Type of the Paper: Article

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

Lara Dixon [1,*], Rudolf Yeganyan [1,2], Naomi Tan [1,2] Carla Cannone [1,2], Mark Howells [1,2], Vivien Foster [1], Fernando Plazas-Niño [2]

[1] Centre for Environmental Policy, Imperial College London, London, United Kingdom
[2] STEER Centre, Department of Geography, Loughborough University, Loughborough, United Kingdom
* Correspondence: lara.dixon22@imperial.ac.uk

Abstract: The Philippines aspires for a clean energy future, but the effectiveness of its existing renewable energy (RE) targets and the role of emerging technologies remains uncertain. This study examines potential pathways to decarbonise the Philippines' energy sector, assessing the feasibility and economic implications of selected scenarios. The Open-Source Energy Modelling System (OSeMOSYS) was used to model various scenarios, including a least-cost scenario, an RE target scenario, a net-zero scenario, and scenarios investigating the impact of high and low offshore wind growth, as well as the inclusion or exclusion of nuclear power. Present RE targets were found to be insufficient to achieve significant emissions reductions, and suggested increasing the RE target to 52.4% by 2035 as a more cost-effective option. Floating solar PV and offshore wind showed notable potential as decarbonisation technologies, with high uptake in all scenarios. The World Bank's high-growth wind target (around 38 GW by 2050) is shown to be cost-effective. Achieving net-zero by 2050 proved technically feasible but highly capital-intensive, and will require significant private sector investment. The addition of nuclear power offers limited benefits in terms of cost savings and reducing emissions by 2050. The Philippines can improve its energy transition ambitions by raising RE targets and strategically integrating new technologies. While nuclear power may not be crucial, focusing on mobilising private capital and promoting renewables remains key to achieving a cleaner and more secure energy future.

Keywords: Decarbonisation Pathways, Renewable Energy Targets, Net Zero, Floating Solar PV, Offshore Wind, Least-Cost Planning

1. Introduction

1.1 Background

The global energy sector is responsible for nearly 75% of greenhouse gas emissions, highlighting the urgency of its decarbonisation to mitigate the worst effects of climate change [1]. The Philippines, an archipelago nation in Southeast Asia, faces a complex challenge in balancing its rising energy demand, driven by a growing service sector, with decarbonisation efforts [2]. Unlike its ASEAN counterparts, the Philippines lacks a national policy commitment to Net Zero target for the energy sector [3]. The nation has become increasingly reliant on imported fossil fuels in recent years to meet energy demand (48.5% of the primary energy mix in 2021), and is among the top four coal importers in 2023 [4, 5].

In an effort to move towards cleaner energy sources and away from import dependence, which leaves the country vulnerable to price shocks and supply disruption, the Philippines has defined targets to increase the uptake of renewable energy, aiming for a 35% share of the power generation mix by 2030 and 50% by

Citation: To be added by editorial staff during production.

Received: date
Revised: date
Accepted: date
Published: date

2040[2,6]. Additionally, the Philippines imposed a moratorium on new coal power plant permits in 2020 [7]. Neither policy has yet to translate into a tangible decrease in fossil fuel dependence. To address these challenges and move towards energy independence, the Philippines is exploring the integration of emerging low-carbon technology options into its energy mix. This study aims to evaluate the potential for these technologies (offshore wind (floating and fixed), floating solar PV, in-stream tidal, and nuclear power) to contribute to the energy transition in the Philippines, and examine the feasibility of a net zero target.

This paper first presents the context and a literature review for the study (Section 1), then details the methodology (Section 2), results (Section 3), and discussion (Section 4). Section 4 covers key findings, policy insights, limitations, and future research. The article concludes with closing remarks (Section 5).

1.2 Literature Review

A growing body of research explores pathways for a low-carbon energy transition in the Philippines (**Table 1**). These studies highlight the potential for achieving Net Zero, often emphasising solar PV as a crucial technology, and point to potential benefits such as improved air quality and economic growth [8, 9, 10, 11, 12]. However, limited interconnection within Southeast Asia could pose challenges to achieving this [9].

Table 1. Summary of existing research studies and key findings

Study	Scope	Key Findings
Jacobson et al. (2018)	Global study modelling pathways for 100% renewable energy by 2050	Low-cost 100% renewable solution is possible globally and in the Philippines
Teske (2019)	Global study for achieving zero GHG emissions by 2050	Zero GHG emissions possible across all sectors, potential challenges with interconnection for SE Asia
Mondal et al. (2018)	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 decarbonisation efforts
Gulagi et al. (2021)	Analysis of the Philippines' transition to 100% renewable energy (2015-2050)	Transition possible by 2050, solar PV and battery storage key, possible to gain >50% efficiency with significant investment
Alexander et al. (2023)	Assessment of clean energy transition scenarios	Phasing out coal crucial for emission reduction,

	in the Philippines (2015-2070)	solar PV identified as a key technology

This study addresses gaps in previous research by assessing the technical feasibility of achieving Net Zero targets, incorporating emerging technologies like floating solar PV, fixed and floating offshore wind, tidal in-stream, and nuclear power that are not currently utilised in the Philippines alongside existing options. **Table 2** summarises the technical potential and challenges of identified emerging marine technologies in the Philippines.

Table 2. Technical Potential and Challenges of Marine Energy Technologies in the Philippines [13]

Technology	**Potential**	**Opportunities**	**Challenges**
Offshore Wind	178 GW (160 GW floating, 18 GW Fixed)	Mature technology, roadmap available, good port infrastructure	Leasing & permitting, grid connection, port availability
Floating Solar PV	83 GW	Mature technology, competitive in remote regions	Leasing & permitting, political & 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

1.2.1 Offshore Wind Roadmap and Nuclear Power Considerations

1.2.1.1 Offshore Wind Roadmap

The 2022 Philippines Offshore Wind Roadmap, a collaboration between the Department of Energy (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 [14]. 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, it's important to acknowledge that these scenarios haven't been extensively modelled within the existing or projected energy system. This means potential interactions and complexities with the existing infrastructure are not fully considered.

1.2.1.2 Nuclear Power Considerations

Regarding nuclear power, the Philippines currently lacks active projects but has explored the option in the past, with the Bataan Nuclear Power Plant remaining non operational since its construction in the 1970s [15]. Recent discussions have rekindled interest, with consideration of a 2,400 MW nuclear capacity target by 2035 (utilising Small Modular Reactors (SMRs)), and the consideration of the Bataan plant's revival [16, 17]. However, public perception, regulatory hurdles, lack of local expertise, and inherent geographical risks remain significant challenges for nuclear power adoption in the Philippines [17].

1.3 Purpose and Significance

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. Analyse 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. Provide policy recommendations based on the findings to guide the Philippines energy transition, considering technological, economic, and environmental factors.

By shedding light on the viability and potential of emerging technologies and their interaction with the existing energy system, this research aims to provide insights to policymakers, industry stakeholders, and the wider scientific community dedicated to shaping a cleaner and more resilient energy landscape for the Philippines.

2. Methodology

This section details the methodology employed in this study, adhering to the principles of replicability and transparency. All data and protocols used in the analysis will be made available to readers upon publication.

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

This study utilises OSeMOSYS (Open-Source Energy Modelling System), a widely recognized tool for bottom-up, linear energy optimization modelling [18]. OSeMOSYS seeks to determine the minimum net present value (NPV) cost for an energy system while adhering to specified energy demands, system constraints, and policy objectives [18]. **Equation 1** representing this optimization is displayed below:

$$Minimise \sum_{y,t,r} Total\ Discounted\ Cost_{y,t,r}$$

Where y= year modelled, t= technology (power plant), r= region

And where $\forall_{y,t,r} Total\ Discounted\ Cost_{y,t,r} = DiscountedOperatingCosts_{y,t,r} + DiscountedCapitalInvestment_{y,t,r} + DiscountedTechnologyEmissionsPenalty_{y,t,r} - DiscountedSalvageValue_{y,t,r}$ (1)

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. Its open-source nature facilitates transparency for policymakers, enables further refinement, and allows for integration with other tools [19].

2.2 Reference Energy System and Data Inputs

2.2.1 Base Model and Temporal Scope

The initial model was adapted from the Philippines OSeMOSYS Starter data kit, created by [20]. 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 represent improvements through energy efficiency measures, dedicated technologies were included in the model to reflect reduced energy demand. Imported electricity was kept constrained to zero into the future, to ensure 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 3.**

Table 3. Key Parameters for added Technologies. [13,14, 21-23]

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

A diagram of the Philippines energy system as modelled in this study is shown in **Appendix 1.**

2.2.3 Data Inputs and Updates

2.2.3.1 Electricity Demand

Historical electricity demand data for the period 2015-2022 was sourced from the latest Department of Energy Power Statistics Summary (2022) [24]. 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) [25]. These projections are further categorised into commercial, industrial, and residential sectors and are presented in **Figure 1.**

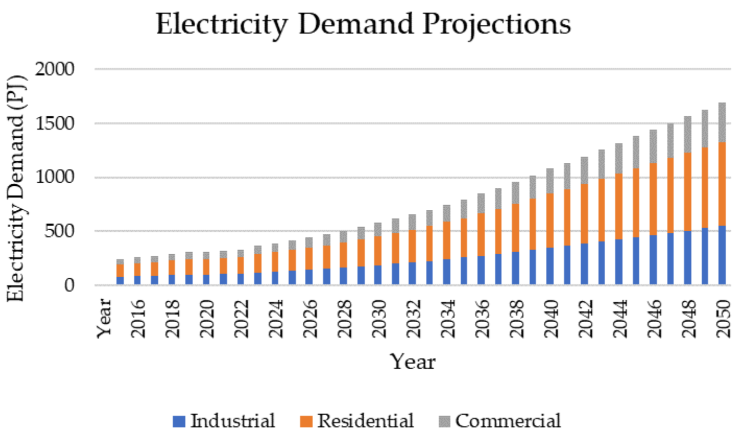


Figure 1. Updated electricity demand by sector.

2.2.3.2 Generation

Historical generation values for 2022 were added to the model. **Table 4** presents the historical generation data for various power plants in the Philippines in 2022. This data was obtained from the latest Department of Energy gross generation statistics per plant type [26].

Table 4. Generation in 2022 from each plant type. [26]

Plant Type	Generation (PJ)
Biomass	4.76
Coal	239.15
Geothermal	37.53
CCGT	2.65
SCGT	22.41
Natural Gas	64.38
Solar PV	6.56
Large Hydropower(>100MW)	26.11
Medium Hydropower (10-100MW)	3.87
Small Hydropower	1.02
Offgrid Hydropower	0.53
Onshore Wind	3.71
Offgrid Oil-Based	1.58

2.2.3.3 Residual Capacity

Residual capacity projections for various power plants in the Philippines are presented in **Table 5**. 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. [27-31]

Table 5. Residual Capacity in 2023, and projections to 2030 and 2050. [27-31]

Power Plant	2023	2030	2050
Coal Power Plant	12.7726	14.7776	14.1113
Natural Gas	4.2675	4.8794	2.4125
Large Hydropower Plant	3.83527	3.42327	3.42327
Medium Hydropower Plant	0.4694	0.42073	0.16093
Small Hydropower	0.14144	0.12704	0.07604
SCGT	2.93137	1.23747	0.35277
CCGT	0.65	0	0
Geothermal	1.9658	1.3463	0.1721
Onshore Wind	0.5369	0.7001	0.2732
Biomass Power Plant	0.68528	0.68948	0
Solar PV	2.02467	4.07528	3.41458
Gas Turbine	0.13	0.13	0
<1kw LFO generator	0.357568	0.255609	0.031128
Solar PV with storage	0.010139	0.010139	0.000761
Off-grid Hydropower	0.026625	0.026625	0

2.2.3.4 Resource Potential

The resource potential estimates for all energy sources in the Philippines modelled are presented in **Appendix 2** [13,14,20,21,32-37]. These values consider technical feasibility, limitations, and variability factors for both fossil fuels and renewable energy technologies.

2.2.3.5 Costs

Table 5 presents the capital costs (in USD per kW) for various renewable energy technologies in the Philippines as of 2021. These costs are based on information provided by the International Renewable Energy Agency (IRENA) in their 2022 Renewable Power Generation Costs report [12,38]. Costs are projected using the same method as a previous OSeMOSYS study [12].

Table 5: Capital Costs (USD/kW) for Renewable Energy Technologies [12,38]

Technology	Cost
Onshore Wind	1325
Solar PV	857
CSP	9091
Small Hydropower	2000
Large Hydropower	2135
Geothermal	3991
Biomass	2353

2.3 Limitations of Model and Data Inputs

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

- Linear growth projections: While projections for residual capacity, demand, and costs utilise 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 was unavailable, proxies were used. For example, capacity factors for tidal power were borrowed from a European study [24].
- 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.

2.4 Scenario Definition

Several scenarios were designed to assess the economic and technical feasibility of various decarbonisation strategies and analyse the impact of the newly added technologies:

Unconstrained Least Cost (UNC): This baseline scenario does not impose any additional constraints.
Renewable Energy Targets (RE): 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, aiming to achieve net-zero CO2 emissions.
High Growth Offshore Wind (HGW): This scenario reflects the projections outlined in the World Bank's offshore wind roadmap for high-growth development.
Low Growth Offshore Wind (LGW): 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 (RENN): This scenario replicates the net zero scenario but excludes nuclear power generation capacity investment.

2.5 Discount Rate

The model results present undiscounted fixed, variable, and operating costs. Discounting equation (**Equation 2**) is applied to calculate the net present cost, considering a 10% global discount rate applied over the modelling period (2022-2050).

$$Discounted\ Cost = \sum_{t=0}^{28} \frac{Undiscounted\ Cost}{(1+r)^t} \quad (2)$$

where:
t: number of years after 2022 (28)
r: global discount rate (10%)

3. Results

Tables summarising key results are presented below. Full graphical representations of power generation, installed capacity,capital costs and emissions for each scenario are presented in **Appendix 3.**

3.1. Electricity Generation

Table 6 presents key findings regarding electricity generation. Across all scenarios, generation is projected to increase significantly by 2050 to meet growing demand. The Net-Zero (NZ) scenario exhibits the most significant rise (322%) compared to the base year (2020) due to the electrification of transport and heating sectors, currently reliant on fossil fuels (See appendix 3 for graphical representation of results).

Table 6: Percentage of Energy Generation from key technology groups in key years.

% of Generation from different sources	UNC	RE	NZ	LGW	HGW	RENN	NZNN
Renewables in 2035	19.88%	52.40%	56.57%	23.89%	33.72%	54.44%	56.57%
Renewables in 2050	29.59%	61.18%	92.67%	24.37%	50.24%	65.74%	100.00%
OSW in 2050	11.07%	22.71%	12.02%	3.31%	28.56%	20.57%	13.49%
Floating Solar PV in 2050	16.20%	20.60%	11.34%	18.75%	19.36%	22.71%	11.35%
Nuclear in 2050	0	7.33%	10.16%	0	0	0	0

- **NZ scenario in 2050:** Renewables account for 92.67% of generation, compared to 29.59% in the Unconstrained (UNC) scenario.
- When minimum constraints for RE generation are set to 35% by 2030 and 50% by 2040, the least-cost solution adopts 52.4% of renewables in the energy generation mix by 2035, and 61.18% by 2050.
- Over 10% of generation comes from the new technologies offshore wind and floating solar PV in all scenarios except LGW.

3.2 Installed Capacity

Table 7: Installed Capacity in 2050, broken down into key technologies

Installed Capacity 2050 (GW)	UNC	RE	NZ	LGW	HGW	RENN	NZNN
Total	151.4	243.0	633.3	152.9	166.6	272.6	685.9
OSW	19.0	38.4	38.8	5.6	40.4	38.4	43.4
Floating Solar	62.2	78	82	72	73.6	78	82
Nuclear	0	7.7	10.6	0	0	0	0
Total Renewables	88.7	192.5	605.7	85.1	122.3	219	669
Total % Renewable	58.58%	79.21 %	95.66 %	55.67%	73.40%	80.33%	97.54%

Table 7 breaks down the installed capacity in 2050 in each scenario. Renewable energy technologies experience remarkable growth across all scenarios, with the NZ scenario demonstrating the most significant expansion. By 2050, the NZ scenario installed capacity rises to 605.7 GW to accommodate the transition to electric transport. Floating solar PV and offshore wind make up a large proportion of this, reaching 82 and 38.8 GW installed respectively by 2050. These technologies are positively favoured in all scenarios, with a minimum of 19GW of offshore wind and 62.2GW of floating solar PV installed by 2050.

3.3 Emissions

Table 8: Emissions in 2050 in each scenario and total emissions reduction in comparison to UNC.

	UNC	RE	NZ	LGW	HGW	RENN	NZNN
Annual Emissions in 2050 (Thousand KG CO2)	769.68	466.89	0.0	802.50	639.65	477.84	0.0
% Total Reduction from UNC scenario	0%	-23.37%	-47.39%	+0.44%	-9.7%	-22.74%	-50.23%

Table 8 presents key results on emissions. The significant shift towards renewables positively impacts emission reduction. Compared to the UNC scenario, all scenarios except the LGW scenario demonstrate emission reductions by 2050:

- The NZ scenario achieves the most substantial reduction (50.23%) compared to UNC, successfully transitioning away from fossil fuels and maximising renewable energy generation.
- The Renewable Energy (RE) scenario achieves a 23.37% reduction from UNC, however annual emissions remain high across the model period.

3.4 Costs

Table 9: Total Discounted Cost, Capital cost in each scenario.

	UNC	RE	NZ	LGW	HGW	RENN	NZNN
Total Discounted Cost ($USD Billion)	$672.17	$678.43	$799.36	$671.98	$678.26	$684.52	$828.73
Discounted Capital Cost ($USD Billion)	$63.10	$90.47	$297.74	$63.38	$73.59	$86.96	$319.21

Table 9 presents the total discounted and capital cost from each scenario. Achieving net-zero emissions in the NZ scenario comes with significant capital costs.) A Net Zero target is highly capital intensive, with a discounted capital cost of $297.74 billion USD over the model period. This is in large part due to investment in electric transport in renewables from 2037 to 2050 (see Appendix 3) . The RE scenario demonstrates the feasibility of achieving renewable energy targets without incurring significant additional costs, with only a 0.93% increase in total discounted cost compared to UNC.

3.5 Impact of Nuclear Power

The inclusion of nuclear power does not have a strong impact on the total cost or emissions reduction compared to the unconstrained scenario. Including nuclear minorly effects installed capacity requirements.

- **Emission Reduction (Table 8):** Including nuclear power results in modest reductions in emissions, with differences of 0.63% and 2.84% compared to non-nuclear scenarios.
- **Cost (Table 9):** The cost increase associated with discluding nuclear power is minimal to achieve both RE and NZ targets (0.89% and 3.67%).

- **Installed Capacity (Table 7)**: Removing nuclear power in RENN and NZNN scenarios leads to a 12.1% and 8.3% increase, respectively, compared to their nuclear counterparts.

4. Discussion

4.1 Findings and Implications

Findings offer insights essential for policymakers and stakeholders:

Ambitious Renewable Energy Targets are Feasible: The results indicate that increasing RE contributions to 52.4% by 2035 and 50% by 2040 can be achieved with minimal cost increases in comparison to the Unconstrained (UNC) scenario. This suggests that current RE targets for the Philippines are less ambitious than what is both technically and economically feasible. Even with this increased renewable generation, emissions reduction is under half the level in the Net Zero scenario. 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 is Capital Intensive: While achieving net-zero emissions by 2050 is technically possible, the modelled scenarios demonstrate that it would necessitate substantial capital investment—particularly for transitioning the transport sector alongside renewable energy expansion. As state finance flows into renewable energy are low (~8 million USD annually [39]), the success of a transition will hinge on the mobilisation of private capital for the energy sector. Therefore, it is recommended the Department of Energy (DOE) implement financial and regulatory incentives to encourage private capital mobilisation.

Offshore Wind is a Strategic Resource: Recommendations by the World Bank regarding offshore wind development align with the Philippines' potential for this technology. Model results consistently indicate both fixed and floating offshore wind as substantial contributors to decarbonisation. Establishing specific capacity targets (in the range of 38-41 GW by 2050, attune with the HGW scenario) could maximise cost-effectiveness and catalyse economic benefits associated with the introduction of the technology.

Limited Impact of Nuclear Power: The inclusion of nuclear power in the energy mix does not significantly reduce emissions or total system cost to reach renewable energy and net zero targets. Further, nuclear power's potential to reduce installed capacity requirements could lead to overcapacity if not carefully managed. A thorough cost-benefit analysis, factoring in socio-political complexities, environmental risks, and potential opportunity costs, is recommended before considering nuclear integration.

Harnessing Potential of Emerging Renewable Technologies: Floating solar PV and offshore wind exhibit significant potential across scenarios, and it is therefore recommended that the Philippines focuses on the addition of these two technologies to the energy mix. Prioritising 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 is advised as explained above.

4.2 Limitations and Future Research

4.2.1 Limitations

Data Uncertainties: Limitations of data inputs (highlighted in section 2.3) require a cautious interpretation when translating results into actionable policy. Future work should prioritise improving data quality and refining modelling assumptions to increase robustness.

Need for Comprehensive Analysis: This study primarily investigates technical and economic aspects of the energy transition. A broader assessment should include detailed analyses of socio-political factors, environmental impacts, and the potential synergies and trade-offs among different energy sources and technological interventions.

4.2.2 Opportunities for further research

While the study indicates the importance of transport transition to achieving net zero, further investigations are needed to evaluate the impact of policy and fiscal incentives on the transition costs for both the transport sector and the uptake of renewables. 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.

5. Conclusions

This study used OSeMOSYS to investigate pathways to decarbonise the energy sector in the Philippines'. The research uncovered several key findings;

- Current renewable energy (RE) targets are not sufficiently ambitious to achieve a significant emissions reduction by 2050. Increasing the share of RE to 52.4% by 2035 is a feasible and cost-effective target, but even more ambitious goals are necessary to achieve a decline in CO2 emissions by mid-century.

- Emerging technologies floating solar PV and offshore wind show great potential in the Philippines. Adopting the World Bank's high-growth wind target (around 38 GW by 2050) and prioritising the integration of floating solar can contribute significantly to decarbonisation efforts.

- Achieving net-zero emissions by 2050 is technically feasible but comes with challenges. The transition requires substantial capital investment, especially in the transport sector. Mobilising private finance alongside specific policies and incentives is vital for success.

- The role of nuclear power in the transition should be carefully evaluated. While its use can reduce capacity requirements, its integration does not notably impact the emission profile or the overall investment needed to achieve renewable energy targets and net zero. A comprehensive cost-benefit analysis should be undertaken subsequent to its deployment due to socio-political concerns and high upfront costs.

In conclusion, by raising its RE targets, strategically implementing floating solar PV and offshore wind technologies, and implementing fiscal incentives for investment in renewables and electric transport, the Philippines can progress towards a more secure and sustainable energy future.

Author Contributions: Conceptualization, L.D.; methodology, L.D;. formal analysis,L.D.; investigation, L.D.; data curation, L.D.; writing—original draft preparation, L.D; writing—review and editing, L.D., R.Y., C.C., M.H. and F.P.; supervision, M.H., V.F.,N.T.; project administration, R.Y. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Climate Compatible Growth (CCG) programme, XXX.

Data Availability Statement: The data and model code used for this study is fully accessible and licensed under MIT license. Supplementary material is available at Zenodo repository 10.5281/zenodo.10382707

Acknowledgments: This material has been produced under the Climate Compatible Growth (CCG) programme, which brings together leading research organizations and is led out of the STEER centre, Loughborough University. CCG contributed in funding the time dedication of the co-authors for the production of this material, and CCG funded the publishing fees associated with the publishing of this material. CCG is funded by the Foreign, Commonwealth and Development Office (FCDO) from the UK government. However, the views expressed herein do not necessarily reflect the UK government's official policies.

Funding: For this research, CCG contributed to funding the time dedication of the co-authors for the production of this material, and CCG funded the publishing fees associated with the pub-lishing of this material (APC).

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 car-ried 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), licensed 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), ensur-ing the transfer of data, assumptions and results to other projects, analyses, and models (in-teroperability), and facilitating peer-review through transparency (auditability).

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Climate Watch. (2020) | Greenhouse Gas (GHG) Emissions | Climate Watch. https://www.climatewatchdata.org/ghg-emissions?breakBy=sector&chartType=percentage [Accessed Sep 5, 2023].
[2] World Bank. (2022) Philippines: Overview. https://www.worldbank.org/en/country/philippines/overview [Accessed Aug 25, 2023].
[3] IRENA (2022a), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi
[4] Department of Energy. [DOE]. (2021a) Energy Situationer. https://www.doe.gov.ph/sites/default/files/pdf/energy_statistics/doe-pes-kes 2021.pdf?withshield=1.
[5] Maguire, G. (May 25, 2023) The 'Big 4' drivers of coal imports and power emissions. https://www.reuters.com/business/energy/big-4-drivers-coal-imports-power-emissions-maguire 2023-05-25/#:~:text=China%2C%20India%2C%20The%20Philippines%20and,from%20ship%20tracking%2 0firm%20Kple
[6] National Renewable Energy Program (NREP). (2021) National Renewable Energy Program 2020 - 2040. https://www.doe.gov.ph/sites/default/files/pdf/announcements/nrep_2020- 2040.pdf?withshield=1.
[7] Department of Energy. [DOE]. (2022a).Amendments to section 19 of Department Circular No. DC2009-05-0008.
[8] Jacobson, M. Z., Delucchi, M. A., Cameron, M. A. & Mathiesen, B. V. (2018) Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renewable Energy. 123 236- 248. 10.1016/j.renene.2018.02.009.
[9] Teske, S. (2019) Achieving the Paris Climate Agreement Goals Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C.
[10] Mondal, M. A. H., Rosegrant, M., Ringler, C., Pradesha, A. & Valmonte-Santos, R. (2018) The Philippines energy future and low-carbon development strategies. Energy. 147 142-154. 10.1016/j.energy.2018.01.039
[11] Gulagi, A., Alcanzare, M., Bogdanov, D., Esparcia, E., Ocon, J. & Breyer, C. (2021) Transition pathway towards 100% renewable energy across the sectors of power, heat, transport, and desalination for the Philippines. Renewable and Sustainable Energy Reviews. 144 110934. 10.1016/j.rser.2021.110934
[12] Alexander, K., Yeganyan, R., Cannone, C., Tan, N. & Howells, M. (2023) Evidence-Based Policy Making: Analysis and Policy Recommendations for how the Philippines can manage a Cost Effective Clean Energy Transition. 10.21203/rs.3.rs-2446174/v3
[13] Energy Transition Partnership. (2023) Marine Renewable Energy in the Philippines: Sustainable Energy from Ocean Spaces and Resources.https://www.energytransitionpartnership.org/resource/marine-renewable-energy-in-the philippines-sustainable-energy-from-ocean-spaces-and-resources
[14] World Bank. (2022) Offshore Wind Roadmap For The Philippines. https://documents1.worldbank.org/curated/en/099225004192234223/pdf/P1750040b777da0c 30935a0e2aa346f4e26.pdf.
[15] Tan, R. & O.Enano, J. (Jan 25, 2023) Clean-energy push puts abandoned Philippine nuclear plant back in spotlight. The Washington Post. https://www.washingtonpost.com/world/2023/01/25/philippines-nuclear-marcos-climate change/ .
[16] Power Philippines. (2023) DOE eyeing 2,400 MW goal for nuclear power. Power Philippines. - 07-20. https://powerphilippines.com/doe-eyeing-2400-mw-goal-for-nuclear-power/ [Accessed Aug 25, 2023]
[17] World Nuclear Association. (2023) Nuclear Power Philippines | Philippines Nuclear Energy - World Nuclear Association. https://world-nuclear.org/information-library/country profiles/countries-o-s/philippines.aspx
[18] Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M. & Roehrl, A. (2011) OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy. 39 (10), 5850-5870. 10.1016/j.enpol.2011.06.033.
[19] Gardumi, F., Shivakumar, A., Morrison, R., Taliotis, C., Broad, O., Beltramo, A., Sridharan, V., Howells, M., Hörsch, J., Niet, T., Almulla, Y., Ramos, E., Burandt, T., Balderrama, G. P., Pinto de Moura, G. N., Zepeda, E. & Alfstad, T. (2018) From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS. Energy Strategy Reviews. 20 209-228. 10.1016/j.esr.2018.03.005.
[20] Allington, L., Cannone, C., Pappis, I., Cervantes Barron, K., Usher, W., Pye, S., Brown, E., Howells, M., Zachau Walker, M., Ahsan, A., Charbonnier, F., Halloran, C., Hirmer, S., Cronin, J., Taliotis, C., Sundin, C., Sridharan, V., Ramos, E., Brinkerink, M., Deane, P., Gritsevskyi, A., Moura, G., Rouget, A., Wogan, D., Barcelona, E., Niet, T., Rogner, H., Bock, F., Quirós-Tortós, J., Angulo-Paniagua, J., Krishnamurthy, S., Harrison, J. & To, L. S. (2022) Selected 'Starter kit' energy system modelling data for selected countries in Africa, East Asia, and South America (#CCG, 2021). Data in Brief. 42 108021. 10.1016/j.dib.2022.108021
[21] Joshi, P., Rosenlieb, E. & Gadzanku, S. (2023) ENABLING FLOATING SOLAR PHOTOVOLTAIC (FPV) DEPLOYMENT FPV Technical Potential Assessment for Southeast Asia. https://www.nrel.gov/docs/fy23osti/84921.pd
[22] World Bank. (2019) Where Sun Meets Water FLOATING SOLAR HANDBOOK FOR PRACTITIONERS. https://documents1.worldbank.org/curated/en/418961572293438109/pdf/Where-Sun Meets-Water-Floating-Solar-Handbook-for-Practitioners.pdf

[23] European Commission. (2018) MARKET STUDY ON OCEAN ENERGY. https://www.oceanenergy-europe.eu/wp content/uploads/2018/07/KL0118657ENN.en-1.pdf [24] Department of Energy. [DOE]. (2023a) 2022 Power Statistics. Summary https://www.doe.gov.ph/sites/default/files/pdf/energy_statistics/2022_power_statistics_01 _summary.pdf

[24] Department of Energy. [DOE]. (2023) 2022 Power Statistics. Summary https://www.doe.gov.ph/sites/default/files/pdf/energy_statistics/2022_power_statistics_01 _summary.pdf

[25] Department of Energy. [DOE]. (2021b) Power Development Plan 2020 - 2040. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/pdp-2020-2040.pdf

[26] Department of Energy (2022) 2022 Power Statistics. Department of Energy gross generation statistics per plant type https://www.doe.gov.ph/sites/default/files/pdf/energy_statistics/02_2022%20Gross%20Generation%20per%20Plant%20Type%20per%20Grid_0.pdf

[27] Department of Energy. [DOE]. (2023) LIST OF EXISTING POWER PLANTS (GRID-CONNECTED) AS OF DECEMBER 2022 - LUZON GRID. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/01_Luzon%20Grid.pdf.

[28] Department of Energy. [DOE]. (2023) LIST OF EXISTING POWER PLANTS (GRID-CONNECTED) AS OF DECEMBER 2022- Mindanao. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/03_Mindanao%20Grid.pdf

[29] Department of Energy. [DOE]. (2023) LIST OF EXISTING POWER PLANTS LIST OF EXISTING POWER PLANTS (GRID-CONNECTED) AS OF DECEMBER 2022- VISAYAS GRID. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/02_Visayas%20Grid.pdf

[30] Department of Energy. [DOE]. (2023) LIST OF EXISTING POWER PLANTS (OFF-GRID) AS OF DECEMBER 2022. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/05_LVM%20Off Grid%20Plants_rev1_0.pdf.

[31] Department of Energy. [DOE]. (2023) SUMMARY OF COMMITTED POWER PROJECTS As of 31 March 2023. https://www.doe.gov.ph/sites/default/files/pdf/electric_power/05_LVM%20Committed%20 Summary%20-%202023-03-31.pdf.

[32]EIA. (2022) International Statistics- U.S. Energy Information Administration (EIA). https://www.eia.gov/international/data/world/other-statistics/emissions-by fuel?pd=40&p=0000000000000000000000000000000000000000000000000000b0001& u=0&f=A&v=mapbubble&a=&i=none&vo=value&t=C&g=00000000000000000000000000000 000000000000000000001&l=249ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvvnvvvs 0008&s=-662688000000&e=1609459200000& [Accessed Aug 26, 2023]

[33] Biomass Renewable Energy Alliance. (2019) BIOMASS POWER IN THE PHILIPPINES: REALIZING OUR TRUE POTENTIAL. https://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2019_events/PPTS_Manila_2019/PPTs_Manila_26/12.b.Don_Mario_Dia.pdf [Accessed Aug 26, 2023].

[34] Department of Energy. [DOE]. (2022) Hydropower | Department of Energy Philippines. https://www.doe.gov.ph/hydropower

[35] Halcon, R. M. (2015) Geothermal Energy Development in the Philippines. https://www.irena.org/-/media/Files/IRENA/Agency/Events/2015/Jun/5/5-Philippines.pdf?la=en&hash=8F8463F890B79A264F318A7084EC998803909AF9 [Accessed Aug 26, 2023]

[36] Elliott, D. (2000) Philippines Wind Energy Resource Atlas Development. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy01osti/28903.pdf.

[37] Lee, N., Flores-Espino, F., Oliveira, R., Roberts, B., Bowen, T. & Katz, J. (2020) EXPLORING RENEWABLE ENERGY OPPORTUNITIES IN SELECT SOUTHEAST ASIAN COUNTRIES. https://www.nrel.gov/docs/fy19osti/71814.pdf.

[38] IRENA (2022a), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi

[39] Department of Energy. [DOE]. (2022) Approved Budget FY2023 DOE. https://www.doe.gov.ph/sites/default/files/pdf/transparency/approved-budget_fy2023_doe-gaa-2023.pdf.

Appendix 1

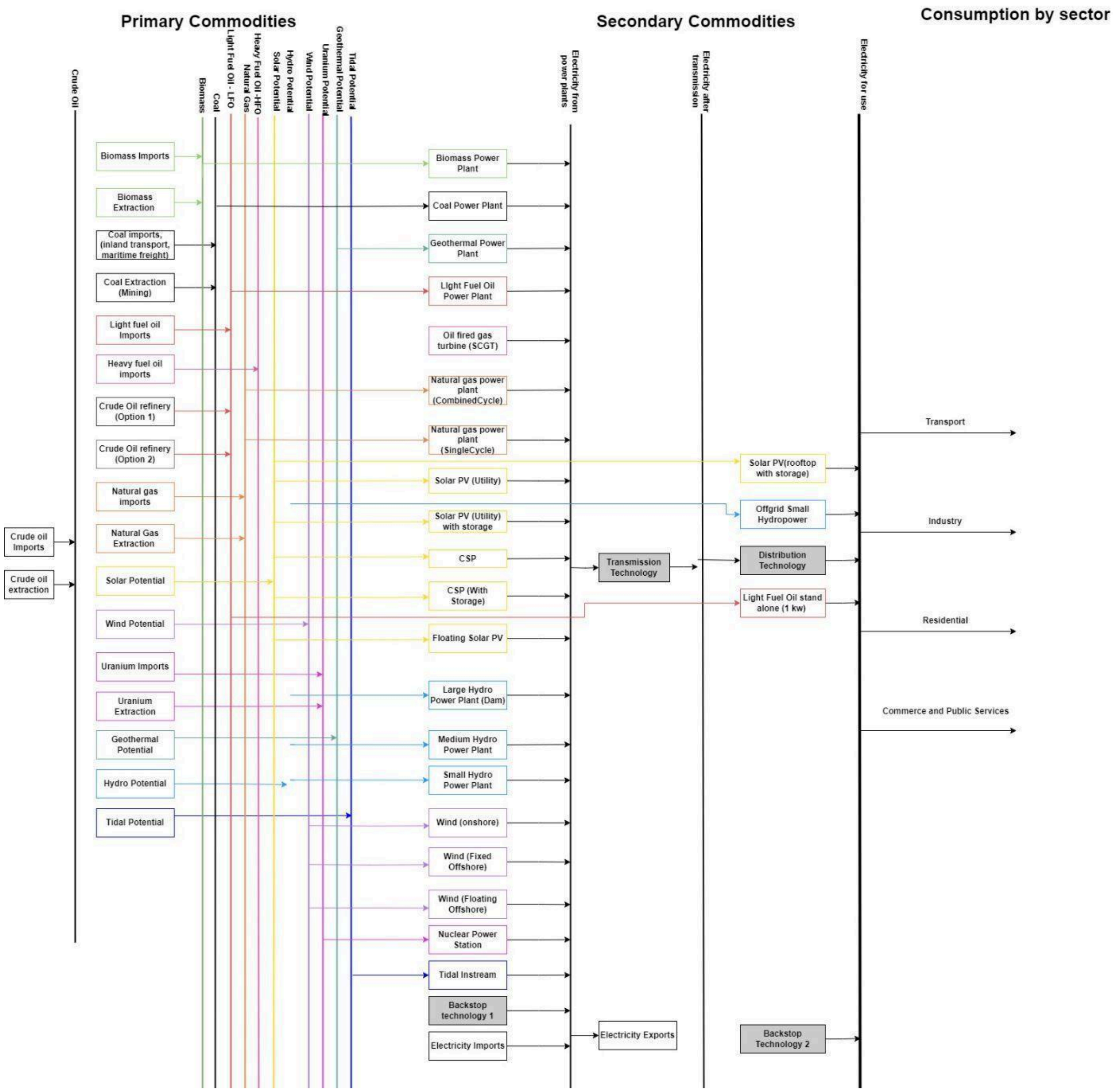


Figure A1. Reference energy system diagram (RES) for the Philippines energy system updated from the starter data kit [20]. Rectangles represent technologies while solid lines represent energy carriers. Note: Energy imports are removed from the model.

Appendix 2

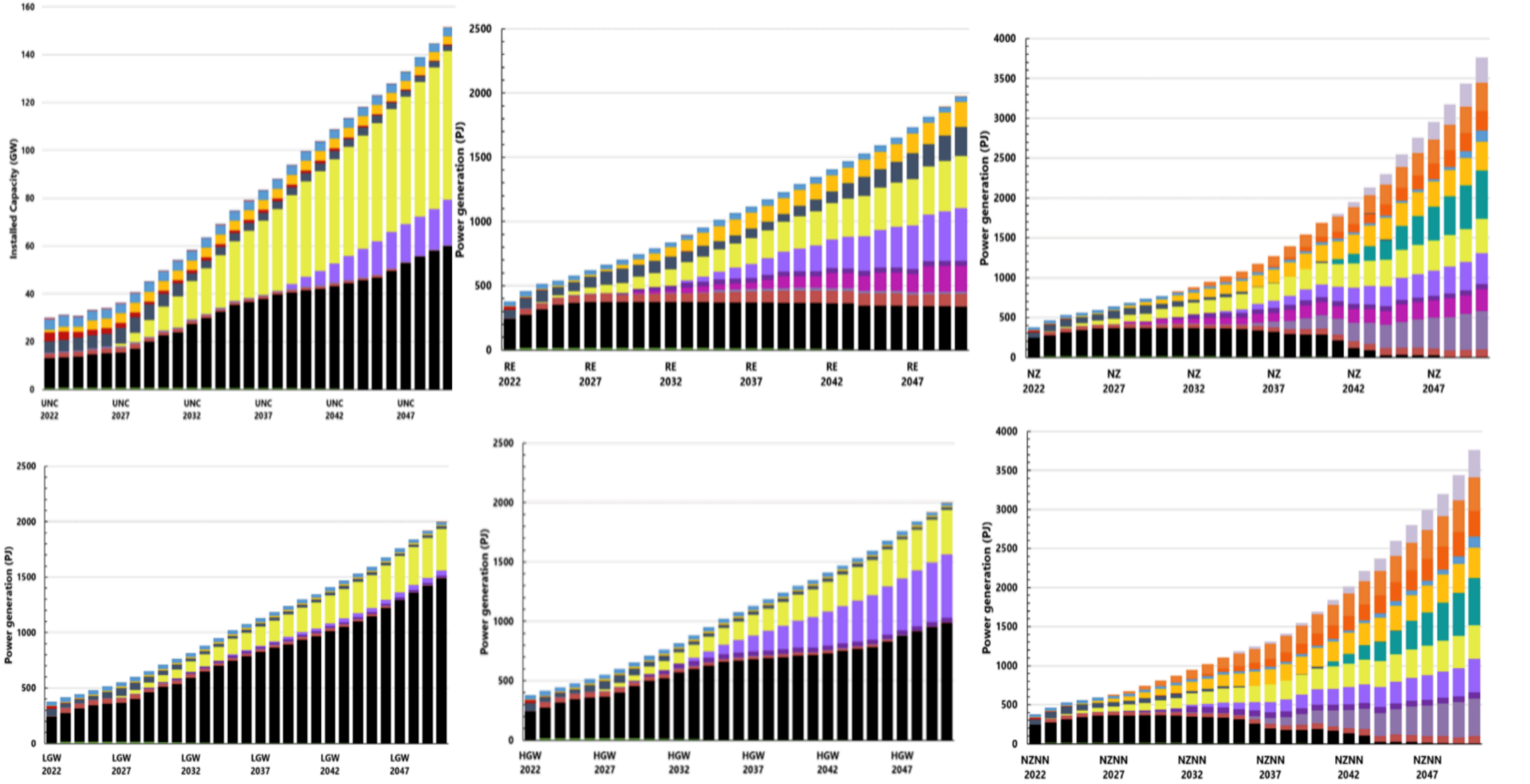
Table A1. Technical Potential for Coal, Crude oil, Natural Gas, and Biomass. [32,33]

Technology	Potential (PJ)
Coal	7620.156
Crude Oil	611.79
Natural Gas	3675
Biomass	136.7584

Table A2. Technical Potential for Renewable Technologies. [13,14,20,21,34-37]

Technology	Potential (GW)
Large Hydropower	14.6808
Medium Hydropower	1.89705
Small Hydropower	0.42002
Mini Hydropower (off-grid)	0.03731
Geothermal Power Plant	4.407
Onshore Wind	61.8
Fixed Offshore Wind	18
Floating Offshore Wind	160
Solar PV	337.2
Off-grid Solar with Storage	337.2
Floating Solar PV	83
Solar PV with storage	337.2
CSP	0
Tidal In-stream	50

Appendix 3



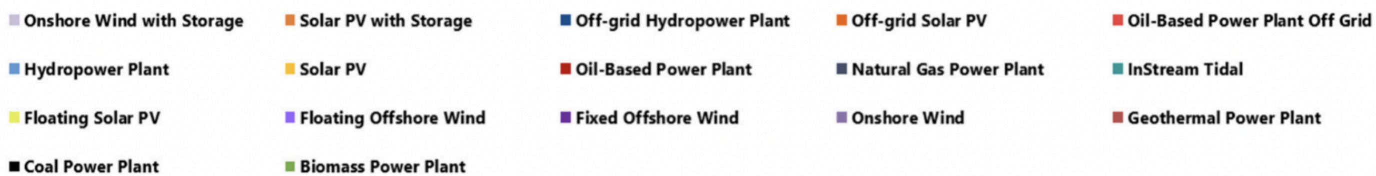


Figure A2. Power Generation in UNC, RE, NZ, LGW, HGW and NZNN scenarios.

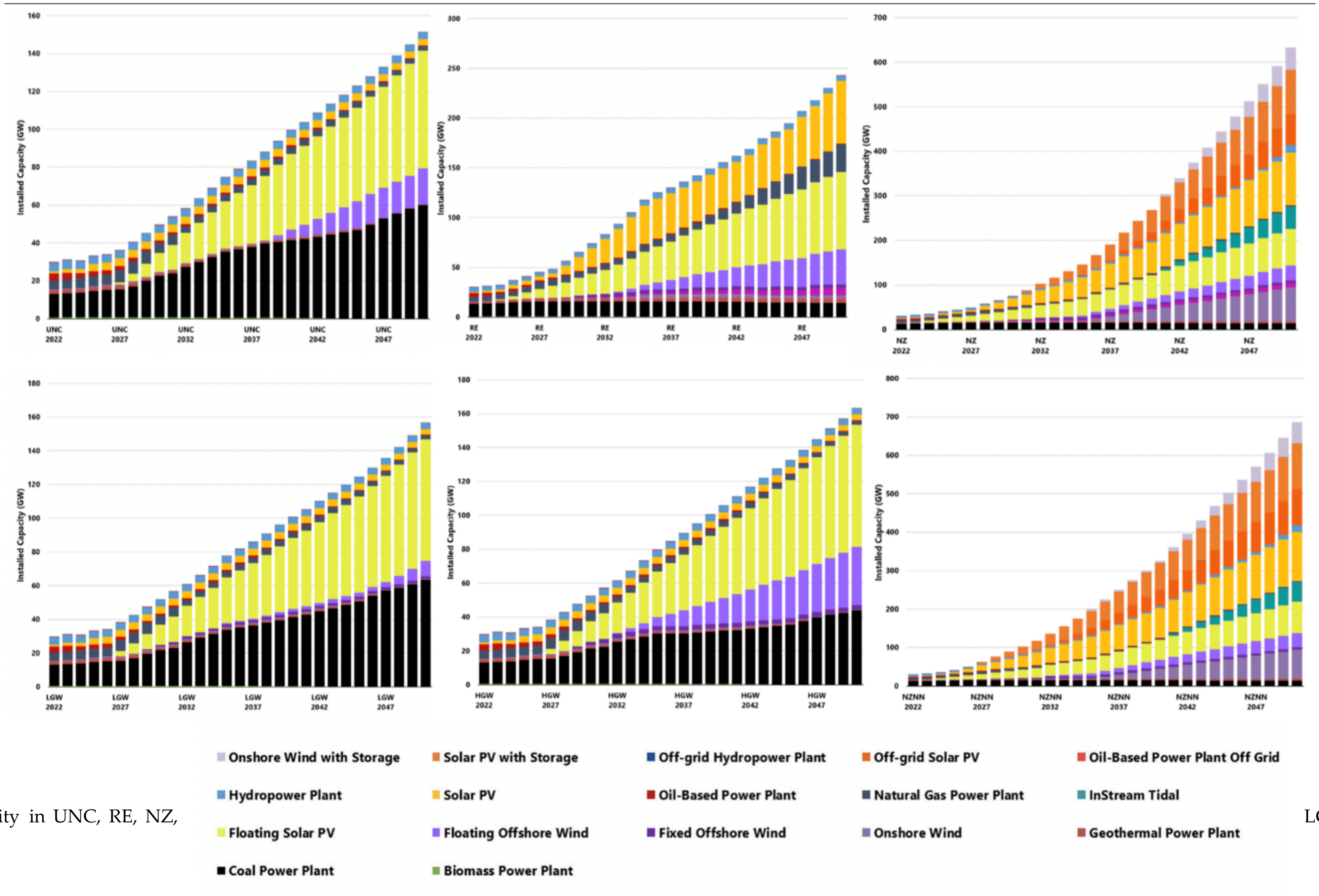


Figure A3. Installed Capacity in UNC, RE, NZ, LGW, HGW and NZNN scenarios.

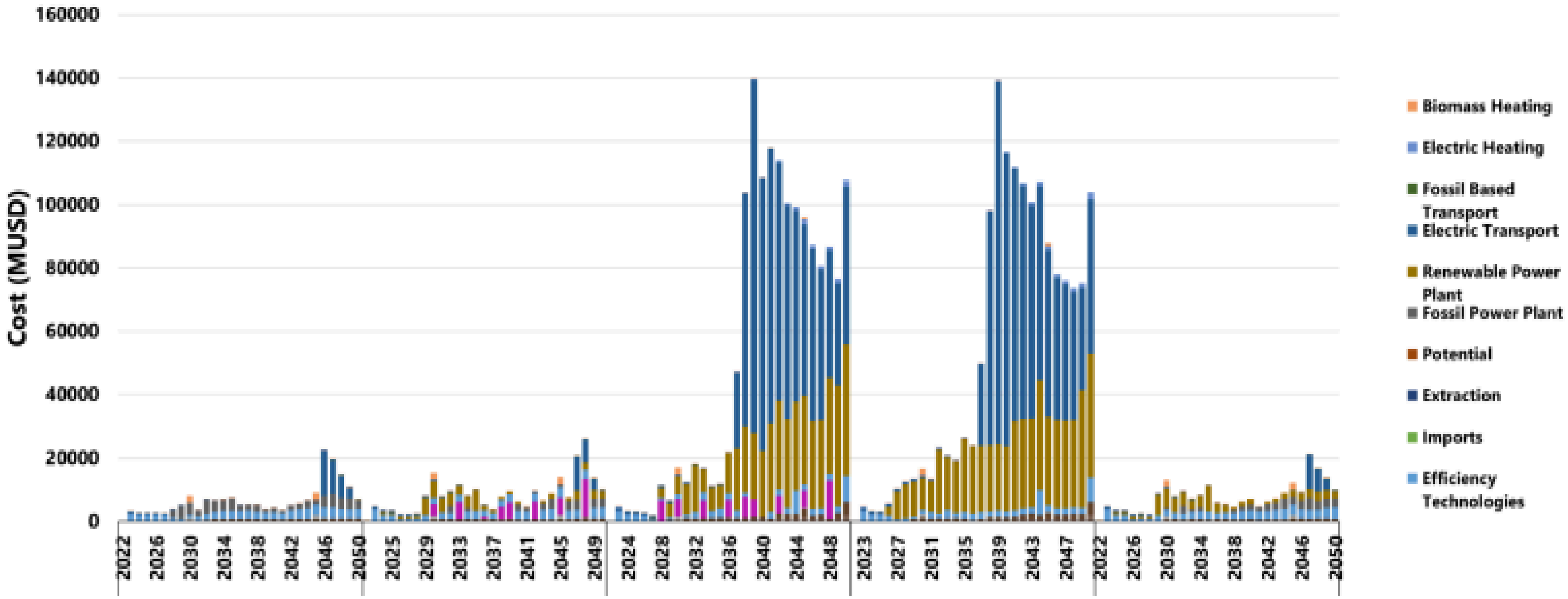


Figure A4. Annual Capital Cost Breakdown from 2022 to 2050. Left to Right (UNC, RE, NZ, NZNN and RENN scenarios.)

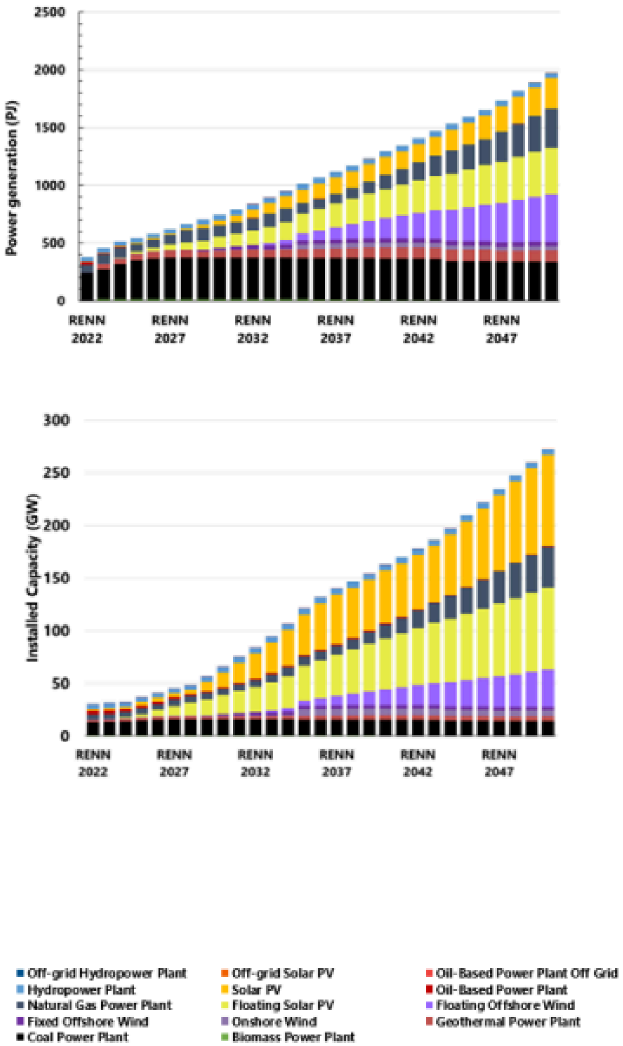


Figure A5. Installed Capacity and Power Generation for RENN Scenarios.

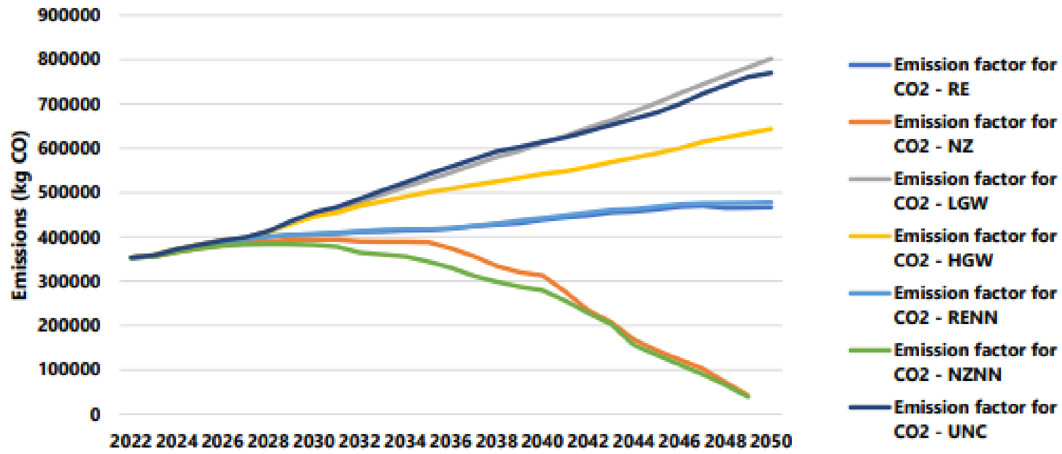


Figure A6. CO_2 emissions across modelling period in all scenarios.