such as floating solar PV, fixed and floating OSW, tidal in-stream, and nuclear power within this model can provide valuable policy insights regarding the interaction of these technologies with a reference energy system and their potential role in decarbonization in the Philippines.

1.2.2. Emerging Technology Options

Table 3 summarizes the technical potential and challenges of identified emerging marine technologies in the Philippines, adapted from [16].

The 2022 Philippines Offshore Wind Roadmap, a collaboration between the Philippines DOE and the World Bank, highlights the country's significant offshore wind potential (178 GW) and outlines two scenarios: "Low Growth" targeting 2 GW by 2040 and "High Growth" aiming for 20 GW by the same date [17]. Both scenarios employ a mix of fixed and floating offshore wind. While the high-growth scenario suggests promising opportunities for cost reduction, job creation, and local investment, these scenarios have not been extensively modelled within the existing or projected energy system. This means that potential interactions and complexities with the existing infrastructure have not been fully considered.

Table 3. Technical Potential and Challenges of Marine Energy Technologies in the Philippines [16].

Technology	Technical Potential	Opportunities	Challenges
Offshore Wind	178 GW (160 GW, floating; 18 GW, fixed)	Mature technology, roadmap available, good port infrastructure	Leasing and permitting, grid connection, port availability
Floating Solar PV	83 GW	Mature technology, competitive in remote regions	Leasing and permitting, political and commercial hurdles
Tidal In-Stream	40–60 GW	High technology readiness level, cost decrease over time, leverages existing shipbuilding	Logistical challenges, knowledge gap, requires subsidies

1.2.3. Nuclear Power Considerations

The Philippines currently lacks active nuclear power projects but has explored the option in the past, with the Bataan Nuclear Power Plant remaining non-operational since its construction in the 1970s [18]. Recent discussions have rekindled interest, with the consideration of a 2400 MW nuclear capacity target by 2035 (utilizing SMRs), and the consideration of the Bataan plant's revival [19,20]. However, public perception, regulatory hurdles, lack of local expertise, and inherent geographical risks remain significant challenges for nuclear power adoption in the Philippines [20].

1.3. Purpose and Significance

This study builds on previous research assessing the technical feasibility of achieving a Net-Zero CO_2 emissions target for the Philippines energy sector, incorporating emerging technologies that are not currently utilized in the country (floating solar PV, fixed and floating offshore wind, tidal in-stream, and nuclear power) into the model alongside existing options.

This study aims to

1. Assess the feasibility of meeting current renewable energy targets and a Net-Zero target in the Philippines, from both a technical and economic perspective.
2. Analyze the contribution of offshore wind (floating and fixed), floating solar PV, in-stream tidal, and nuclear power to Net-Zero energy plans in the Philippines.
3. Offer policy recommendations based on the findings to inform the energy transition in the Philippines, considering technological, economic, and environmental factors.

By examining the viability and potential of emerging technologies and their interaction with the existing energy system, this research aims to provide insights to inform policymakers, industry stakeholders, and the broader scientific community focused on developing a cleaner and more resilient energy landscape in the Philippines.

2. Materials and Methods

This section outlines the methodology utilized in this study, adhering to the U4RIA principles of replicability and transparency. All data and protocols utilized in the analysis will be accessible to readers upon publication.

2.1. Modelling Approach: Open-Source Energy Modelling System (OSeMOSYS)

This study utilizes OSeMOSYS, a widely recognized tool for bottom-up, linear energy optimization modelling [21]. OSeMOSYS seeks to determine the minimum NPV cost for an energy system while adhering to specified energy demands, system constraints, and policy objectives [21]. Equation (1), representing this optimization, is displayed below:

$$\begin{aligned} & \quad\quad\quad\quad Minimise \sum_{y,t,r} Total\ Discounted\ Cost_{y,t,r} \\ \boldsymbol{Where}\ Total\quad & Discounted\ Cost_{y,t,r} \\ & = Discounted\ Operating\ Costs_{y,t,r} \\ & + Discounted\ Capital\ Investment_{y,t,r} \\ & + Discounted\ Technology\ Emissions\ Penalty_{y,t,r} \\ & - Discounted\ Salvage\ Value_{y,t,r} \end{aligned} \tag{1}$$

Emission Penalties were not used in this study. Operating Cost is equal to the sum of fixed and variable cost. Salvage Value is calculated in OSeMOSYS using either straight-line or sinking fund depreciation [21].

The model operates on a linear energy supply pathway, transforming primary energy sources into usable fuels that power specific technologies to generate secondary fuels and meet final energy needs.

OSeMOSYS (Open-Source Energy Modelling Software) with clicSAND Software 3.0 was chosen for this use case due to its alignment with the unique challenges faced by developing economies like the Philippines. Its open-source nature addresses data access issues, facilitates transparency for policymakers, enables further refinement, and allows for integration with other tools [22]. Its versatility in modelling diverse energy technologies and constraints makes it ideal for evaluating emerging technologies in achieving the Philippines' energy goals.

2.2. Reference Energy System and Data Inputs

This section details the reference energy system modelled and key updated data inputs. It covers the temporal scope, model structure, electricity demand, historical power generation, residual capacity, resource potential for power technologies, and cost considerations.

2.2.1. Base Model and Temporal Scope

The initial model was adapted from the Philippines OSeMOSYS starter data kit, a simple zero-order energy system model for 2020–2050, created by the authors of [23]. The temporal scope was condensed from 96 to 8 time slices, representing four distinct seasons (December–February, March–May, June–August, September–November), further subdivided into day and night periods.

2.2.2. Model Structure and Technology Representation

The model incorporates sixteen existing commodities: coal, oil (separate representations for spark-fired combined cycle, combined cycle with carbon capture and storage, and off-grid), gas, biomass, solar PV (utility-scale, utility-scale with storage, and standalone with storage), wind (onshore and onshore with storage), hydropower (large, medium, small, and off-grid), geothermal, and nuclear. Parameters for existing technologies (capital costs, fixed and variable costs, efficiency, capacity factors, operational lifetimes, maximum capacity potential, and emissions intensity) were consistent with the starter kit. To effectively represent energy efficiency improvements, the model can invest in sector-specific energy efficiency technologies, which capture some of the energy demand and thus reduce capacity requirements from power generation technologies. Imported electricity was kept constrained to zero into the future, to ensure that all energy demand can be met through domestic production.

Four novel technologies were incorporated into the model to explore their potential role in the energy transition: fixed offshore wind, floating offshore wind, floating solar PV, and in-stream tidal. Key variables for these added technologies, including capital cost, fixed cost, operational life, average capacity factor, and resource potential, are presented in Table 4.

Table 4. Key Parameters for added Technologies [16,17,24–26].

Technology	Capital Cost (USD/kW)	Fixed Cost (USD/kW)	Operational Life (Years)	Average Capacity Factor	Resource Potential (GW)
Fixed Offshore Wind [17]	2527 (2028)	63.4 (2028)	30	0.37	18
Floating Offshore Wind [17]	3937 (2028)	30	30	0.37	160
Floating Solar PV [16,24,25]	864.3 (2023)	12.5 (2023)	30	0.165	82.6
In-Stream Tidal [16,24]	2967 (2030)	62 (2030)	30	0.385	50

A reference diagram of the Philippines' energy system as modelled in this study is shown in Figure 2 below:

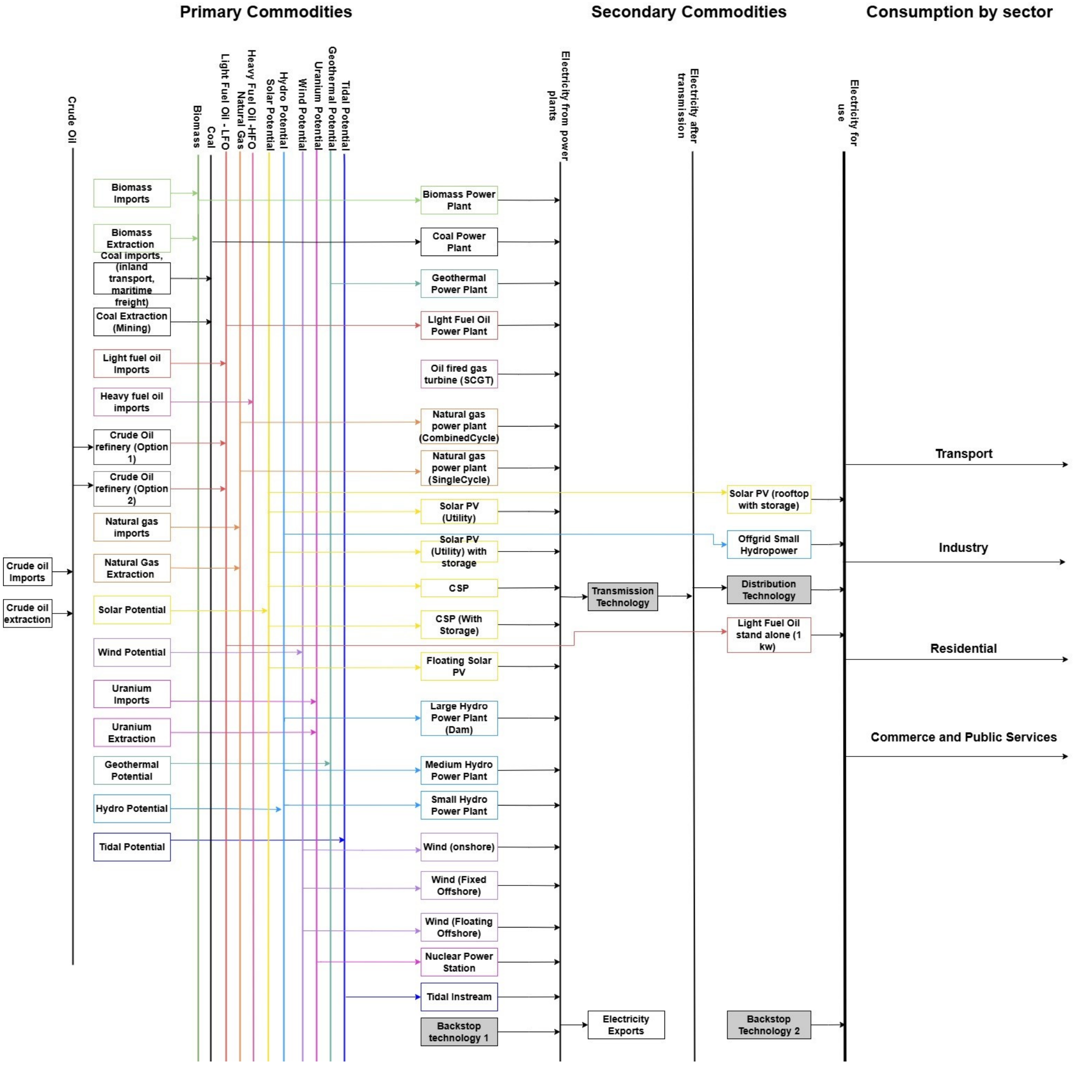

Figure 2. The reference energy system diagram (RES) for the Philippines energy system updated from the starter data kit [23]. Rectangles represent technologies while solid lines represent energy carriers. Note: Energy imports are removed from the model.

2.2.3. Data Inputs and Updates

Data input in the study is described below. More information on data collection and processing for input into the OSeMOSYS model can be found in the associated 'data-in-brief' article [27].

Electricity Demand

Historical electricity demand data for the period 2015–2022 were sourced from the latest DOE Power Statistics Summary (2022) [28]. To project demand for the period 2023–2050, linear growth rates were applied based on information provided in the Philippines Power Development Plan (2020–2040) [4]. These projections are further categorized into commercial, industrial, and residential sectors and are presented in Figure 3.

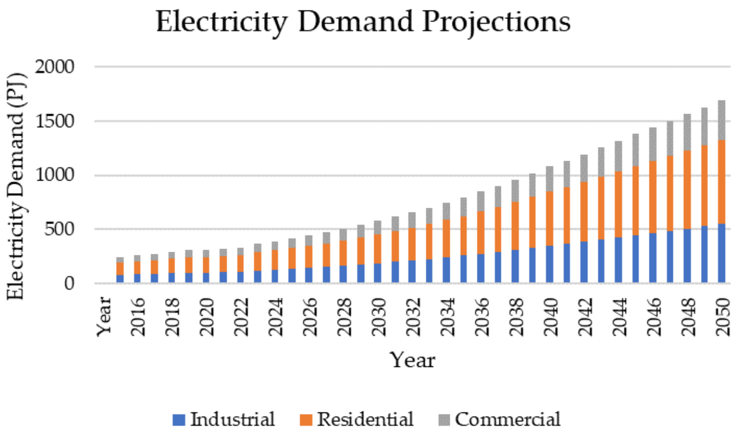

Figure 3. Projected electricity demand up to 2050, by sector (PJ).

Historical Electricity Generation

Historical generation values for 2022 were added to the model. Table 5 presents the historical generation data for various power plants in the Philippines in 2022. These data were obtained from the latest DOE gross generation statistics per plant type [29].

Table 5. Electricity generation by plant type in the year 2022 [29].

Plant Type	**Generation (PJ) [29]**	**% Total Generation**
Biomass	4.76	1.15%
Coal	239.15	57.73%
Geothermal	37.53	9.06%
CCGT	2.65	0.64%
SCGT	22.41	5.41%
Natural Gas	64.38	15.54%
Solar PV	6.56	1.58%
Large Hydropower (>100 MW)	26.11	6.30%
Medium Hydropower (10–100 MW)	3.87	0.93%
Small Hydropower	1.02	0.25%
Off-grid Hydropower	0.53	0.13%
Onshore Wind	3.71	0.90%
Off-grid Oil-Based	1.58	0.38%

Residual Power Capacity

Residual capacity projections for various power plants in the Philippines are presented in Table 6. These projections are based on the latest information regarding existing plant capacities, planned capacity extensions, and off-grid power generation, considering the period from 2023 to 2050 [29–34].

Table 6. Residual capacity of power technologies in the Philippines in 2022, and projections to 2030 and 2050 (GW) [29–34].

Power Plant	2022 (GW)	2030 (GW)	2050 (GW)
Coal Power Plant	12.4726	14.7776	14.1113
Natural Gas	4.2675	4.8794	2.4125
Large-Hydropower Plant	3.6979	3.42327	3.42327
Medium-Hydropower Plant	0.54816	0.42073	0.16093
Small Hydropower	0.14464	0.12704	0.07604
SCGT	3.0425	1.23747	0.35277
CCGT	0.65	0	0
Geothermal	1.9198	1.3463	0.1721
Onshore Wind	0.4269	0.7001	0.2732
Biomass Power Plant	0.61088	0.68948	0
Solar PV	1.1782	4.07528	3.41458
Gas Turbine	0.13	0.13	0
LFO	0.366689	0.255609	0.031128
Solar PV with Storage	0.010139	0.010139	0.000761
Off-grid Hydropower	0.026625	0.026625	0

Resource Potential for Power Technologies

The resource potential estimates for all modelled energy sources in the Philippines are presented in Appendix A [16,17,23,24,35–40]. These values consider technical feasibility, limitations, and variability factors for both fossil fuels and renewable energy technologies.

Capital Cost of Technologies and Discount Rate

Table 7 presents the capital costs (in USD per kW) for various renewable energy technologies in the Philippines as of 2022. These costs are based on the IRENA 2022 Renewable Power Generation Costs report [7,15]. Costs are projected using the same method as a previous OSeMOSYS study [15].

Table 7. Capital Costs (USD/kW) for Renewable Energy Technologies [7,15].

Technology	Cost (USD/kW) [7,15]
Onshore Wind	1325
Solar PV	857
CSP	9091
Small Hydropower	2000
Large Hydropower	2135
Geothermal	3991
Biomass	2353

The discount rate used in this study is 10%, the official social discount rate (SDR) prescribed by the Philippines National Economic Development Authority for all social investments [41].

2.3. Limitations of Model and Data Inputs

The model's input data are inherently subject to limitations arising from

- **Linear growth projections**: Projections for residual capacity, demand, and costs utilize linear growth; this approach may not fully capture real-world complexities and unforeseen events (e.g., the COVID-19 pandemic).
- **Proxies for missing data**: In instances where specific data were unavailable, proxies were used. For example, capacity factors for tidal power were borrowed from a European study [26]. Potential for CSP remained consistent with the starter data kit [23].
- **Technology aggregation**: Certain technologies are amalgamated with uniform attributes, neglecting potential variations in associated costs and output. For example, the model treats all subcritical and supercritical coal plants as having identical characteristics.
- **Homogeneous power plants**: All power plants within a specific category are assumed to share the same operational lifespan, which may not be completely realistic.
- **Singular-region representation**: The model considers the Philippines as a single region, overlooking potential geographical variations in both capacity and demand across its islands.
- **Focus on CO_2 emissions**: The model focuses on CO_2 emissions from the energy sector due to the dominance of this sector in national emissions and the availability of reliable data. Total GHG emissions, including CH_4 and N_2O, and emissions from other sectors such as agriculture, are not explicitly modelled, which may underestimate the broader emissions reduction requirements.

2.4. Scenario Definition

Several scenarios were designed to assess the economic and technical feasibility of various decarbonization strategies and analyze the impact of the newly added technologies; these are presented in Table 8 below.

Table 8. Descriptions of Modelled Scenarios used in the study.

Scenario	Description
Unconstrained Least Cost (UNC)	This baseline scenario does not impose any additional constraints.
Renewable Energy Targets (RE) [8]	This scenario incorporates minimum constraints for renewables (35% of generation mix by 2030, 50% by 2040), aligning with the Philippines' existing renewable energy targets.
Net Zero (NZ)	This scenario introduces a gradual restriction on fossil fuel imports by 2050, to achieve Net-Zero CO_2 emissions by this date.
High-Growth Offshore Wind (HGW) [17]	This scenario reflects the projections outlined in the World Bank's offshore wind roadmap for high-growth development.
Low-Growth Offshore Wind (LGW) [17]	This scenario reflects the projections outlined in the World Bank's offshore wind roadmap for low-growth development.
Renewable Energy Targets, No Nuclear (RENN)	This scenario replicates the renewable energy target scenario but excludes nuclear power generation capacity investment.
Net Zero, No Nuclear (NZNN)	This scenario replicates the Net-Zero scenario but excludes nuclear power generation capacity investment.

3. Results

This section presents key results relating to power generation, installed capacity, capital costs, and emissions for each scenario.

3.1. Electricity Generation

Figure 4 illustrates the resultant electricity generation mix in each scenario from 2022 to 2050, highlighting the shifting contributions of power technologies under different constraints and targets. Across all scenarios, generation is projected to rise substantially by 2050 to meet growing demand, with renewables share increasing significantly in each scenario. Other key insights include

- The NZ scenario exhibits the most significant rise (755%) in generation compared to the base year (2022) due to the electrification of transport and heating sectors, currently reliant on fossil fuels. By 2050, 86.03% of the energy mix is projected to come from renewable sources, with coal being gradually phased out after 2038.
- When minimum constraints for RE generation are set to 35% by 2030 and 50% by 2040, the least-cost optimization adopts 42.18% of renewables in the energy generation mix by 2030, and 50.3% by 2040.
- Over 16.91% of generation comes from the new technology floating solar PV in each scenario, while offshore wind accounts for over 9.73% in all, except LGW, where its growth is restricted.

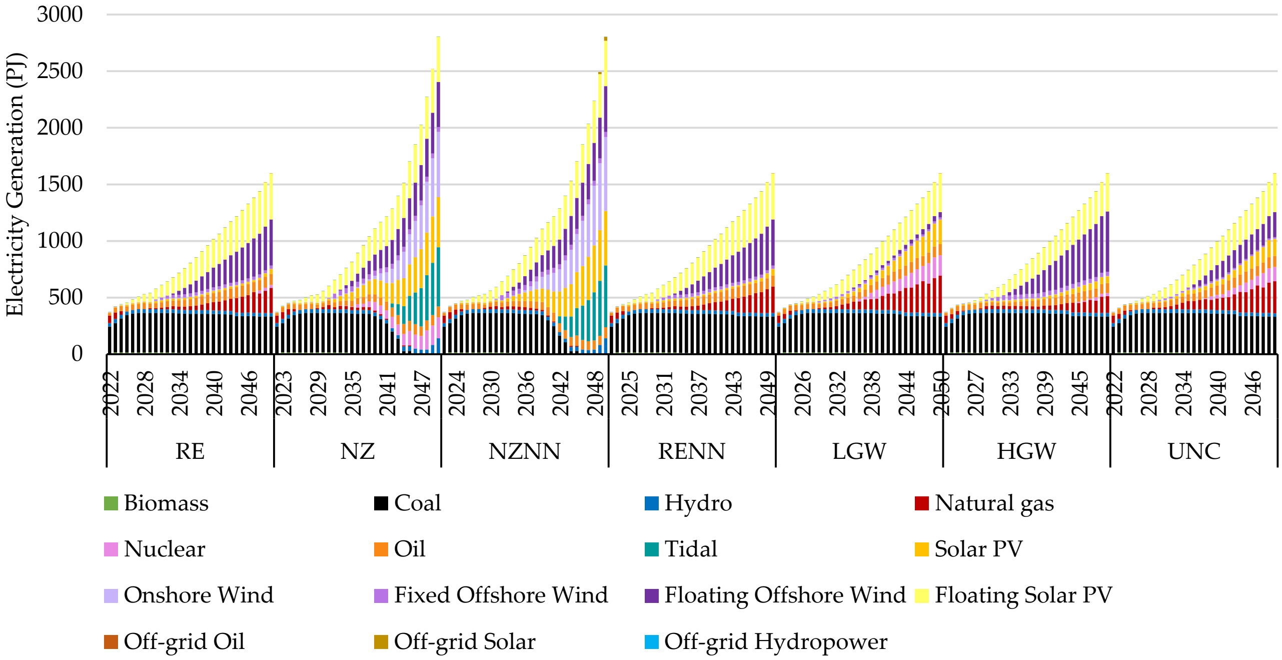

Figure 4. Annual electricity generation from 2022 to 2050, disaggregated by scenario and technology.

3.2. Installed Power Capacity

Figure 5 shows the projected installed capacity of electricity generation technologies in each year over the modelling period, with a detailed breakdown by technology for each scenario. Renewable energy technologies experience remarkable growth across all scenarios, particularly offshore wind and solar, with the NZ scenario demonstrating the largest expansion. By 2050, total installed capacity in the NZ scenario reaches 460.33 GW, to accommodate the transition to electric transport and heating. Floating solar PV and offshore wind make up a large proportion of this, with 77 and 37.89 GW installed, respectively, by 2050. These technologies are favoured in all scenarios, with a minimum of 64.35 GW of floating solar PV installed by 2050. A minimum of 18.96 GW of offshore wind is installed in all scenarios excluding LGW, where its growth is constrained.

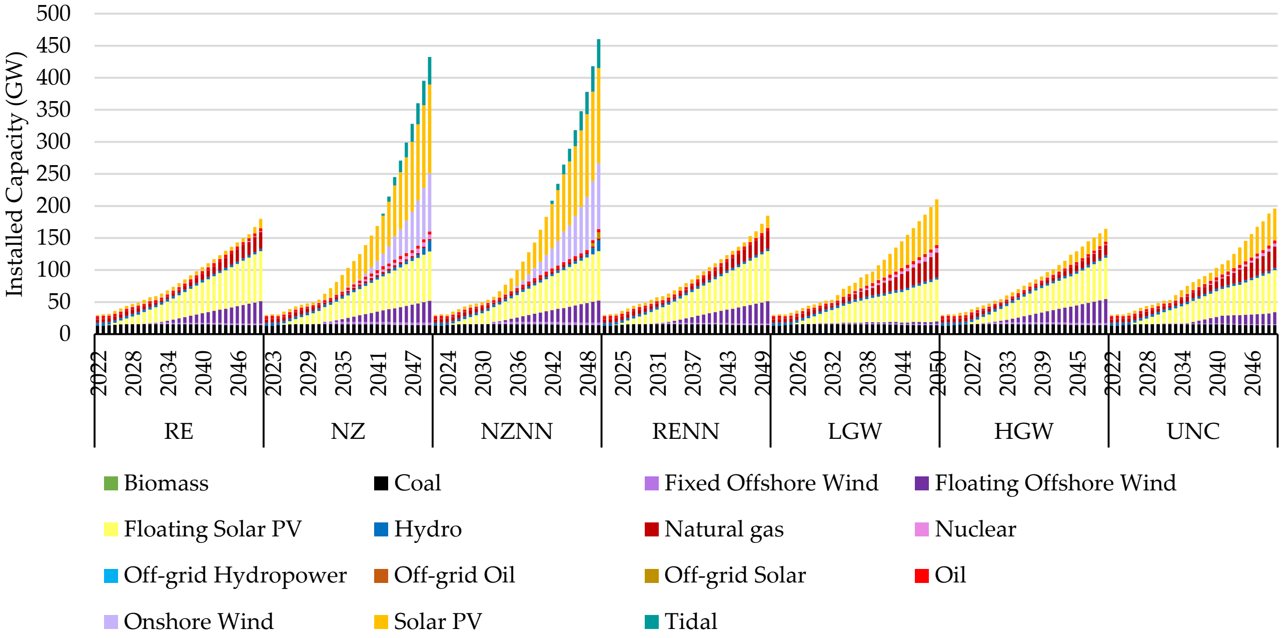

Figure 5. Projected installed capacity for electricity generation (2022–2050).

3.3. Emissions

Figure 6 presents the CO_2 emissions profile over the modelling period in each scenario. Compared to the UNC scenario, all scenarios except the LGW scenario demonstrate emission reductions by 2050. Additionally,

- The NZ scenario achieves the most substantial reduction in CO_2 emissions over the model period, with a 24.21% reduction in cumulative emissions compared to UNC. Rapid decarbonization occurs from 2038 onwards, in line with the phasing out of coal for electricity generation. The NZNN scenario also achieves zero emissions by 2050, demonstrating that even without nuclear power, it is possible to achieve full decarbonization.
- The RE target scenario achieves only a 1.56% reduction in cumulative CO_2 emissions compared to UNC, with annual emissions remaining high across the model period.

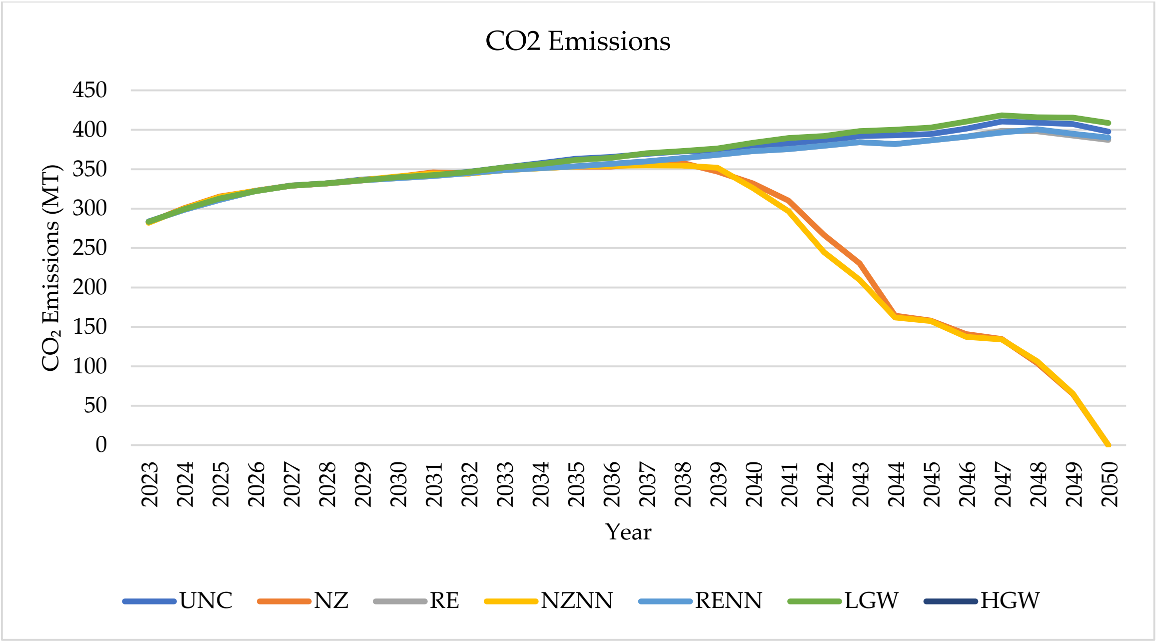

Figure 6. Projected CO_2 emissions in each scenario (2022–2050).

3.4. Discounted and Capital Cost of Scenarios

Figure 7 presents the total discounted capital, variable, and fixed cost in each scenario. The RE scenario results demonstrate the feasibility of achieving renewable energy targets without incurring significant additional costs, with a decrease of 0.58% total discounted cost compared to UNC. NZ is highly capital-intensive, with a discounted capital cost of USD 991.25 billion over the model period. This is in large part due to investment in electric transport and rapid transition to renewable energy from 2037 to 2050 as shown in Figure 8.

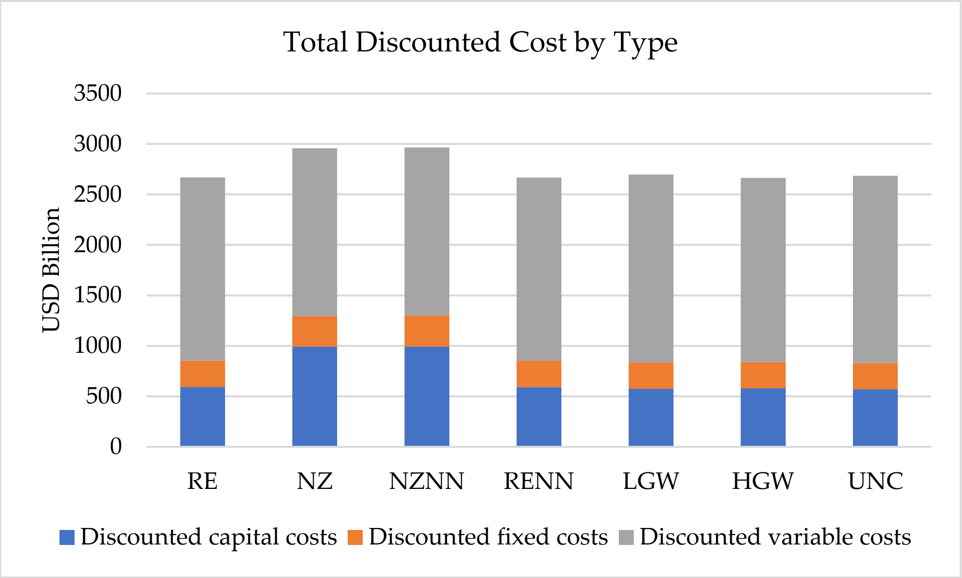

Figure 7. Total discounted capital, variable, and fixed cost of each scenario (USD billion).

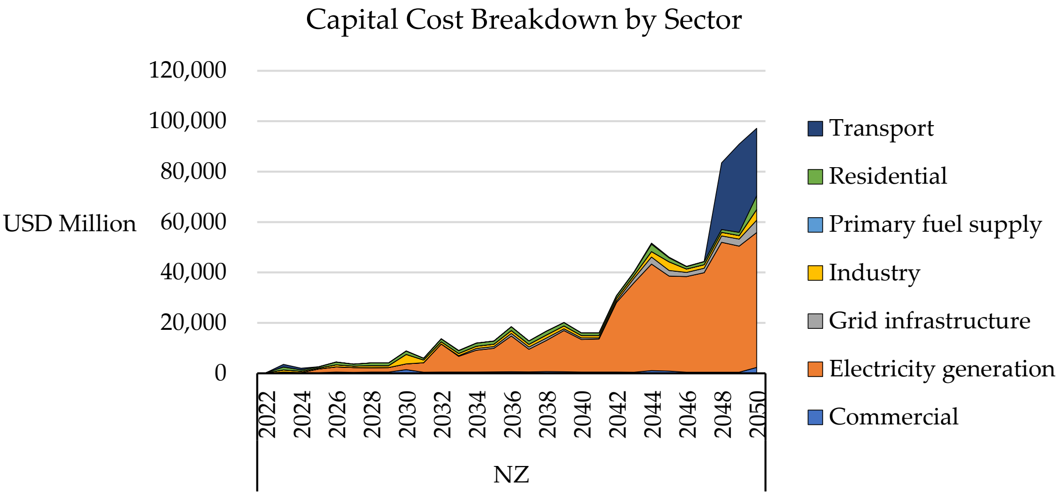

Figure 8. Detailed breakdown of capital cost expenditure in Net-Zero scenario.

3.5. Impact of Nuclear Power

The effect of nuclear power is shown on three key indicators:

- **Emissions:** Including nuclear power resulted in a 0.86% increase in total emissions over the model period to reach Net-Zero targets, and a 0.06% decrease in total emissions to reach RE targets.
- **Cost:** The cost differences associated with including nuclear power is minimal to achieving both RE and NZ targets, decreasing the total discounted cost of meeting renewable energy targets by 0.04%, and increasing the cost of achieving NZ by 0.25%.

- **Installed Capacity**: Removing nuclear power in RENN and NZNN scenarios leads to a 2.67% and 6.04% increase in total installed capacity, respectively, compared to their nuclear counterparts.

4. Discussion

This discussion evaluates the technical feasibility, economic implications, and strategic recommendations for the Philippines' low-carbon energy transition-considering model results. It also presents limitations of the study and opportunities for further research.

4.1. Findings and Implications

The findings offer insights essential for policymakers and stakeholders:

Current renewable energy targets are neither sufficiently ambitious nor cost-effective: The results indicate that increasing RE contributions to 42.18% by 2035 and 50.31% by 2040 can be achieved with minimal cost differences to the UNC scenario. This suggests that current RE targets for the Philippines are less ambitious than what is both technically and economically feasible. Even with increased renewable generation in this scenario, emissions continue to increase across the model period. It is recommended that the DOE adopt even more ambitious targets to induce an emissions decline, including targets for floating solar and OSW technologies.

Net-Zero transition will be highly capital-intensive: While achieving Net-Zero CO_2 emissions by 2050 is technically feasible, the modelled scenarios demonstrate that it would necessitate substantial capital investment, USD 991.25 billion over the model period, driven by investments between 2037 and 2050 to transition the transport sector and expand renewable energy (broken down in Figure 8). As state finance flows into renewable energy are low (~USD 8 million annually [42]), the success of a transition will hinge on the mobilization of private capital for the energy sector. Therefore, it is recommended that the DOE implement financial and regulatory incentives to encourage private capital investment into renewables and electric transport.

Strong potential of offshore wind and floating solar PV: Model results consistently indicate both floating solar PV and offshore wind as substantial contributors to decarbonization. It is therefore recommended that the Philippines focuses on the addition of these two technologies to the energy mix. Prioritizing grid connection infrastructure for floating solar PV, in areas with high marine power potential, and developing a roadmap for the technology will facilitate its seamless integration and prevent confining its application to off-grid areas. For offshore wind, setting precise capacity targets (in the range of 38–41 GW by 2050, attune with the HGW scenario) could maximize cost-effectiveness and catalyze economic benefits associated with the introduction of the technology.

Limited impact of nuclear power: The inclusion of nuclear power in the energy transition should be carefully evaluated. While its use can marginally reduce capacity requirements for electricity generation, its integration does not notably impact the emission profile, or decrease overall investment needed to achieve decarbonization targets. A thorough cost–benefit analysis, factoring in socio-political complexities, environmental risks, and potential opportunity costs, is recommended before considering nuclear integration.

Failure to meet NDC target: None of the scenarios meet the Philippines' Conditional or Unconditional Nationally Determined Contribution (NDC) Target. Even though the ambitious NZ scenario achieves significant emissions reductions, these occur after 2038. This timeline is too slow to align with the 2030 NDC target, suggesting more aggressive actions are needed in the near term. Policies focused on a coal phase out in the nearer future could accelerate the emissions decline, as suggested in [15]. Without immediate policy interventions, the Philippines risks missing its NDC goals and undermining its international climate commitments.

4.2. Limitations and Future Research

This research faces certain limitations inherent to its design that warrant discussion and consideration for future investigations.

4.2.1. Study Limitations

Data Uncertainties: Limitations of data inputs (highlighted in Section 2.3) require a cautious interpretation when translating results into actionable policy. For example, capital cost estimates for generation technologies are inherently uncertain, differing due to factors such as regional variability and the scale of deployment. Future work should prioritize improving data quality and refining modelling assumptions to increase robustness.

Limits of Cost Optimization Analysis: While OSeMOSYS offers valuable insights by focusing on minimizing total discounted costs in the analysis of energy systems, it is essential to acknowledge that a comprehensive assessment should extend beyond technical and economic considerations. Detailed analyses of socio-political factors, environmental impacts including air quality improvements and other externalities, and the potential synergies and trade-offs among various energy sources and technological interventions also must be performed.

4.2.2. Opportunities for Further Research

While the study indicates transport electrification as an important element of the energy transition, a further analysis is required to assess how policy measures can effectively reduce transition costs and accelerate the adoption of electric transport in the Philippines. Additionally, performing a sensitivity analysis on the discount rate would improve the robustness of the results. Regarding nuclear energy, a more detailed cost–benefit analysis is required before its integration into the Philippines' energy landscape, due to socio-political challenges and high capital costs, as it is not crucial for a successful energy transition.

A key finding of this study is that none of the scenarios meet the Philippines' NDC target of a 75% emissions reduction by 2030. A further analysis is needed to examine near-term strategies to accelerate decarbonization, especially in the 2020s. This includes evaluating fast-track policies for renewable energy, a coal phase out, and transport sector transformation.

5. Conclusions

This study used OSeMOSYS to investigate the potential for emerging technologies to contribute to the decarbonization of the energy sector in the Philippines. The research revealed multiple significant findings:

- Current renewable energy targets lack the necessary ambition to facilitate substantial emissions reductions by 2050. Achieving a renewable energy share of 42.18% by 2035 is shown to be both feasible and cost-effective; however, more aggressive targets are required to achieve a reduction in CO2 emissions by mid-century.
- Emerging technologies, floating solar PV and offshore wind, present significant potential in the Philippines. Adopting the World Bank's high-growth wind target of approximately 38 GW by 2050 and prioritizing the integration of floating solar power can significantly aid decarbonization efforts.
- Achieving Net-Zero emissions by 2050 is technically feasible; however, it requires significant capital investment, particularly in the transportation sector. Mobilizing pri-

vate finance in conjunction with targeted policies and incentives is vital to successfully meet Net-Zero targets.

- The role of nuclear power in the transition should be carefully evaluated. Its impact on emissions and investment requirements to meet decarbonization targets is minimal. A thorough cost–benefit analysis is necessary prior to any nuclear deployment.
- None of the scenarios meet the Philippines' NDC target of a 75% emissions reduction by 2030, with significant reductions occurring only post-2038 in the NZ scenario. Immediate policy measures, such as a rapid coal phase out and increased adoption of renewable energy, need to be considered to meet this target.

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U4RIA Compliance Statement: This work follows the U4RIA guidelines, which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios, and results (Ubuntu/Community). The authors ensure that all data, source code, and results can be easily found, accessed, downloaded, and viewed (retrievability), and licenced for reuse (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions, and results to other projects, analyses, and models (interoperability), and facilitating peer review through transparency (auditability).

Abbreviations

OSeMOSYS	Open-Source Energy Modelling System	**DOE**	Philippines Department of Energy
ASEAN	Association of Southeast Asian Nations	**SCGT**	Simple Cycle Gas Turbine
GHG	Greenhouse Gas	**CCGT**	Combined Cycle Gas Turbine
GW	Gigawatts	**LFO**	Light-Fuel-Oil Generator
MW	Megawatts	**IRENA**	International Renewable Energy Agency
PJ	Petajoules	**UNC**	Unconstrained Least-Cost Scenario
SMRs	Small Modular Reactors	**RE**	Renewable Energy Target Scenario
NPV	Net Present Value	**NZ**	Net-Zero Scenario
HGW	High-Growth Offshore Wind Scenario	**RENN**	Renewable Energy Targets, No Nuclear Scenario
LGW	Low-Growth Offshore Wind Scenario	**NZNN**	Net Zero, No Nuclear Scenario

Appendix A

Table A1. Technical Potential for Coal, Crude oil, Natural Gas, and Biomass [35,36].

Technology	**Potential (PJ)**
Coal [35]	7620.156
Crude Oil [35]	611.79
Natural Gas [35]	3675
Biomass [36]	136.7584

Table A2. Technical Potential for Renewable Technologies [16,17,23,24,37–40].

Technology	**Potential (GW)**
Large Hydropower [37]	14.6808
Medium Hydropower [37]	1.89705
Small Hydropower [37]	0.42002
Mini Hydropower (Off-grid) [37]	0.03731
Geothermal Power Plant [38]	4.407
Onshore Wind [39]	61.8
Fixed Offshore Wind [17]	18
Floating Offshore Wind [17]	160
Solar PV [40]	337.2
Off-grid Solar with Storage [40]	337.2
Floating Solar PV [24]	83
Solar PV with Storage [40]	337.2
CSP [23]	0
Tidal In-stream [16]	50

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