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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

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ABSTRACT

The cost of unsubsidized electricity in off-grid areas, particularly in the islands dependent on fossil fuels, is expensive. Previous studies and recent installations have proven that renewable energy-based hybrid systems could be suitable alternative to diesel power plants in island grids. In this comprehensive analysis of small island grids in the Philippines, results show that there is a huge economic potential to shift the diesel generation to solar photovoltaics-battery-diesel hybrid systems, with an average cost reduction of around 20% of the levelized cost of electricity. By encouraging private sector participation, hybridization could help provide electrification for twenty-four hours, stabilize the true cost of generation rate with less dependence on imported diesel prices, and reduce greenhouse gas emissions. Further, the declining cost of solar modules and batteries will significantly improve the economics of energy transition in the island grids.

KEYWORDS

Island energy supply, Techno-economic potential, Solar photovoltaic, Levelized cost of electricity, Philippines, Renewable energy.

INTRODUCTION

Small island energy systems have an enormous potential to transition from using Diesel Power Plants (DPPs) to hybrid energy systems. Diesel-powered island grids are generally operated at low efficiencies and suffer from fluctuating fuel prices, which result in high power generation costs and eventually blackouts due to shortages. Additionally, energy generation in fossil fuel-based island grids leads to environmental pollution through the emission of greenhouse gases and frequent oil spills [1, 2]. These external costs (i.e. adverse health and environmental impacts) increase the costs of fossil fuels and

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are not incorporated [2]. Renewable Energy (RE)-based distributed energy generation on small islands is an attractive option because of its cleaner energy production, the abundance of solar resources in areas where these islands are located, and the technical and economic difficulty encountered when connecting these islands to the main grid [3, 4].

The described energy transition is especially important in an archipelagic country like the Philippines with more than 7,600 islands. A long-standing challenge is how to supply small remote islands with power to improve local living conditions. Supply of electricity in such remote areas is primarily done based on diesel power plants, with the unsubsidized off-grid electricity cost up to six times higher than the on-grid electricity cost. Additionally, the quality of supply is low and in fact more than eighty percent of areas served by the public supplier for small power generation are provided with power for less than 8 hours a day [5]. While the Philippine economy is growing well in the past decade, this unsustainable scheme is still a large burden for a country like the Philippines, where poverty is still prevalent and majority of the population in these islands have limited income. Due to the insufficient power supply in remote areas, however, the rapid economic growth is limited to few highly urbanized regions while the remaining parts of the country lag far behind in terms of living standards, human development and economic opportunities. Additionally, the country faces major challenges such as climate change, globalization, inequality and rapid urbanization [6, 7], which could be mitigated by developing sustainable energy supply schemes in remote areas.

At the same time, a high potential for RE exists in the Philippines, which would allow large-scale transformation from fossil fuel systems to renewable systems [8, 9]. Doing so would specifically contribute to the Sustainable Development Goal 7: "Ensure access to affordable, reliable, sustainable and modern energy for all" [10] as electrification rates in remote areas remain low. Outside the Philippines, hybrid energy systems have already been tested in several environments and have allowed for stable power supply – e.g. the Pacific island nation of Tokelau implemented a hybrid energy system allowing for 100% renewable energy supply [11]. Additionally, the costs of components like solar Photovoltaic (PV), inverters, batteries and energy management systems are decreasing at a rapid pace [12, 13]. The combination of abundant renewable energy resources, available renewable energy technologies, and an expensive conventional power supply system suggests that a rapid change in the island energy supply systems is forthcoming [8]. With regard to the Philippines, the high potential for supplying remote areas with renewable energies was highlighted already two decades ago by Heruela [14], as well as by Morris [15] and Barley *et al.* [16], with the latter two specifically investigating the potential for renewable energy injection in diesel-based energy systems. Several studies highlighted the feasibility of hybrid energy systems in particular locations (San Vicente, Palawan) [17] and islands (Pangan-an) [18].

Nevertheless, the implementation of renewable energy technologies on the Philippine islands is happening rather slowly [19]. Generally, a lot of research work has been performed to resolve such slow implementations and four main categories of barriers are typically identified: technological, economic, political, and social barriers [20, 21]. Here, the technological and economic barriers are studied by simulating power generation costs of hybrid systems based on solar PV and battery energy storage under the constraint of 24/7 hours power supply. The special focus is set on the Universal Charge for Missionary Electrification (UCME) in the Philippines. To cover the difference between the True Cost of Generation Rate (TCGR) and the Subsidized Approved Generation Rate (SAGR), all grid-connected electricity consumers in the Philippines are levied the UCME. However, the financial requirement for UCME is expected to increase further with additional generation and extended coverage resulting to a possible increase in the missionary charge collected from all electricity consumers [5]. As the overseer and main implementer of the missionary electrification development program, it is in the interest of the National Power Corporation-Small Power Utilities Group (NPC-SPUG) to pursue investments in renewable energy in NPC-SPUG areas having technically sound hybridization scheme to replace the diesel power plants and commercial viable and replicable business models. According to NPC-SPUG projections, the difference between TCGR and SAGR is expected to dramatically rise in the years to come [5].

In this work, an overview of the economic and technical requirements of transitioning these islands grids to renewable-energy based grids are demonstrated. While solar PV is often regarded as too expensive and not competitive enough with conventional fuels – especially in a developing country like the Philippines, this study shows that on the average the Levelized Cost of Electricity (LCOE) could decrease by 20% when using solar PV-battery-diesel hybrid systems. This particular work is, however, limited only to majority of the current NPC-SPUG locations and does not cover the off-grid areas covered by private DPPs.

MATERIAL & METHODS

A modified methodology following our recent publication estimating the global potential of renewable energies on small islands and island states was used [8]. This is based on an energy system simulation tool considering solar irradiation data and additional input parameters [e.g. capital and operating requirements and technical data for solar PV plants, DPPs, and Lithium-ion (Li-ion) battery energy storage systems] for the LCOE minimization. With the availability of rated capacities of the DPPs from NPC-SPUG, only the solar potential data is sourced from the DPP-location based on Geographic Information System (GIS) studies.

Small island inventory

For this study, isolated grids operated by the National Operator NPC-SPUG, where data are available, were considered. Due to the archipelagic structure of the Philippines, it is costly and in many cases even not technically feasible to connect all demand clusters to the national grid. These isolated grids are mainly relying on diesel power generation, which implies high generation and operational costs due to varying fuel costs and high transport costs. As a paradigm shift, it is attractive to implement renewable energies in these island grids first and to gain experiences and learnings, which could be transferred to the larger Philippine grids later.

A government agency, NPC-SPUG is the largest operator of off-grid systems in the Philippines. In particular 215 NPC-SPUG off-grid systems, located in Luzon (139), Visayas (55), and Mindanao (21), are studied for their potential of implementing renewable energies. These off-grid systems vary in sizes. The peak demand of the three largest grids exceeds 10 MW_p, followed by 20 grids in a range between 1-10 MW_p, and the remaining grids have peak capacities of several 100 kW_p down to 4 kW_p.

Energy systems model

A Python-based energy systems simulation tool was utilized to optimize the least cost hybrid combination of PV, battery, and diesel capacity for each of the 215 micro-grid/mini-grids operated by NPC-SPUG. The tool has been successfully used in several studies and is validated using Homer Energy [8, 22]. It simulates the energy flow in hourly time steps for one reference year, looking at the energy generated from solar PV and DPP, energy stored to/discharged from the battery, and energy demand of the grid, as derived from the solar insolation data and techno-economic input parameters (see Figure 1).

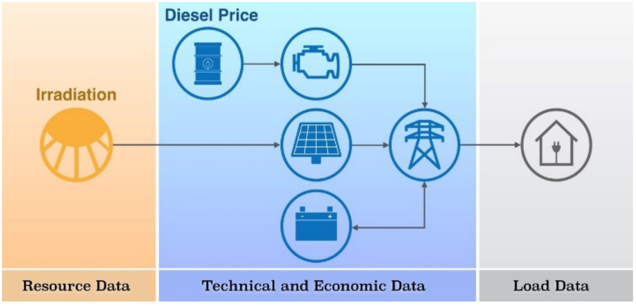

Figure 1. Scheme of the island energy supply model indicating the energy flows within the system

The energy flows were calculated using the dispatch strategy displayed in Figure 2, with the grid load requirement to be supplied from solar power, battery charge, and/or diesel power. At each hour for the entire reference year, the energy systems model applies the dispatch strategy of maximizing the amount of energy coming from the solar power plant. First, the model checks if the load in the island can be supplied entirely by solar power. If it is, it then verifies if the stability requirement (rotating mass), which is set at 40% of the island's energy demand, is followed. With the system always operating at least 40% of the power coming from the battery or diesel generator, the stability is ensured. If charged, the battery should be discharged first before turning on the diesel generator.

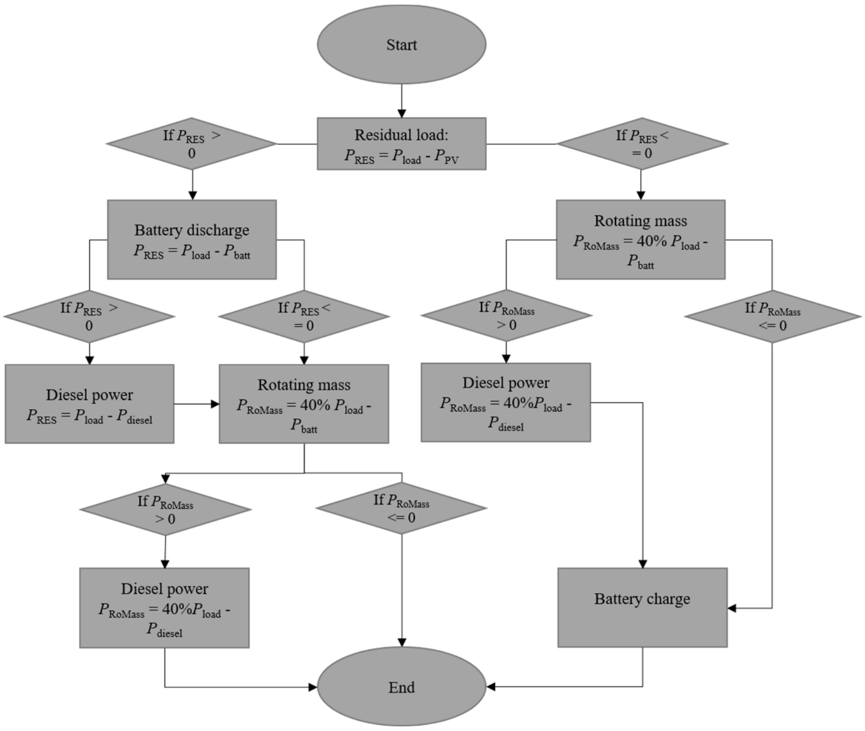

Figure 2. Dispatch strategy of the energy systems model used in the study

On the other hand, if the solar power generated is insufficient to supply the load, the system discharges the battery. Once the battery is fully discharged to its allowable State-of-Charge (SOC), which is 20% in the case of Li-ion battery, the diesel generator is operated. In any case, the stability criterion must be fulfilled by the battery or the diesel generator.

Looking at the available data from NPC-SPUG, the DPPs rated capacities were assumed to be twice that of the peak loads for the island grids. It was assumed that no additional installations of DPPs or replacement of old capacities are to be done during the project lifetime of 20 years. The variable parameters in the study are the size of solar PV and Battery Energy Storage System (BESS). By changing the solar PV and BESS share of the hybrid system, the simulation tool minimizes the LCOE under the constraints imposed by the equations discussed in Short and Packey [23]. The simulations are automated to run independently and simultaneously for each small island grid location.

Geospatial information and techno-economic input data

The location of the individual DPPs were gathered from the NPC-SPUG website†. For a single DPP supplying electricity to a mini-grid, the actual GIS location was taken. Otherwise, the centroid of the multiple DPPs connected to a single micro-grid was taken as the location.

A normalized load profile was used for the simulations. This load profile is based on an average daily load profile, which was derived from the actual data of 22 island grids [24]. The applied daily load profile is characterized by a peak demand in the evening hours and slightly higher demand during the afternoon hours (see Figure 3). The minimal load never falls below 50% of the peak load. These characteristics (low demand during the day, peak demand in the evening) are typical for rural consumers in the Philippines. The monthly variations in energy demands according to [24] were incorporated. Annual variations are quite low with peak values in June reflecting additional demands for cooling appliances, as shown in Figure 3. A generalization of load profiles was necessary for this study as not for each of the NPC-SPUG areas real load profiles were available. The daily load profile was normalized according to the peak demand during the day while the annual load profile was normalized according to the average load during the entire year. It is certain that a number of the considered grids are not operated 24/7 hours. Nevertheless, for this study, it is assumed that all future hybrid systems provide uninterrupted electricity supply to reflect the development goals of the government of the Philippines. For scaling the normalized load profile to each of the considered island grids, peak demand was defined as 50% of the installed power generation capacity in place.

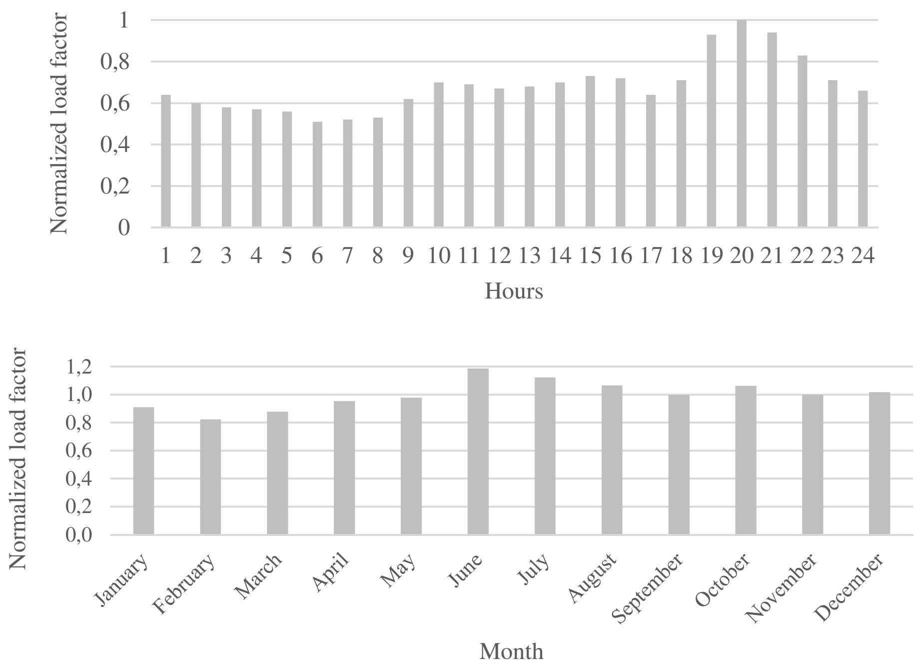

Figure 3. Normalized daily load profile applied for the simulation (top figure) and normalized annual load profile applied for the simulation (bottom figure)

† www.npc-spug.ph

Data on the Global Horizontal Irradiation (GHI) were gathered from global databases in order to quantify the solar PV potential for all island grids considered (see Figure 4). The NASA database covering the period 1984-2005 was used [25]. To get the GHI time-series at a spatial resolution of 0.5° by 0.5°, the method developed by the German Aerospace Center (DLR), where they applied a clear sky index approach and accounted for hourly changes in the irradiance data, as adopted. In the modelling, the resource pixel of the DPP location or the centroid for multiple DPPs in a single grid was chosen. To translate the irradiation data to actual electricity production, a model using crystalline silicon PV modules was utilized [26]. The effect of daily average temperature and irradiation on the module efficiency was considered following previous works [27, 28]. Using our previous approach, a degradation rate of 0.3% per year and a power reduction factor of 3% to account for the adverse effect of clouding and pollution were applied. When the various models are combined, the system generates the island-based PV yield in hourly time steps.

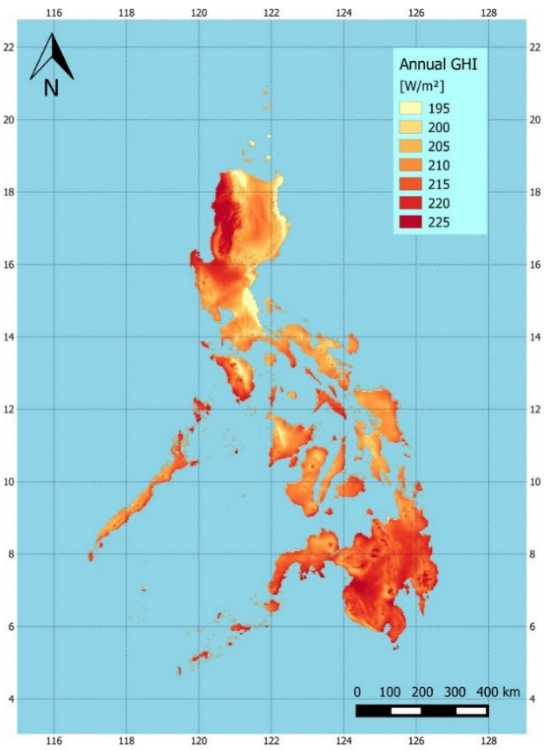

Figure 4. Map of the Philippines showing solar PV resource in terms of the GHI

To complete the simulation parameters, the technical and economic data of the Philippine small island grids were loaded into our energy systems model, as shown in Table 1. From previous experiences, diesel fuel cost influences the most the power generation cost of the hybrid system. For the diesel cost, an average value of USD 0.90 per liter across all island grids considered was used, which was taken from the average landing cost of diesel in NPC-SPUG islands [24]. A diesel price inflation of 3.8% per year was used. While the national average price is lower, the landing cost of diesel typically rises due to the transport cost in bringing the diesel by boat to these islands. As discussed later in the sensitivity analysis section, this study also looked into the effect of the diesel prices on the LCOE in each island grid.

Since the DPPs exist already in the NPC-SPUG small islands and are verified to be in operation, it was assumed that there would be no initial cost for the diesel technology. The operational costs, however, which are based on expenditures such as maintenance and lubricant oils, account to around 0.05 USD/kWh [29]. The lifetime of the DPPs was set to be at 20 years. To calculate the efficiency of the DPP as the actual loading changes, the efficiency values described by [30] was used, which were between 30% and 40%. To maintain the stability of the off-grid system, a rotating mass of 40% was set to ensure enough diesel or battery capacities to maintain frequency and voltage control [31].

Table 1. Summary of technical and economic input parameters used in the techno-economic simulations

Technology	Parameter	Value	Unit
Diesel plant	Initial costs	0	[USD/kW]
	Operational and maintenance expenditures (var)	0.05	[USD/kW/yr]
	Lifetime	10	[yr]
	Efficiency at min loading	30	[%]
	Efficiency at max loading	35	[%]
	Rotating mass	40	[%]
PV	Initial costs	1,200	[USD/kW]
	Operational and maintenance expenditures	25	[USD/kW/yr]
	Lifetime	25	[yr]
Battery	Initial costs (capacity)	260	[USD/kWh]
	Initial costs (power)	540	[USD/kW]
	Operational and maintenance expenditures	7.25	[USD/kWh/yr]
	Lifetime	15	[yr]
	Maximum C-rate	0.5	[kW/kWh]
	Maximum depth of discharge	80	[%]
	Charging efficiency	90	[%]
	Discharging efficiency	90	[%]
	Round trip efficiency	81	[%]
	Maximum no. of cycles	5,000	cycles
	Initial state of charge	0	[%]
Other	Project development cost (fixed)	20,000	[USD]
	Project lifetime	20	[yr]
	Weighted average cost of capital	9.94	[%]
	Diesel inflation rate	3.8	[%]

The solar PV power plant is economically defined by the initial cost or Capital Expenditure (CAPEX), Operational and Maintenance Expenditures (OPEX), and lifetime. Typically, turn-key PV plants in the Philippines costs around 1,200 USD/kW$_p$ and the OPEX is at 25 USD/kWh/yr for a lifetime of 25 years. On the other hand, the Li-ion battery-based BESS was assumed to have an initial cost of 260 USD/kWh for capacity and 540 USD/kW for power, combining the costs at a fixed C-rate of 0.5 to 800 USD for both as a modular unit. OPEX is set at 7.25 USD/kWh per year and a lifetime of 15 years. For the cycle efficiency, a conservative estimate of 90% charging and discharging efficiency, leading to a roundtrip efficiency of 81%, was used.

To initiate the hybridization process, a fixed development cost of 20,000 USD per small island grid was assumed for a project lifetime of 20 years. The Weighted Average Cost of Capital (WACC) was taken to be 9.94% for a typical energy and utility project in the Philippines. Table 1 shows the summary of the technical and economic input parameters loaded into the energy systems model.

For studying the effect of battery costs on the LCOE of hybrid energy systems, the techno-economic sensitivity modelling and optimization was performed across all the surveyed island grids on four scenarios with different battery costs. To generate the four scenarios, the battery investment costs was decreased (−50%, −25%) and was increased (+25%, +50%) relative to the original battery costs in the calculations discussed above. All other parameters were fixed as in the main scenario (see Table 1). The applied values for the sensitivity analysis are listed in Table 2.

Table 2. Applied costs values for battery cost sensitivity analysis

Parameter	Unit	−50%	−25%	Base scenario	+25%	+50%
Initial costs (capacity)	[USD/kWh]	130	195	260	325	390
Initial costs (power)	[USD/kW]	270	405	540	675	810

RESULTS AND DISCUSSION

When pertaining to off-grid systems in the Philippines, there are mainly two types:

- Off-grid areas not connected to the three main electricity transmission grids (Luzon, Visayas, and Mindanao) and are serviced by the NPC-SPUG;
- Off-grid areas declared as unviable districts within the jurisdiction of the distribution utilities or electric cooperatives.

The distribution utilities or electric cooperatives are usually getting their power from among the three main grids. Majority of these off-grid areas are islands and are powered by diesel generator sets.

After the deregulation and privatization of the Philippine energy sector in the 1990s, only the major power plants were sold leaving the small islands still dependent on the services of the government-owned and operated NPC. However, only around 10% of the 215 NPC-SPUG areas have access to 24/7 electricity [5]. As it stands, there are still over four million households in the Philippines who are without access to electricity [32].

Figure 5 shows the location of the 215 NPC-SPUG off-grid systems. While majority are located in small islands, some are still in the main islands of Luzon, Visayas, and Mindanao. Among the 215 island grids operated by NPC-SPUG surveyed in this work, the majority is located in Luzon (139) while the rest are located in Visayas (55) and Mindanao (21). The peak capacities, however, of these DPPs vary from several kW (i.e. mainly found in many locations in Masbate) to as large as several MW each (e.g. Marinduque, Mindoro Occidental, Tawi-tawi, etc.). It is evident from the large red circles that there are several large grids operated by NPC-SPUG. While already operating for decades, these island grids suffer from frequent system breakdown and instability depending on the arrival of diesel fuels [32].

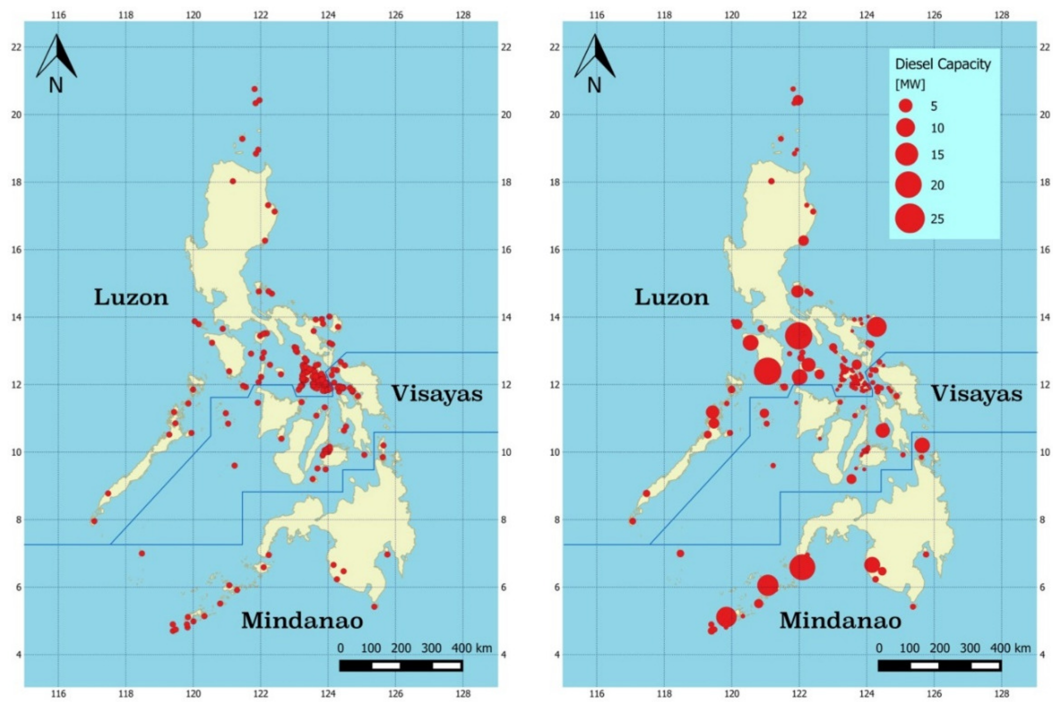

Figure 5. Location of the 215 NPC-SPUG diesel power plants (left) and the corresponding rated peak capacity (right), the blue lines delineate the boundaries of the three main island regions, where the three main electricity grids are located

Presently, multiple diesel power plants, either stationary or barge-type power plants, operate large mini-grids in the NPC-SPUG areas. It should be noted that the techno-economic optimization performed in the island grids and not on individual DPPs.

As an example, the Marinduque grid is composed of six DPPs. Hence, the total peak capacity of the diesel resource is taken as the sum of the individual capacities.

The results in this section are derived from the individual island energy supply system based from the technical and economic data, the solar PV yield, and the load data of each island grid. In each case, the data are loaded into the energy systems model and the tool optimizes the hybrid configuration to minimize the LCOE over a period of 20 years. To be specific, it calculates the RE share, which in this case corresponds to solar power only, in the installed capacities with the minimized cost of generation. The cost of diesel power generation and RE-based hybrid power generation in Luzon, Visayas, and Mindanao is illustrated in Table 3. These costs reflect the average cost for the next 20 years, using an assumption of 3.8% annual increase of diesel. On the average, the energy generation cost is around 0.4 USD/kWh at a diesel price of 0.9 USD/L. The calculated energy generation cost for the diesel only case is close to the global average of our previous work [8]. It should be noted that a uniform diesel price was set across all diesel grids, in order to be able to study the effect of the various configuration and location. A sensitivity test, which will be discussed in a later section, shows that even under affordable diesel prices, hybrid energy systems still offer advantages over diesel only generation.

Table 3. Results of the techno-economic analysis of the island grids in the Philippines grouped according to the three main islands – LCOE Reduction and Optimal Hybrid Configuration

Island group	$LCOE_{ave}$ (diesel only) [USD/kWh]	$LCOE_{ave}$ (hybrid system) [USD/kWh]	LCOE $reduction_{ave}$ [%]	PV $potential_{sum}$ [MW_p]	Battery $potential_{sum}$ [MWh]	RE share [%]
Luzon	0.44	0.36	18.4	132	197	50.5
Visayas	0.44	0.35	20.5	40	66	49.7
Mindanao	0.44	0.34	23.5	88	141	52.0
National	0.44	0.35	19.8	260	404	50.4

As shown also in Table 3, the optimal average RE share for the island grids where hybridization is feasible is around 50.4% across all surveyed islands grids. The lowest obtained optimized LCOE is around 0.32 USD/kWh for the Siasi mini-grid in Mindanao, while the highest optimized LCOE is around 0.4 USD/kWh for the Pinanaan mini-grid in Luzon. Even at the latter's electricity cost, this still represents a reduction of 8.4% of the electricity cost. It should be emphasized that there are 53 existing DPP-based grids with very low capacities where it is not feasible to hybridize due to the high project cost and investment cost. All of these NPC-SPUG areas are powered by small diesel generator sets with capacities between 7-15 kW_p. While hybridization in these areas will be difficult and costly due to its scale, these areas can be catered to by smaller solar hybrid systems or by solar home systems instead.

In general, hybridization of the NPC-SPUG island grids leads to an average LCOE reduction of 19.8%. Mindanao (23.5%) has a slightly higher LCOE reduction potential than Luzon (18.4%) and Visayas (20.5%), which is most likely due to its more favourable location near the equator and the corresponding larger solar resources. As shown in Table 3, the average optimal RE share is around 50.4% across all surveyed islands grids. This means that for RE, on the average, increasing the share of solar PV would increase the LCOE due to higher CAPEX for both oversized batteries and solar PV plants. While a lower RE share lowers the CAPEX, OPEX increases due to the amount of power generation from imported diesel fuel. The optimized RE share ranges from 40% (Itbayat DPP, Northern Luzon, 1,376 kWh/yr) to 61.2% (Sibutu DPP, Mindanao, 1,563 kWh/yr).

As shown in Figure 6, the bigger the island energy system, the higher the magnitude of the solar PV potential. In 53 small island grids, it is not economical to transition to a hybrid system due to higher capital costs driving the LCOE upwards. An alternative to hybridization would be the use of Solar Home System (SHS) or distributed diesel generator sets. Overall, transforming the current island energy systems into RE based hybrid systems would reflect a solar PV potential of around 260 MW_p. While this economic potential is small in contrast to the grid-connected planned PV power plants across the Philippines, capacity investment is targeted towards where electricity is really needed.

On the other hand, a Li-ion battery potential of roughly 400 MWh was computed. The installation of the BESS is a crucial piece in further decreasing the LCOE of hybrid systems. Without the Li-ion BESS, an oversized solar PV plant is needed to provide the electricity during daytime, while the DPP generates electricity for the rest of the day. This results to an increase in the diesel consumption, which increases the LCOE for a solar PV-diesel only system. The use of Li-ion BESS in recent years have increased dramatically owing to the decreasing cost of energy storage. Various estimates suggest that the cost of both solar PV and Li-ion BESS will continue to decrease in the coming years [12].

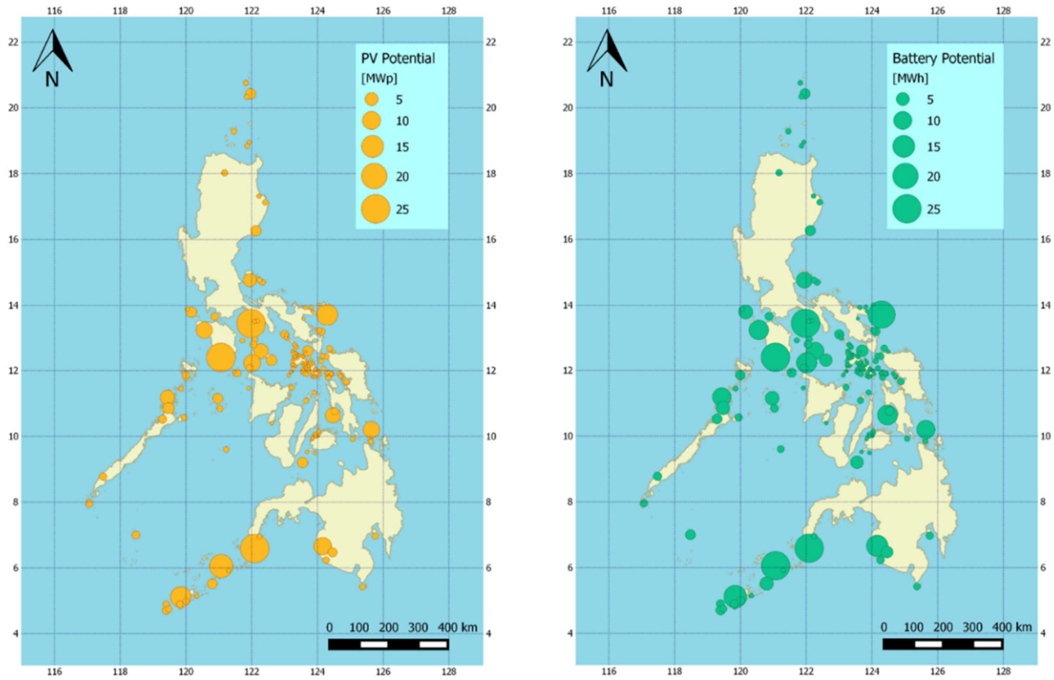

Figure 6. Map of the calculated techno-economic PV potential (left) and Li-ion battery potential (right) on NPC-SPUG island grids in the Philippines

Economic and environmental potential of hybridization

Hybridization of the islands avoids the importation of approximately 92 million liters of diesel per year. At a diesel price of 0.9 USD/L, this corresponds to a diesel importation cost of 82 million USD (4.3 billion PhP) annually. For the diesel only case, it was estimated that the annual total importation cost to operate the existing DPPs is around 166 million USD (8.6 billion PhP) annually. Recently, there was a proposal from the Philippine Department of Finance (DOF) to increase the excise tax on diesel by PhP 6 per liter [33]. Surely, this move would impact the future UCME resulting from the increase in the TCGR in these island grids.

Aside from the economic benefits of energy transition, hybridization enables the Greenhouse Gas (GHG) emission savings of around 246 thousand metric tons of CO_2 annually. Luzon (45.6 million L/yr) has the biggest diesel savings potential, followed by Mindanao (31.8 million L/yr) and Visayas (14.5 million L/yr). For the above things to happen, a capital infusion of around 529 million USD is needed (see Table 4).

Recent works argue that not all RE megawatts are created equal [34, 35]. They propose that RE power generation could be strategically used to promote social outcomes where it is really needed (i.e. off-grid rural areas). While the Philippines in recent years has a good track record in increasing the RE share with new solar, wind, and hydro power plants constructed and planned, smaller RE based project would never come into fruition if only megawatts were the only consideration. There is a bias for large, grid-connected facilities. The availability of electricity in the off-grid areas should provide an impetus for an increase and economic activity and production of high value good in the countryside.

Table 4. Results of the techno-economic analysis of the island grids in the Philippines grouped according to the three main islands – diesel savings, CO_2 emissions credits, and investment requirement

Island group	Diesel savings [L/yr]	CO_2 emissions avoided [ton_{CO_2}/yr]	Investment requirement [million USD]
Luzon	45,678,000	122,000	264
Visayas	14,504,000	39,000	84
Mindanao	31,888,000	85,000	181
National	92,070,000	246,000	529

Sensitivity analyses on diesel price

For studying the effect of diesel costs on the LCOE of hybrid systems, a techno economic sensitivity modelling and optimization for three scenarios of RE penetration across all the surveyed island grids was performed. A high RE penetration scenario corresponding to an average 60% RE share, a medium RE penetration scenario corresponding to an average 45% RE share, and a low RE penetration scenario corresponding to an average 30% RE share. As shown in Figure 7, at low diesel prices (below 0.4 USD/L, it is expected that the diesel generation only system has the lowest LCOE, followed by the low, medium, and high RE shares. On the other hand, at diesel prices in between 0.5 to 1.0 USD/L, the 30% RE share configuration is the most financially attractive. As diesel prices rise further, more RE penetration decreases the LCOE. For instance, if the diesel prices reach 2.0 USD/L, a 60% RE penetration configuration becomes the cheapest option. While the odds are low in the near future that diesel prices reach that price, a high RE share has the most price stabilizing effect among all options considered. While having a higher LCOE due to the increased capital expenditure on the solar power plant and the Li-ion BESS, the 60% RE scenario is the least dependent on the diesel price, not to mention the avoidance of importing millions of liters of diesel each year and the associated GHG emissions.

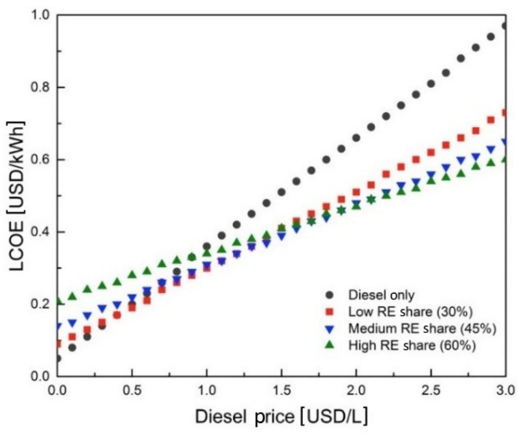

Figure 7. Sensitivity analyses for diesel fuel price at different hybrid system configurations according to the optimized RE shares

Sensitivity analyses on battery costs

The sensitivity analysis reveals the impact of battery costs on the overall LCOE reduction potential and the cost optimized hybrid system design (see Table 5). As expected, decreased battery costs (−50% and −25%) would result in lower LCOE and higher RE shares. Decreased battery costs of −50% lead only to a marginal increase in the RE share (+0.16%) compared to the −25% battery cost scenario. The applied stability criteria (40% rotating mass) and diesel price prevent a higher RE share and a higher battery potential. Further, decreasing battery and PV investment costs in combination with higher initial diesel costs or a higher annual diesel price growth could change this pattern.

A remarkable "tipping point" can be observed when comparing the base scenario to the +25% battery cost scenario. With increasing battery costs, the battery potential shrinks significantly (−70%) and the RE share decreases from 50.4% to 37.1%. In contrast to the battery potential, the PV potential is decreased by 21%. Thus, with the increased battery costs of +25%, it is less economically feasible to implement battery capacities in the hybrid system to increase the overall RE share, however, it is still economically feasible to implement PV capacities for substituting diesel power generation. This "tipping point" reflects the economic breakpoint for hybrid "fuel saver" systems (diesel and PV) to hybrid battery systems (diesel, PV and battery).

With regard to the LCOE of the hybrid systems the sensitivity analysis reveals that changing battery costs would only slightly affect the overall power generation costs. Lower battery costs (−50%) result in an additional average hybrid LCOE reduction potential of 0.03 USD/kWh whereas higher battery costs (+50%) increase the average hybrid LCOE by 0.01 USD/kWh.

Overall, the sensitivity analysis highlights that even when applying high battery costs (+50%) a significant LCOE reduction potential (17.6%) compared to the diesel only system exists. Nevertheless, with increasing battery costs the cost optimized RE share and battery potential decreases significantly. Recent papers argue that the cost of battery energy storage systems for microgrids will continue to decrease due to economy of scale and continuous deployment of grid-scale battery technologies and ramping up in R&D investments [13, 36].

Table 5. Results of sensitivity analysis of battery investment costs for base scenario and the four considered cost scenarios– LCOE reduction and optimal hybrid configuration

Scenario	$LCOE_{ave}$ (diesel only) [USD/kWh]	$LCOE_{ave}$ (hybrid system) [USD/kWh]	LCOE $reduction_{ave}$ [%]	PV $potential_{sum}$ [MW_p]	Battery $potential_{sum}$ [MWh]	RE share [%]
−50%	0.44	0.315	28.1	293	570	58.8
−25%	0.44	0.335	23.7	283	518	57.2
Base sc.	0.44	0.352	19.8	260	404	50.4
+25%	0.44	0.359	18.3	204	117	37.1
+50%	0.44	0.362	17.6	197	71	35.1

Implication on the universal charge for missionary electrification

Continuing on the reliance on diesel in the future will surely lead to a rise in missionary electrification subsidies. The steeper slope of the "diesel only" case emphasizes the heavy dependence of the LCOE to the diesel price in the worldwide market. For instance, according to the first official draft of the Missionary Electrification Development Plan (MEDP) of the DOE for the period 2017-2021 [5] the total UCME subsidy will increase from 138.5 million USD (7.2 billion PhP) in 2015 up to 273.1 million USD (14.2 billion PhP) in 2021. In 2016, the distribution utilities were collecting an average UCME of PhP 0.19/kWh to all electricity consumers in the country.

For the planning period 2017-2021 considered above, missionary electrification in the Philippies requires a total subsidy of 1.463 billion USD (76.06 billion PhP). Additionally, DOE expects the addition of around 111.7 MW of installed capacity in the NPC-SPUG areas, which could stretch further the UCME requirements. While there are on-going privatization program in the NPC-SPUG areas in recent years, the reduction of costs and improved operational efficiency are not yet sufficient to significantly reduce or even remove the UCME subsidies. There are already fifteen NPPs with a total rated capacity of around 206 MW powering nine off-grid areas with 24-hr electricity service. Most of the generation plants, however, are still based on conventional fossil fuels like coal, natural gas, and diesel. Yet, even with the power generation based on GHG-emitting plants, there is still a need to infuse the gap between the true cost and the subsidized generation rates by the missionary electrification subsidy.

Although the electricity consumers in the NPC-SPUG areas, who are mainly in the marginalized sectors, pay a subsidized rate, this dependence on fossil fuels makes electricity more expensive to everyone because UCME is eventually collected to all grid-connected consumers. Taking into account the identified LCOE reduction potential of 19.8% on average, our study underlines the feasibility of reducing the UCME charge through investing in renewable energies. As emphasized above, dependence on diesel has its associated externalities costs such as GHG emissions and environmental pollution. Aside from improving the efficiency of the diesel-fired power plants, increasing the penetration of renewable energy in missionary areas to rationalize the UCME subsidy should be a key step going forward.

CONCLUSIONS

In this work, the techno-economic potential of transitioning the 215 micro and mini-grids in islands spread across the Philippine archipelago was surveyed. This is the first study quantifying the aggregate economic and environmental benefits of transforming the DPPs into solar PV-battery-diesel hybrid systems. This transformation brings benefits to all parties concerned. First, the government can avoid the increase or even reduce the subsidy given for missionary electrification in these islands. In turn, this would prevent in the increase of UCME collection from all electricity consumers in the Philippines. Second, the private sector, who are expected to enter into Power Purchase Agreement (PPA) with the utility companies as New Power Producers (NPPs) or as Qualified Third Party (QTP) entrants, are provided with financial incentives with a less costly energy production from the hybrid system and the additional incentives for RE-based generation (i.e. tax rebates, RE incentives as percentage of the amount of RE supplied). Third, residents in these island grids will be provided with access to cleaner electricity for 24/7. This could hopefully translate into better economic opportunities and productivities, thereby, improving their overall welfare.

In order for this to happen, it is in the government’s hands to improve and fast track the application process for NPPs or QTPs in the NPC-SPUG islands. For instance, a priority can be made for applications for power generation plants based on renewable energy (i.e. micro hydroelectric, solar PV-battery-diesel hybrids, wind). In recent years, private companies have power supply agreements with the electric cooperatives in the NPC-SPUG areas, yet, most of them are still based on coal and other conventional fuel sources. In the updated MEDP, the government has identified possible strategies in the rationalization of the missionary electrification subsidy from universal charge to address challenges such as a focusing on rural and peasant communities, redesigning of the business model of NPC-SPUG in missionary areas, promoting private sector investment, and leading towards an integrated and inclusive economic development in small island grids. To this end, they have identified possible strategies such as the following [5]:

- Institutionalize a graduation policy where NPC-SPUG will submit to DOE its assessment and prospects of all existing areas towards meeting the commercial viability and recommendation for graduation from the UCME;
- Develop a tarriff differential mechanism among customers (e.g. large commercial and industrial consumers in resorts and shopping malls in big islands) and missionary areas to allocate the subsidy mainly to areas with low economic development;
- Review the determination of the SAGR to assess of the rates are still reflective of commercial and economic viability of the areas;
- Review the implementation of the cash generation-based incentive for renewable energy developers;
- Conduct a study to interconnect some SPUG islands to the main grids of Luzon, Visayas, and Mindanao. Hopefully, this work could provide guidance to the policy-makers and the private sector to move towards rapid transformation to a cleaner and efficient energy production and distribution in these islands.

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