Optimal Dispatch with Renewable Energy Generators for the Mitigation of Carbon Dioxide Emission

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Abstract

The reliance on coal-fired power plants for electricity generation in Mindanao, Philippines, poses significant environmental concerns due to their substantial carbon dioxide emissions. According to the Department of Energy, the total projected projects for coal-fired plants are 2,538 MW, accounting for approximately 30% of the carbon dioxide emissions. There were previous studies on mitigating the carbon footprint of a power system. However, it requires complex computational solutions and analysis, with the assumed required renewable energy to be implemented. To align with the country's commitment to reduce carbon emissions by 75% by 2040, this study explores the optimization of energy dispatch with the available renewable energy sources in the Mindanao grid. To achieve this, PowerWorld simulation software was utilized to perform the technical and economic analysis of the power system. Five-generation mix scenarios were also created based on sustainable load dispatching in Mindanao by 2030. It involved modeling the power system of various scenarios and conducting economic power flow simulations. The simulation results show that Case 3 (mix of coal, biomass, hydro, and geothermal) has the optimal mix with 20.51% carbon emission reduction and the cheapest marginal cost of 379,814.18 pesos/hr. This study highlights the practical potential of optimizing energy dispatch to transition towards a sustainable and clean energy generation system in Mindanao.

Keywords: blended generation cost, carbon dioxide emission, optimal generation mix PowerWorld software, renewable energy

1. Introduction

As society progresses, the increasing need for energy and the warning signs of rising global temperatures have become the two main focuses of human life. Over the next century, global temperatures will rise continually, with increasingly severe negative impacts on natural and socioeconomic systems (Tarafdar and Sinha, 2018). This rise in global temperatures is primarily attributed to coal usage, with coal-fired power plants accounting for approximately 30% of total carbon dioxide emissions. With these projections and the relationship between carbon dioxide and rising temperatures, the reduction of carbon emissions must be seriously considered. Much research on carbon emissions has focused on three key areas: the mechanisms and processes underlying carbon emissions, the relationship between carbon emissions and economic growth, and the connection between carbon emissions and energy consumption patterns. The Philippine government committed to reducing emissions by 75% by 2040 (Climate Change Commission, 2022). To achieve the targeted 75% emission reduction, knowing the estimated carbon dioxide output from coal power plants would be highly beneficial. This is complicated by the desire for rapid economic growth, which has driven industrialization and increased electricity demand in the region.

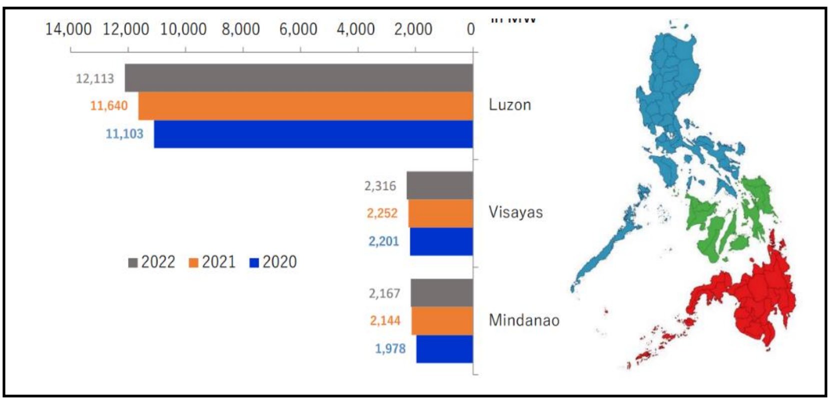

Figure 1. 2020 vs.2022 Peak Demand (Department of Energy, 2022)

As shown in Figure 1, the total peak electricity demand across the Philippines reached 16,596 MW in 2022, an increase of 3.5% over 2022. Mindanao, in particular, accounted for 2,167 MW or 13.9% of the national peak demand. Furthermore, electricity demand grew by 3.5% in 2022 compared with the previous year. This growth in industrial activity and power consumption, much of which relies on coal, presents a challenge to reducing overall carbon emissions in line with the target of 75% (Department of Energy, 2022). Currently, the average peak demand in the Mindanao area is 2,316 MW. The region's power demand is expected to double by 2024 and increase by 6.6% from 2025 to 2040 (Nicolas, 2017).

Figure 2 shows the gross power generation in Mindanao in 2022. Remarkably, coal-fired plants account for the highest portion of the generation mix, 60.1% (9,303 GWh). According to the data, the Department of Energy (DOE) sees 3,800 MW by 2022 as additional capacity for Mindanao power generation.

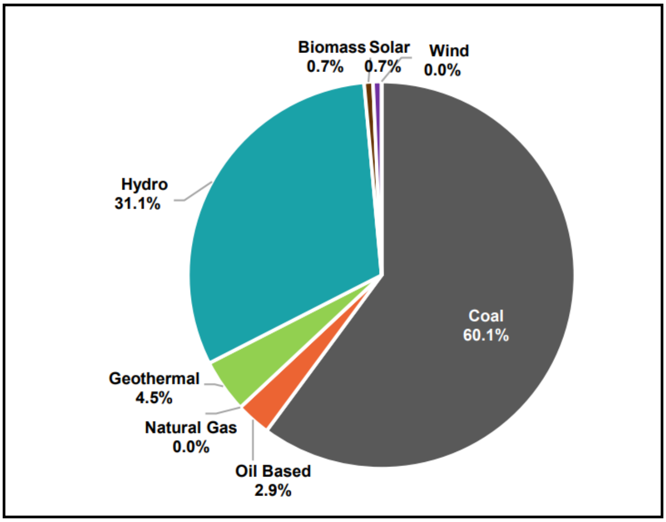

Figure 2. Gross Generation of Power in Mindanao (Department of Energy, 2022)

Currently, the total existing installed and dependable capacity for coal-fired plants in Mindanao is 2,268 MW. Based on the projections by DOE, the combined capacity for coal-fired plants will be 2,538 MW.

Table 1 shows the planned and committed projects for various regions in Mindanao (Department of Energy, 2022). It can be seen that renewable energies can have a share of 57.5% in the generation mix as compared to coal-fired plants, which can only share 7.1%. Therefore, optimizing energy dispatching is possible and essential to mitigate the contributions of large amounts of carbon dioxide emissions. However, these power plants may have benefits and drawbacks to consider. Take, for example, factors affecting the levelized cost of electricity (LCOE) are: Operation and Maintenance (O&M), Capital, Performance, etc. (Thunder Said Energy, 2024). Entler *et al.* (2018) compared the levelized cost of electricity for several types of power plants, such as Gas power stations, coal-fired, nuclear, and photovoltaic systems. From their study, the investment costs, cost of electricity, techno-economic analysis, sensitivity analysis, and external costs were also considered. The results show that some renewable energies, like solar, hydro, and wind, have more expensive LCOE than fossil fuels.

Table 1. Mindanao Energy Projects (Department of Energy, 2022)

Type of Power Plant	Committed Capacity (MW)	% Share	Indicative Capacity (MW)	% Share	No. Commenced Projects
Coal	270	51.2	120	7.1	0
Oil-Based	11	2.1	0	0	1
Natural gas	0	0	600	35.4	0
Renewable Energy	246	46.7	975	57.5	2
a. Geothermal	0	0	0	0	1
b. Hydro	100	19	747	44.1	1
c. Biomass	26	4.9	62	3.7	0
d. Solar	120	22.8	130	8	0
e. Wind	0	0	36	2.1	0
2022 Total	527	100	1695	100	3
BESS	280		118		1
2021 Total	675		1790		

The Philippines has heavily relied on fossil fuel (coal) in its power supply mix for the past years because of its cheaper operational cost. A significant study conducted by Gonocruz *et al.* (2024) evaluates the minimization of coal usage, suggesting using Renewable Energy Sources (RES) in different scenarios to mitigate carbon emissions in the Philippines. The study highlights using a battery energy storage system (BESS) to maximize the utilization of RES. Using linear programming optimization methods, the result shows a significant reduction of coal usage by 30% in the year 2030. However, the study suggests the required expansion of transmission lines to connect Grids in the Philippines and additional RES to address the environmental issues.

While RES is a good alternative energy source, it has several issues during its implementation, such as reliability, sustainability, economic, and even environmental aspects. The study by Tshikovhi *et al.* (2024) presented the different technologies and innovations in biomass energy. Biomass energy is determined as environmentally benign renewable energy. Nonetheless, conversion of such technologies faces certain difficulties regarding scaling up and commercial viability because of their significant operational costs, investment requirements, and elevated energy consumption. Other RES such as Hydro and Solar Energy have been determined to have less environmental impact during operation. However, these RES have high investment costs during the pre-development stage and could alter the ecosystem, displacing people and wildlife (Kitey *et al*., 2024). For the case of a hydroelectric plant, it can alter the water flow of the river, affect aquatic life, and produce noise pollution. Kitey *et al*. (2024) also summarize the issues governing solar energy systems, such as intermittency and variability, energy storage, land use and environmental impact, material chain and recycling, Grid integration, and waste management (Akashie, 2022).

This study uses a simplified method that uses only the available energy resources, including future committed projects by the DOE in Mindanao. However, the penetration level of different power plants is not considered. The selection of five (5) cases was based on the previous studies related to the pros and cons of RES. The optimal generation mix considering economic and environmental concerns will be determined using reliable simulation software such as PowerWorld. In which the software can solve optimal power flow using the Newton-Raphson Method (Randhawa *et al.*, 2010). It has a Linear Programming algorithm for optimizing the economic dispatch of the power system. A study by Kaur *et al*. (2010) shows the software's capability in finding an optimal solution to minimize generation cost and lower electricity cost.

2. Methodology

The methods and steps for this research include identifying new renewable energy sources, optimizing the generation mix through economic load dispatching, assessing the mitigation of carbon dioxide emissions, and evaluating the blended costs of renewable energy integration.

2.1 Identification of Additional Potential Renewable Energy Sources

The Mindanao Energy Plan (MEP) for 2018–2040 was cited to identify additional possible renewable energy sources. The two demand predictions recommended by the MEP, shown in Figure 3 and Table 2, are the Low

Growth Scenario (LGS), which only covers on-grid operations, and the High Growth Scenario (HGS). For the HGS projection, the peak demand for Mindanao is estimated to increase by 9.6% annually, tallying 2,278 MW in December 2020 (Department of Energy, 2018) and 14,575 MW in 2040. In the low-demand scenario, the peak demand increases to 8,632 MW by 2040, representing an annual increase of 7.1% (National Grid Corporation of the Philippines, 2020).

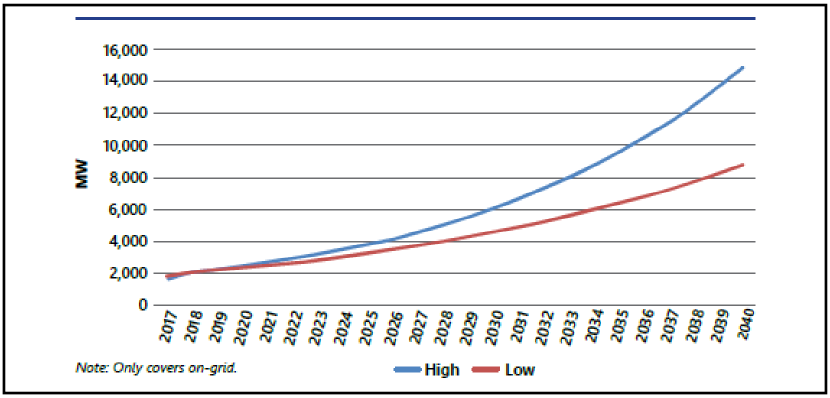

Figure 3. Mindanao Peak Demand, 2018 - 2040 (High and Low) (Department of Energy, 2018)

Table 2. System Peak Demand (in MW) (Department of Energy, 2018)

Year	High Growth	Low Growth
2017	1,760	1,760
2018	2,095	2,064
2020	2,364	2,226
2025	3,695	3,165
2030	5,916	4,416
2035	9,280	6,171
2040	14,575	8,632
Average Annual Growth Rate (%) (2018-2040)	9.6	7.1

The reference scenario will be the basis for determining the required power reserves, termed as “Reference High” or “Reference Low”. This also implies that existing development strategies used by different agencies will be used. The reference scenario assumes the following: as of April 2018, all committed power projects and RE-based indicative power projects will be finished (a); and the RE capacities from the granted and pending RE service contracts (RESCs) will also materialize and bolster the grid's electricity supply (b).

2.2 To optimize the Generation Mix

“PowerWorld” simulator tools were employed to calculate the economic power dispatch problem, power-flow equations, and to allocate distributed generation in the region at the optimum level. A study done by Nawaz *et al*. (2023) proved the reliability of PowerWorld in solving Economic Load Dispatch. To get the optimized generation mix, the authors relied on the result of the cost-efficient blended generation cost. According to Glover *et al*. (2017), economic dispatch identifies the megawatt outputs of the regulated units that reduce the overall operating expenses for a specified load requirement. Hence, the MW values of the cheapest value based on the case scenario was accounted for as the optimal mix.

2.3 To determine the mitigated Carbon Dioxide Emissions

When generating the same quantity of power, the emission reduction (ER) in Equation 1 is the difference between baseline and projected emissions. The baseline in Equation 2 is the continuous inefficient use of present equipment. The ER difference between baseline (BE) and projected emissions (PE) for generating the same amount of power (Asian Development Bank, 2017). BE is the product of annual electricity generation and the emission grid factor shown in Table 3.

$$ER = BE - PE \tag{1}$$

$$BE = EG \; x \; EF_{grid} \tag{2}$$

For applicable RE projects, PE is considered to be zero (0). In the calculation process, emissions were calculated using the data of the annual additional potential for coal and RE, which was calculated using Equation 1.

For comparison purposes, the researchers assumed that by 2030, all committed and pending power plant projects would be completed and operational. The following are important key parameters set by the Asian Development Bank in determining the mitigated/reduced carbon dioxide emissions.

Table 3: Emission Factor of Different Power Plants

Types of Power Plant	Grid Emission Factor *(tCO_2/MWh)*
Coal Fired	0.648
Biomass	0.096
Solar PV	0.551
HydroElectric	0.09
Geothermal	0.128

2.4 To determine the blended generation cost considering the additional Renewable Energy Sources.

Cost functions were considered in the simulation of the economic dispatch. Thus, the cost of blended generation was determined. Determining the blended generation cost for each case is essential for identifying the most cost-efficient mix.

Djurovic *et al*. (2012*)* provided the thermal cost functions used for Biomass and Geothermal plants, as shown in Equations 4 and 7, respectively. Martinez and Rivera (2018) approximated the cost function for Solar PV in Equation 5 and Hydro in Equation 6, while Morcilla and Caliao (2010) provided the cost function for Coal-fired power plants in Equation 3.

$$\textit{Coal-fired Power Plants: } C_c P_c = 0.015\,P_c^2 + 16.395 P_c + 4.5 \quad (3)$$

$$\textit{Biomass Power Plants: } C_B P_c = 0.005\,P_c^2 + 6 P_c + 100 \quad (4)$$

$$\textit{Solar PV Power Plants: } C_{PV} P_c = 0.331\,P_c^2 + 33.544 P_c + 918 \quad (5)$$

$$\textit{Hydro Power Plants: } C_H P_c = P_c^2 + 386 P_c + 914 \quad (6)$$

$$\textit{Geothermal Power Plants}\textbf{: } C_G P_c = 0.002211\,P_c^2 + 16.5\,P_c + 680 \quad (7)$$

The derivation of these cost functions is tedious. Martinez and Rivera (2018) selected the cost functions based on the standard practices in power system studies, as presented in the table for thermal generators, which includes their corresponding constraints. In this study, the authors opted to determine such cost functions due to the unavailability of other resources that approximate thermal generators, such as biomass and geothermal power plants. Therefore, using the data available at DOE, the range of available MW values was used as constraints for approximate equations from previous literature.

Analytical solutions for the mathematical formulation are based on the study of Martinez and Rivera (2018). Monte Carlo simulations were used to validate the obtained result. This simulation can also be used to study the behavior of complex non-deterministic systems by computing and generating a large number of random values y and forecasting the system's behavior.

Solar energy's main technology is irradiance, which depends on environmental availability. In this study, solar irradiance is similar to the behavior of a log-normal distribution, which can be used under specific circumstances. The log-normal probability function can be solved using Equation 8:

$$f_G(G) = \frac{1}{G\beta\sqrt{2\pi}} * \exp\{-\frac{[ln(G)-\lambda]^2}{2\beta^2}\} \quad (8)$$

where G is the solar irradiance, f_G is the corresponding probability distribution function and λ and β are the parameters of scale and location of the Log-normal distribution. Underestimation and overestimation are presented to get the approximate cost function for solar (Martinez and Rivera, 2018).

The main technology for hydroelectric power is the river flow where the plant is located. The Gumbel distribution function behaves like a river-flow scenario. Gumbel distribution function can be solved using Equation 9.

$$f(Q) = \frac{e^{\left|\frac{Q-\mu}{\sigma}\right|} e^{-e^{\left|\frac{Q-\mu}{\sigma}\right|}}}{\sigma} \quad (9)$$

where Q is the flow of water received by the generator, μ is the average value and σ is the mean square deviation.

3. Results and Discussion

3.1 Identification of Additional Potential Renewable Energy Sources

In the identification of peak demands in the long term, a supply outlook which coincides with the additional capacity potential per renewable energy source is presented for HGS and LGS.

In addition to Mindanao's recognized available capacity, committed fossil and renewable energy (RE) power projects and indicated RE power projects were considered capacity additions, shown in Table 4. Coal supplies more than half of the total committed capacity of approximately 1,300.49 MW, with hydro-based RE projects making up the remainder. For illustration purposes, RE power projects with a total capacity of 829.30 MW were considered. The total RE-based capacity (including committed and indicated capacity) was 1,429.8 MW (Department of Energy, 2018).

Potential RE capabilities were also added based on the Department of Energy's awarded and pending RE Service Contracts (RESC) issued as of December 2017, including potential capacity (with RESC application) shown in Table 5. As previously stated, the potential capacity of these RESCs is 2,471 MW, which includes 1,728 MW awarded RESC, 415 MW pending RESC, and 328 MW prospective capacity from the RESC application.

Table 4. Committed and Indicative Power Projects in Mindanao (as of April 2018)

	Committed Capacity (MW)	Indicative Capacity (MW)
Coal	700.00	-
Geothermal	-	30.00
Hydro	588.49	249.90
Solar	120	460.00
Biomass	12.00	89.40
Total	1,300.49	829.30

Table 5. Potential Capacity of Awarded and Pending RE Projects (as of December 2017)

	Awarded RESC (MW)	Pending RESC (MW)	RE Potential (MW)	Total RE Potential (MW)
Geothermal	80.00	60.00		140.00
Hydro	1012.00	160.36	328.33	1500.00
Solar	636.11	161.50		797.61
Biomass		33.19		33.00
Total	1728.11	415.05	328.33	2470.97

Note: Potential Provided by Renewable Energy Management Bureau -Hydropower and Ocean Energy Management Division (REMB-HOEMD)

By 2030, the total installed capacity will reach 7,395 MW with an annual average growth rate of 7.8%. Coal also accounts for 53.2% (4,470 MW) of the total capacity, followed by renewables (40.8%) (3,429 MW) and oil (6.0%) (506 MW). These are considered as the Reference High (RH) reserve.

For the Reference Low reserve, 5,520 MW of the total installed capacity would have an annual growth rate of 5.7%. By 2030, 3,814 MW of installed capacity will be dominated by coal as compared to the Reference High with 4,470 MW production.

3.1.1 Possible Test Cases / Scenarios of Generation Mix

Table 6. Test Cases

Test Cases	Energy Mix	Total Energy Reserve (MW) by 2030
Case 1	*Initial (Base Case)*	*8, 138.58*
Case 2	*Hydro + Coal + Solar + Geothermal*	*7,996.20*
Case 3	*Biomass + Coal + Hydro + Geothermal*	*6,722.33*
Case 4	*Biomass + Coal + Solar + Geothermal*	*6,169.63*
Case 5	*Biomass + Coal + Solar + Hydro*	*7,843.33*

Based on the previous studies considering the benefits and drawbacks for each power plant, the authors proposed the possible generation mix for Mindanao Grid shown in Table 6. These possible combinations of energy reserves can supply the required energy demand in Mindanao for the year 2030, as shown in Table 2. Coal-fired plant is included in every test case since it is considered a dependent source. For Case 1, the initial scenario of generation mix in Mindanao compose of Hydro, Coal, Solar, Biomass, and Geothermal plants. Other cases have set of different power plant based on projected data provided by DOE.

3.2 Optimization Generation Mix

To obtain an optimized generation mix, the author relies on the results of the cost-efficient blended generation cost. According to Glover *et al.* (2017), "*economic dispatch determines the megawatt outputs of the controlled units that minimize the total operating cost for a given load demand*". Hence, the MW values of the cheapest value based on the case scenarios were considered as the optimal mix of generation. Each year from 2022-2030, the total energy dispatch, cost, and carbon footprint for each case will be determined using PowerWorld Simulator.

3.2.1 Case 1: Initial Scenario

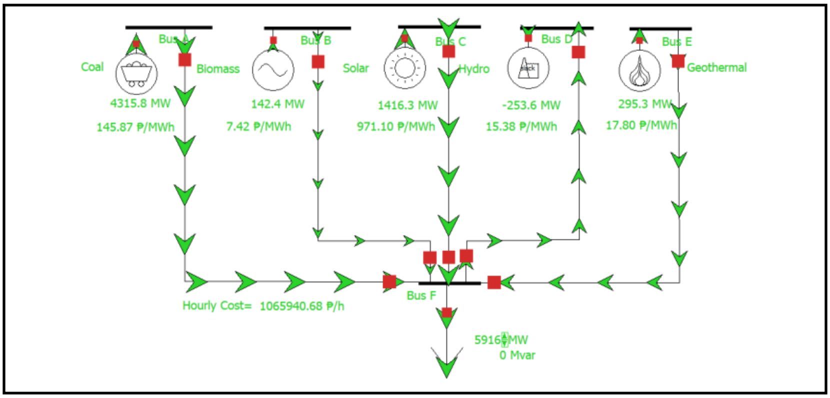

Figure 4. Generation Case 1 Scenario

Figure 4 shows the simulation sample of the base case scenario for the Mindanao mix using the optimal power flow of the simulator. Generation cost and capacity for each type of power plant were the important key parameters in the simulation. The goal is to optimize the generation mix by determining the most economical dispatch with the least carbon footprint.

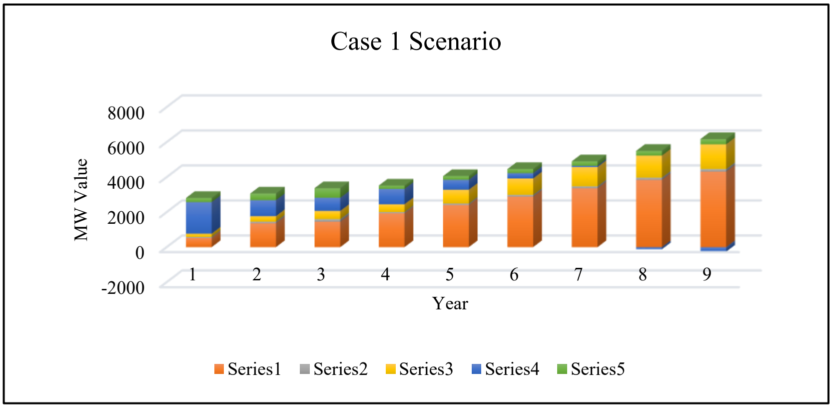

Figure 5. Projected Generation Case 1 Scenario

Case 1, shown in Figure 5, shows the upward trend for the utilization of coal, solar, and geothermal energy from 2022 to 2030. Biomass plants had no significant changes over the years. However, the Hydro plant was underutilized from 2029 to 2030, resulting in negative MW values. A total of

3,805.63 tons of CO_2 (tCO_2) carbon footprint would be mitigated for this case with a Marginal Cost of 1.065 x 106 Php/hr for 2030.

3.2.2 Case 2: No Biomass

For case 2, shown in Figure 6, there is a discontinuity in hydro energy due to negative MW values, which have an excess generation of approximately 111 MW for 2030. The rapid increase in production is seen in coal and solar, peaking at 4,315.8 MW and 1,416.3 MW, respectively. The geothermal plant was observed to be gradually increasing from 233 MW in 2022, peaking only at 295.3 MW in 2030. This case has an estimated carbon mitigated of 3,791.96 tCO_2 or 0.36% and a marginal cost of 1.067 x 10^6 Php/hr.

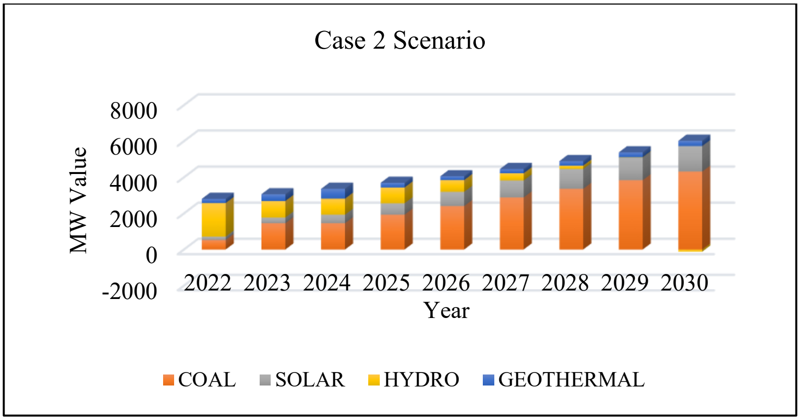

Figure 6. Generation Case 2 Scenario

3.2.3 Case 3: No Solar PV

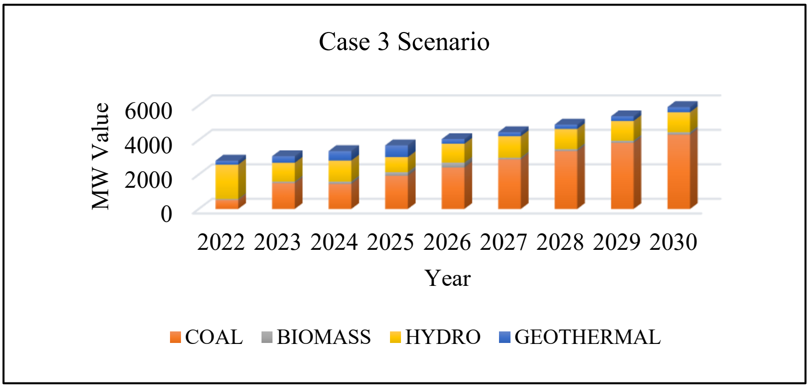

Figure 7. Generation Case 3 Scenario

Figure 7 shows the simulation result without the Solar PV plant. All power plants were utilized showing no excess in generation. It means that all types of plants were increased at a specific rate from year 2022 to 2030. Result shows also that there is a significant increase in the utilization of Hydro plant through the years. This combination has enormous reduction of electricity cost with an estimated amount of 0.379 x 10^6 Php/hr. Moreover, the total carbon emission was reduced by 3,025.27 or 20.51%.

3.2.4 Case 4: No Hydro

The dependency on coal-fired power plants can still be observed in Figure 8. Although Solar PV peaked at 1,000 MW level might not be guaranteed to sustain the load demand due to unpredictable weather. A decline in geothermal power is also observed at 41.6 MW level by the year 2030 from 233.2 MW at year 2022. Only 4.66 % of carbon footprint reduced from base case scenario while the estimated hourly cost for year 2030 is at 1.065 x 10^6 Php/hr.

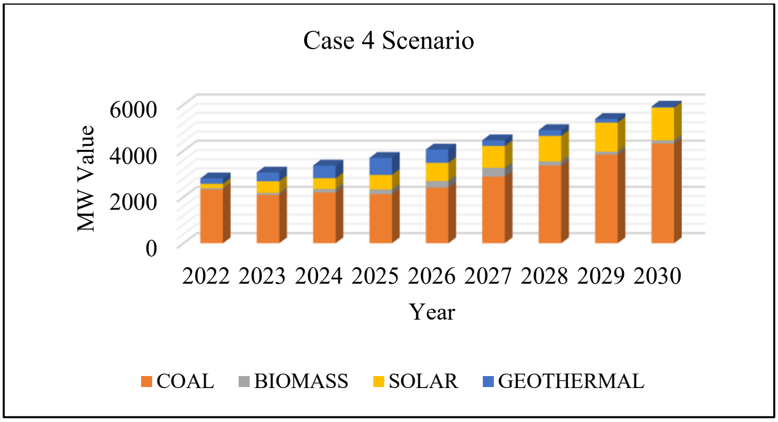

Figure 8. Generation Case 4 Scenario

3.2.5 Case 5: No Geothermal

There could be a decline in the power production from Hydro in case 5, shown in Figure 9. From 2022, it peaked at 2,038.6 MW of generated power and will become 41.6 MW by 2030. Meanwhile, biomass and solar PV energy have continued to increase throughout the years. The highest peak for a coal-firedd plant can be observed in all cases with 4,315.8 MW power. This scenario of generation mix has 0.993% reduction of CO_2 emission with an estimated hourly cost of 1.064 x 10^6 Php/hr in 2030.

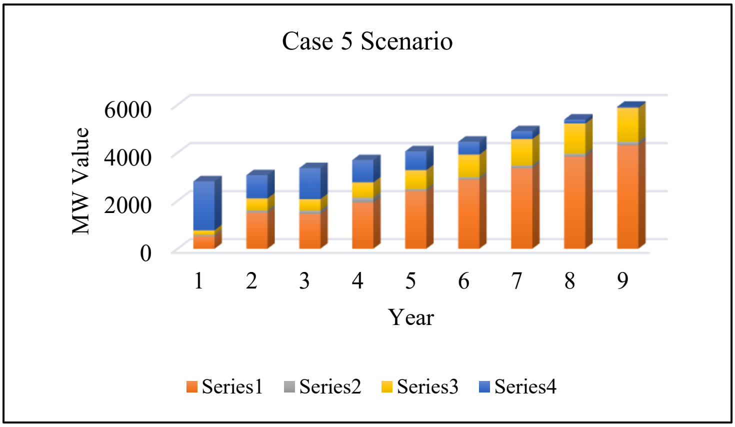

Figure 9. Generation Case 5 Scenario

3.3 Summary of Carbon Dioxide Emission Mitigation

The authors arrived at the following result based on the Guidelines for Estimating Greenhouse Gas Emissions set by the Asian Development Bank for project implementation.

Over the years, coal has been the top contributor to carbon emissions. Even with the rough penetration of Renewable Energy Sources, coal still emerges as a heavy hitter in terms of carbon emissions. Figure 10 shows the summary of carbon emissions mitigated for each power plant. The coal energy would have a total of 2,796.61 tCO_2 or 73.5% to be mitigated in the generation mix. The second largest contributor is the solar energy which has 780.35375 tCO_2 or 20.51% by 2030.

Table 7 shows the summary of carbon mitigated for each case from 2022 to 2030. Based on this result, Case 3 has the lowest carbon footprint, with 3,025.27 tCO_2, or 20.51% less than the other cases.

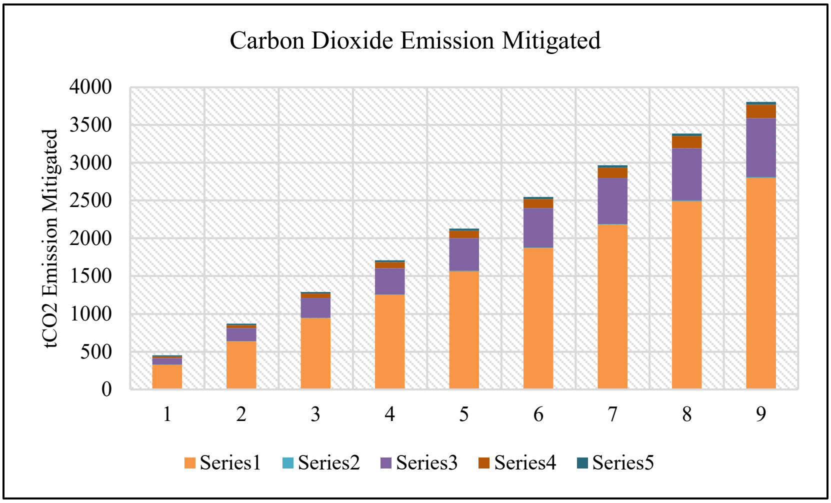

Figure 10. Carbon Dioxide Emission Mitigated

Table 7. Summary of Carbon Mitigated (tCO2) for each Case Scenario

Cases	Year								
	2022	2023	2024	2025	2026	2027	2028	2029	2030
Case 1	449.928	869.390	1288.852	1708.314	2127.777	2547.239	2966.701	3386.163	3805.626
Case 2	448.067	866.054	1284.040	1702.026	2120.012	2537.999	2955.985	3373.971	3791.957
Case 3	362.732	695.549	1028.367	1361.184	1694.002	2026.819	2359.637	2692.454	3025.272
Case 4	430.222	829.997	1229.772	1629.546	2029.321	2429.096	2828.871	3228.645	3628.420
Case 5	433.896	850.638	1267.380	1684.122	2100.865	2517.607	2934.349	3351.091	3767.834

3.4 Determination of the Blended Generation Cost of Electricity

As shown in Figure 11, the summary of cost per year compares the operational cost of each case scenario. Graph shows that Case 2 has the most expensive among the group tallying at 1,067,120.03 Php/hr. Cases 4 and 5 have 1.065 x 10^6 and 1.064 x 10^6 Php/hr respectively. Meanwhile, Case 3 has the cheapest marginal cost with only 379,814.18 Php/hr. Based on the economic dispatching results, Case 3 has the most optimized generation mix from year 2022 to 2030.

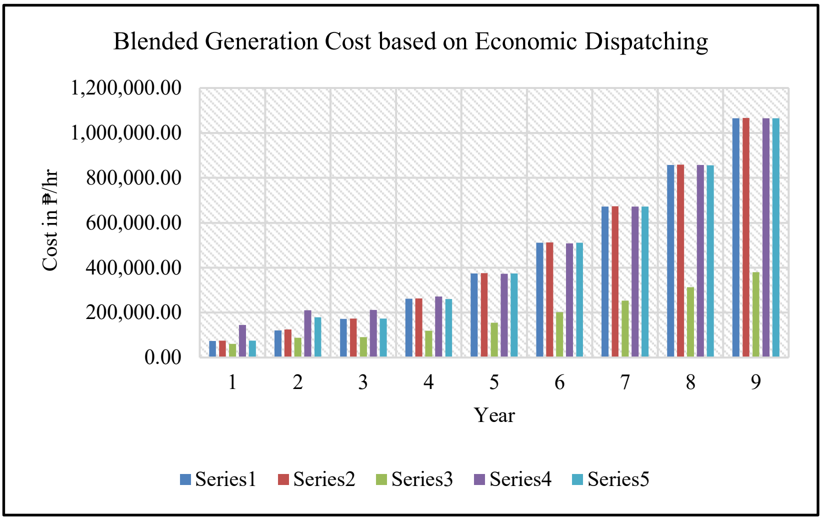

Figure 11. Blended Generation Cost based on Economic Dispatching

4. Conclusion and Recommendation

The data from the Mindanao Energy Plan based on Additional Capacities per technology source shows the existence of coal-fired plants until 2030. It will still dominate the energy mix in Mindanao. Based on results, the Case 3, consisting of Coal, Biomass, Hydro, and Geothermal plants presents the optimum generation mix. It is 50% cheaper marginal generation cost as compared to other cases with an average of only 379,814.18 Php/hr. It has also the lowest carbon footprint with 3,025.27 tCO_2 or 20.51% less among other generation mix. The use of PowerWorld simulation software shows significant result in computing power flow and economic load dispatch of power generations. A practical simulation-based tools for guiding Mindanao's transition toward a cleaner and more sustainable energy future.

To further improve the study in mitigation of carbon emissions of power plants researchers recommend conducting a transient analysis of the system to reinforce the utilization of renewable energy sources. It also needs to evaluate the overall capacity of renewable energy sources to mitigate substantial carbon emissions. Consider other emissions such as Sulfur Oxides (SO_x) and Nitric Oxide (NO) from coal-fired power plants.

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6. References

Akashie, E. (2022). Advantages and disadvantages of hydroelectric energy. https://doi.org/10.13140/RG.2.2.31028.94081

Asian Development Bank (2017). Guidelines for estimating greenhouse gas emissions of Asian Development Bank projects: additional guidance for clean energy projects. Retrieved from https://www.adb.org/sites/default/files/institutional-document/296466/guidelines-estimating-ghg.pdf

Climate Change Commission (2022). Climate Change Impacts. Retrieved from https://niccdies.climate.gov.ph/climate-change-impacts

Department of Energy (2018). Mindanao Energy Plan 2018-2040. Retrieved from https://doe.gov.ph/sites/default/files/pdf/pep/mindanao-energy-plan-2018-2040.pdf

Department of Energy (2022). 2022 Power Situation Report. Retrieved from https://doe.gov.ph/sites/default/files/pdf/electric_power/2022_Power_Situation_Report_as_of_02Dec2024_ADLGB_DICE_CLEAN_rev1_FINAL.pdf

Djurovic, M., Milacic, A., & Kršulja, M. (2012). A simplified model of quadratic cost function for thermal generators. In Proceedings of the 23rd DAAAM International Symposium, Zadar, Croatia, 24-27.

Entler, S., Horacek, J., Dlouhy, T., & Dostal, V. (2018). Approximation of the economy of fusion energy. Energy, 152, 489-497. https://doi.org/10.1016/j.energy.2018.03.130

Glover, D.J., Overbye, T.J., & Sarma, M.S. (2017). Power system analysis & design (3rd ed.). Boston, NY: McGraw Hill Inc.

Gonocruz, R.A.T., Yoshida, Y., Silava, N.E., Aguirre, R.A., Maguindayao, E.J.H., Ozawa, A., & Santiago, J.V. (2024). A multi-scenario evaluation of the energy transition mechanism in the Philippines towards decarbonization. Journal of Cleaner Production, 438, 140819. https://doi.org/10.1016/j.jclepro.2024.140819

Kitey, H., Chandankhde, P., Jajulwar, K., Shaikh, M.S., & Fatinge, P.M. (2024). Solar power generation technique and its challenges-a comprehensive review. Grenze Int J Eng Technol (GIJET), 10

Martinez, C.A., & Rivera, R.S. (2018). Quadratic Modelling of Uncertainty Costs for Renewable Generation and its Application on Economic Dispatch. Revista Del Programa De Matematicas, 5(1), 36-61. https://core.ac.uk/download/pdf/229959989.pdf

Morcilla, R.V., & Caliao, N.D. (2010). A Methodology in Determining the Optimum Mix Generation Units. Mindanao Journal of Science and Technology, 8(1), 35-56.

National Grid Corporation of the Philippines. (2020, February 20). NGCP urges government to address impending power shortage in 2020. National Grid Corporation of the Philippines. Retrieved from https://www.ngcp.ph/article?cid=16172

Nawaz, S., Bhardwaj, E., Sharma, D.R., & Parmar, D. (2023). Comparison of Different Simulation Tools for Load Flow Analysis in Power Systems. International Journal of Advanced Engineering Management and Science, 9(5), 088–093. https://doi.org/10.22161/ijaems.95.12

Nicolas, J. (2017, October 5). DoE sees 3,800-MW requirement in Mindanao by 2022 - BusinessWorld Online. BusinessWorld Online. Retrieved from https://www.bworldonline.com/the-nation/2017/10/06/57963/doe-sees-3800-mw-requirement-mindanao-2022

Randhawa, J.S., Kaur, H., & Brar, Y.S. Optimal power flow using power world simulator. In Proceedings of 2010 IEEE Electrical Power Conference, Halifax, Canada, 1-6.

Tarafdar, A., & Sinha, A. (2018). Polycyclic Aromatic Hydrocarbons (PAHs) Pollution Generated from Coal-Fired Thermal Power Plants: Formation Mechanism, Characterization, and Profiling. In: R. A. Agarwal, A. K. Agarwal, T. Gupta, & N. Sharma (Eds.), *Pollutants from Energy Sources: Characterization and Control (*73-90). Singapore: Springer Singapore

Thunder Said Energy (2024). Levelized cost of electricity: stress-testing LCOE. Retrieved from https://thundersaidenergy.com/downloads/levelized-cost-of-electricity-database

Tshikovhi, A., & Motaung, T.E. (2023). Technologies and Innovations for Biomass Energy Production. Sustainability, 15(16), 12121. https://doi.org/10.3390/su151612121