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High Renewable Energy (Solar Photovoltaics and Wind) Penetration Hybrid Energy Systems for Deep Decarbonization in Philippine Off-grid Areas

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The Philippines has many off-grid areas relying on diesel generators for energy access, but have high greenhouse gas emissions, high electricity costs, and intermittent operation. An opportunity to decarbonize the energy system of off-grid islands is by harnessing both solar photovoltaic (PV) and wind power. This work evaluates the techno-economic viability of putting up solar PV-wind-battery-diesel hybrid energy systems in 143 existing off-grid island areas operated by the National Power Corporation-Small Power Utilities Group (NPC-SPUG) using HOMER® Pro. The application obtains the optimal system component sizes with the least levelized cost of electricity (LCOE). The results suggest that there are 137 islands capable of using both solar PV and wind generation, 4 islands using solar PV only, and 2 islands using wind only. The hybrid energy systems in the sample islands require USD 774,171,061 (~ PHP 40,643,980,682) worth of investment cost with potential annual savings of USD 132,403,163 (~ PHP 6,951,166,051). The resulting system capacities and their corresponding LCOEs suggest high sensitivity towards wind potential due to lower capital cost of wind and potential higher energy share up to 58.47 %. Wind generation for off-grid islands should be considered alongside solar PV, especially in areas with high wind potential, to provide reliable energy access and reduce greenhouse gas emissions.

1. Introduction

Many off-grid areas rely on diesel fuels since main grid interconnection is currently impractical (Bertheau and Blechinger, 2018). This limits socio-economic growth due to expensive electricity costs and unreliable supply. The diesel-powered grids also emit greenhouse gases which contribute to the increasing frequency and severity of tropical cyclones (Kreft et al., 2014) that hinder diesel fuel imports (Michalena and Hills, 2018).

Hybridizing the grids economically solves these problems by having low operating costs from using indigenous renewable resources instead of expensive diesel fuels (Kuang et al., 2016). Hybrid energy systems are often modelled to achieve the lowest levelized costs of electricity (LCOE) by avoiding undersized or oversized components (He et al., 2017). Using solar and wind resources potentially reduces the LCOE by 20 % and attains a renewable energy (RE) fraction of 49.9 % in 1,785 islands globally (Blechinger et al. 2016).

Wind power is especially attractive since it is cheap (Lazard, 2017) and developments in small turbines, such as current control systems (Kumar Sharma et al., 2018) and turbine blades (Tenghiri et al., 2018), encourage their use in small grids. Adding wind power to solar-battery hybrid systems reduced the electricity costs in a remote island (Ma et al., 2014); and in the Philippines, wind power is viable in some areas through resource assessment (Meschede et al., 2018) and optimal for a simulated hybrid energy system (Rey et al., 2017), however the feasibility of wind energy in off-grid areas is not yet determined in a national scale.

This work expands the previous works by incorporating wind power into solar-based hybrid energy systems which were simulated to determine their contribution in achieving the United Nations Sustainable Development

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Goal 7 (Bertheau and Blechinger, 2018) and policies needed to attain the promised benefits (Ocon and Bertheau, 2019).

2. Methodology

A total of 143 existing Philippine off-grid areas mostly under the National Power Corporation-Small Power Utilities Group (NPC-SPUG) were simulated to incorporate solar and wind power through the Hybrid Optimization of Multiple Electric Renewables (HOMER® Pro) microgrid software (HOMER Energy, 2018). The solar global horizontal irradiance (GHI) and wind power density (WPD) datasets were obtained from the Philippine Light Detection and Ranging 2 (Phil-LiDAR 2) Program and processed using QGIS® to generate monthly resource data. HOMER Pro® generated the synthetic hourly resource availabilities from the monthly data and incorporated variabilities for each day. The electric load was based on the NPC-SPUG's 2017 monthly data with the hourly load behaviour based on the work of Ocon and Bertheau (2019). The techno-economic parameters (Table 1) for the project, solar PV panel, and lithium-ion battery system components were derived from Ocon and Bertheau (2019), and those of the wind turbine were derived from Baek et al. (2016). Only the existing diesel generators were used such that no capital expenditure was needed. The project component indicates the systemwide parameters for each grid. The project lifetime was only used for calculating the LCOE and not for the actual operating lifetime of the grids. Each component has their own lifetime in which the replacement costs incurred before the end of the project lifetime were included in the LCOE calculation.

Table 1: Techno-economic parameters used in the hybrid energy system model

Component	Parameter	Value	Unit
Diesel Generator	Capital expenditure	0	USD/kW
	Operation and maintenance cost	0.03	USD/kWh
	Fuel price	0.90	USD/L
	Lifetime	15,000	h
	Replacement cost	600	USD/kW
Solar PV Panel	Capital expenditure	1,200	USD/kW
	Operation and maintenance cost	25	USD/kW/y
	Derating factor	80	%
	Lifetime	25	y
	Replacement cost	1,200	USD/kW
Wind Turbine	Unit size	10	kW/unit
	Capital expenditure	15,000	USD/unit
	Operation and maintenance cost	92	USD/unit/y
	Height	30	m
	Lifetime	20	y
	Replacement cost	15,000	USD/unit
Li-ion Battery	Capital expenditure	780	USD/kWh
	Operation and maintenance cost	21.75	USD/kWh/y
	Minimum state of charge	20	%
	Rate constant	1	kW/kWh
	Lifetime	15	y
	Replacement cost	780	USD/kWh
Project	Fixed development cost	20,000	USD
	Lifetime	20	y
	Discount rate	9.94	%
	Inflation rate	3.8	%

The LCOE of the hybrid energy system for each grid was minimized and compared to the diesel only system. Not all components were required for the cost-optimal systems. The grids were simulated to have an uninterrupted operation including the diesel systems even though most of the existing grids are operated for certain hours of the day only (NPC-SPUG, 2017) since an uninterrupted operation increases the optimal RE fraction (Bertheau and Blechinger, 2018).

The hybrid energy system model used a load following dispatch strategy where the batteries are primarily charged by the excess RE generation (Barley and Winn, 1996). The operating reserve requirements of 10 % of the current demand, 80 % of the solar power output, and 50 % of the wind power output (HOMER Energy, 2018) were used to assure grid stability (Bertheau and Blechinger, 2018) since the RE availabilities are intermittent.

3. Results and Discussion

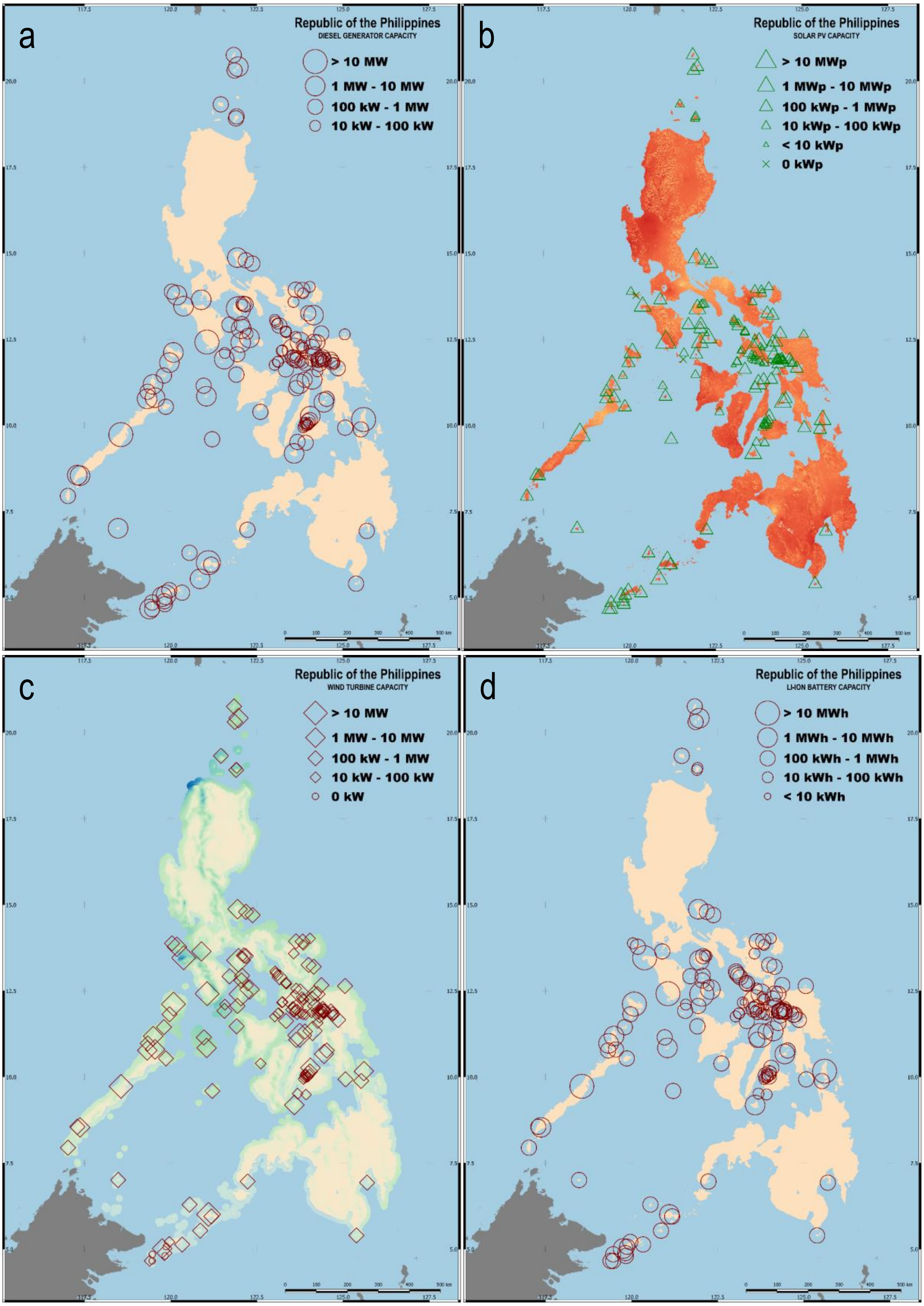

Figure 1: Optimal diesel generator (a), solar PV (b), wind turbine (c), and Li-ion battery (d) capacities in each island grid

The hybrid energy system configuration that yields the lowest LCOE possible were elucidated for the 143 off-grid islands and grouped by island group. The relationship between the optimal configuration and resource potential of each area was also elucidated. The hybrid energy systems favour both resources since they prioritize the cheapest source of electricity at every instant based on the renewable resource availabilities so that solar and wind power is optimal in 137 grids (Figure 1). The optimal component sizes in each grid follow the peak demand since RE sources have lower operating costs than diesel generators. The generators are still needed, retaining 330.30 MW (Table 2) out of the 346.76 MW installed capacity. A total of USD 774,171,060.61 (~ PHP 40,643,980,682.03) in capital expenditures is needed to construct the hybrid energy systems.

The use of both resources reduced the LCOE to USD 0.204 per kWh (Table 2) from USD 0.347 per kWh for the diesel systems. For comparison, the existing grids have true cost of generation rates (TCGR) from USD 0.183 per kWh to USD 3.153 per kWh (~ PHP 9.6011/kWh to PHP 165.5121/kWh) (NPC, 2017). The 41.1 % LCOE reduction doubled the 19.8 % cost reduction for solar-based hybrid energy systems (Ocon and Bertheau, 2019) which is attributed to the less use of diesel fuels since the overall RE fraction of 61.38 % exceeded their 50.4 % RE fraction. The reduced LCOE also shows that continuously operating the hybrid energy systems is economically feasible which will improve the quality of life for the residents (Bertheau and Blechinger, 2018) especially in areas where the electricity is only available for 6 h per day (NPC, 2017).

The LCOE reduction corresponds to a total of USD 132,403,162.87 (~ PHP 6,951,166,050.86) in annual savings which significantly reduce the difference of the TCGR and the subsidized rates the consumers pay (NPC-SPUG, 2019). Without hybridization, the subsidies are projected to reach USD 368,703,429 (~ PHP 19,356,930,000) by 2020 (DOE, 2016) which are sourced from the Philippine taxpayers.

Table 2: Projected overall attributes of the hybrid energy systems in the Philippines and each island group

	Luzon	Visayas	Mindanao	Philippines
Electricity Demand (GWh/y)	709.83	97.12	119.94	926.89
Average Demand (MW)	81.03	11.09	13.69	105.81
Diesel Generator Capacity (MW)	247.40	39.47	43.83	330.30
Solar PV Capacity (MWp)	100.36	17.84	32.59	150.79
Wind Turbine Capacity (MW)	220.81	34.88	26.54	282.23
Li-ion Battery Capacity (MWh)	143.40	41.65	29.07	214.12
Capital Expenditures (10^6 USD)	565.00	107.20	101.97	774.17
Weighted Average LCOE (USD/kWh)	0.193	0.234	0.251	0.204
LCOE reduction (%)	43.26	38.67	31.53	41.13
Savings (10^6 USD/y)	104.22	14.32	13.86	132.40
CO_2 emissions (10^3 t/y)	180.10	23.21	43.32	246.63
CO_2 emissions avoided (10^3 t/y)	315.53	46.72	43.64	405.89
Weighted Average RE Fraction (%)	63.04	66.37	47.49	61.38

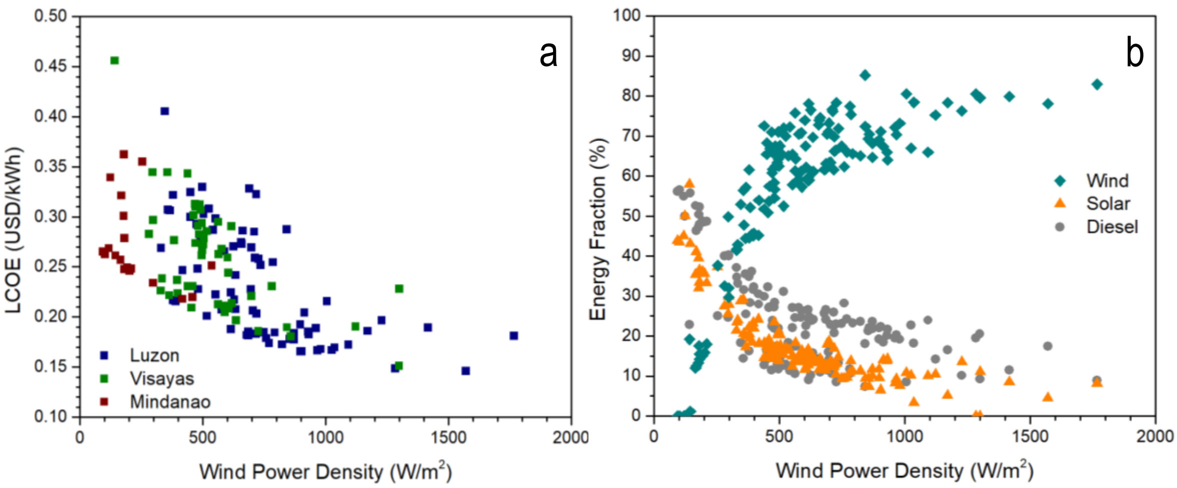

Figure 2: Effect of WPD on the LCOE (a) and electricity generation mix (b).

The LCOEs of the hybrid energy systems are sensitive to WPD (Figure 2a) since wind power is the cheapest energy source among those considered; having no fuel costs and generation not limited to the daytime hours.

As a result, the solar GHI has no similar effect on the LCOE such that they are highly variable even in areas with similar GHIs. Areas with WPDs > 300 W/m^2 prefer wind power (Figure 2b), allowing an overall wind energy generation fraction of 58.47 % (Figure 3). The two (2) hybrid energy systems where solar power was not optimal were in islands with WPDs > 1,200 W/m^2 and have the lowest LCOEs. The LCOEs are more expensive in areas with lower WPDs since the grids require larger solar panels and batteries to compensate the lower wind power generation. The four (4) hybrid areas where wind power was unviable have WPDs < 125 W/m^2 and have high LCOEs (Figure 2).

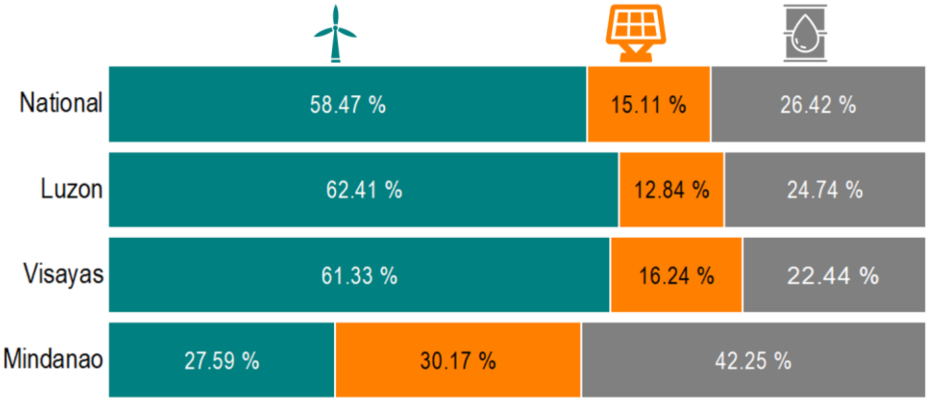

Figure 3: Overall electricity generation mix in the Philippines and each island group

Diesel power is preferred over solar power since the diesel generators have a flexible generation schedule and have no capital expenditures. The diesel and solar energy shares increase as the WPD decreases and that wind power is least preferred in areas with WPDs < 200 W/m^2 (Figure 2b). With Mindanao having low wind resource availabilities, the RE fraction is only at 47.49 % (Table 2).
The batteries also contribute to the RE fraction and LCOE reduction by storing the RE produced during the day. The batteries then supply the peak evening loads and displace diesel fuel usage even if the RE generation is insufficient. The high RE fraction reduces the CO_2 emissions from 652,520 t/y to 246,629 t/y (Table 2) during operation. The hybrid energy systems incorporating solar and wind power with storage should be considered to minimize electricity costs and attain deep decarbonization. Incorporating additional renewable resources is expected to further improve the attributes of the hybrid energy systems. The optimization can be more accurate by accounting for the detailed conditions of each area and determining the actual load and resource data to reduce the uncertainties.

4. Conclusions

This work shows that solar and wind power is feasible in the Philippine off-grid areas and decarbonizes the energy mix by 61.38 %. With an LCOE reduction of 41.1 %, the potential hybrid energy systems provide continuous access to electricity in the off-grid areas and reduce the subsidies needed to operate the grids. Hybridizing the off-grid energy systems contributes to sustainable development by increasing the socio-economic productivity, and reducing import dependence, subsidies, and gaseous emissions. Rapidly implementing the systems maximizes the sustainable development from the local to the global scales. Future works should explore additional renewable resources and incorporate sensitivity analyses especially in component costing.

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References

Baek S., Kim H., Chang H.J., 2016, Optimal hybrid renewable airport power system: Empirical study on Incheon International Airport, South Korea, Sustainability (Switzerland), 8, 562.

Barley C.D., Winn C.B., 1996, Optimal dispatch strategy in remote hybrid power systems, Solar Energy, 58, 165-179.

Bertheau P., Blechinger P., 2018, Resilient solar energy island supply to support SDG7 on the Philippines: Techno-economic optimized electrification strategy for small islands, Utilities Policy, 54, 55-77.

Blechinger P., Cader C., Bertheau P., Huyskens H., Seguin R., Breyer C., 2016, Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands, Energy Policy, 98, 674–687.

DOE (PH), 2016, 2016-2020 Missionary Electrification Development Plan, Department of Energy (Philippines) <doe.gov.ph/sites/default/files/pdf/electric_power/medp_2016-2020.pdf> accessed 03.09.2018.

He G., Cheng L., Xu. J, Chen L., Wen-Quan T, 2017, Optimal Configuration of a Wind/PV/Battery Hybrid Energy System Using HOMER Software, Chemical Engineering Transactions, 61, 1507-1512.

HOMER Energy, 2018, HOMER Pro 3.12, HOMER Energy LLC <homerenergy.com/products/pro/docs/3.12/index.html> accessed 16.10.2018.

Kreft S., Eckstein D., Junghans L., Kerestan C., Hagen U., 2014, Global Climate Risk Index 2015, Germanwatch <germanwatch.org/sites/germanwatch.org/files/publication/10333.pdf> accessed 13.11.2018.

Kuang Y., Zhang Y., Zhou B., Li C., Cao Y., Li L., Zheng L., 2016, A review of renewable energy utilization in islands, Renewable and Sustainable Energy Reviews, 59, 504-513.

Kumar Sharma H., Samaria A., Gondwana L., 2018, Power optimization technique for small wind turbine system using an incremental current control, 2018 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC), 381–387.

Lazard, 2017, Lazard's Levelized Cost of Energy Analysis—Version 11.0, Lazard <lazard.com/media/450337/lazard-levelized-cost-of-energy-version-110.pdf> accessed 13.11.2018.

Ma T., Yang H., Lu L., 2014, A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island, Applied Energy, 121, 149-158

Meschede H., Esparcia E.A., Holzapfel, P., Bertheau, P., 2018, On the transferability of smart energy systems on off-grid islands using cluster analysis – a case study for the Philippine archipelago, 13th Conference on Sustainable Development of Energy, Water and Environment Systems, Palermo, Italy <researchgate.net/publication/328163051_ON_THE_TRANSFERABILITY_OF_SMART_ENERGY_SYSTEMS_ON_OFF-GRID_ISLANDS_USING_CLUSTER_ANALYSIS-A_CASE_STUDY_FOR_THE_PHILIPPINE_ARCHIPELAGO> accessed 01.11.2018.

Michalena E., Hills J.M., 2018, Paths of renewable energy development in small island developing states of the South Pacific, Renewable and Sustainable Energy Reviews, 82, 343-352.

NPC, 2017, True Cost Generation Rate, National Power Corporation, <napocor.gov.ph/images/Downloads/TCGR/CY2017_TCGR.pdf> accessed 03.05.2019

NPC-SPUG, 2017, SPUG Grid Statistics, National Power Corporation-Small Power Utilities Group, <spug.ph/index.php/2015-05-27-06-23-45> accessed 25.10.2018.

NPC-SPUG, 2019, Existing Effective Rates January 2019, National Power Corporation-Small Power Utilities Group, <spug.ph/rates/201901_SPUGRates.pdf> accessed 01.02.2019.

Ocon J.D., Berheau P., 2019, Energy transition from diesel-based to solar photovoltaics-battery-diesel hybrid system-based island grids in the Philippines – Techno-economic potential and policy implication on missionary electrification, Journal of Sustainable Development of Energy, Water and Environment Systems, 7, 139-154.

Rey A.L., Santiago R.V.M., Pacis M.C., 2017, Modeling of a hybrid renewable power system for Calayan Island, Cagayan using the HOMER software, NICEM 2017 - 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management, 1-6.

Tenghiri L., Khalil Y., Abdi F., Bentamy A., 2018, Optimum design of a small wind turbine blade for maximum power production, IOP Conference Series: Earth and Environmental Science, 161, 1.