CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš
Copyright © 2021, AIDIC Servizi S.r.l.
ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188071

Can Off-grid Islands Powered by Renewable Energy Microgrids be Operated Sustainably without Subsidies? A Techno-economic Case Study in the Philippines

Michael T. Castro[a], Joey D. Ocon[a,b,*]

[a] Laboratory of Electrochemical Engineering (LEE), Department of Chemical Engineering, University of the Philippines Diliman, Quezon City 1101, Philippines
[b] Energy Engineering Program, National Graduate School of Engineering, College of Engineering, University of the Philippines Diliman, Quezon City 1101, Philippines
jdocon@up.edu.ph

The Philippines is home to thousands of off-grid islands that are too distant from the mainland and consequently expensive to connect to the main grid. These islands are typically powered by diesel generators, which will require more subsidies as fuel costs continue to increase. Hybrid renewable energy systems (HRES) are an alternative energy source with lower reliance on fuel and generation costs. In this work, the financial sustainability of deploying HRES in Philippine off-grid islands of various sizes was evaluated. Patongong Island, Lapinigan Island, Balabac Island, and Sibuyan Island were selected as case studies as their peak electrical demand varies from 4.4 kW in Patongong Island to 3.2 MW in Sibuyan Island, representing a large fraction of off-grid islands in the country. HRES consisting of solar photovoltaics, wind turbines, lithium-ion batteries, and diesel generators in these islands were modeled in Island Systems $LCOE_{min}$ Algorithm (ISLA), an in-house energy systems modeling tool. Profitability metrics, such as the net present value, internal rate of return (IRR), and payback period (PBP), were then calculated at varying electricity prices. The large Sibuyan island was already profitable at 0.2 USD/kWh, comparable to the mainland rate, which suggests that subsidies in large islands can be removed. The low 11 % IRR and 13-year PBP may not be attractive to private investors, but this may be alleviated by raising electricity prices. Other islands, however, will still require subsidies as the small Patongong Island becomes profitable only at 1.5 times the mainland rate. This work encourages private sector participation by providing financial insights absent in many techno-economic studies. Moreover, this study enlightens the public sector about the necessity of subsidies for providing energy access in small off-grid islands.

1. Introduction

The Philippines is inhabited by about 5.5×10^6 people without access to electricity (World Bank, 2020). This is attributed to the country's archipelagic geography, which results in thousands of off-grid islands that are too expensive to interconnect to the main grid. Electricity in these islands is generated by diesel generators operated by the National Power Corporation - Small Power Utilities Group (NPC-SPUG). The logistical difficulty in transporting diesel fuel, however, has resulted in a costly electricity supply that is limited to a few hours each day. The combustion of fossil fuels also generates greenhouse gases that contribute to climate change. Lastly, the subsidies required to operate these generators is projected to increase due to rising fuel costs and the growing demand for electricity (Aziz et al., 2019).

Hybrid renewable energy systems (HRES) have therefore been investigated as an alternative energy source in off-grid islands (Manoj Kumar et al., 2020). These consist of a renewable energy (RE) technology, such as solar photovoltaics (PV) and wind turbines, to displace reliance on fossil fuels, energy storage technologies, such as lithium-ion (Li-ion) batteries to stabilize the intermittency of RE, and conventional sources, such as diesel generators, that can be dispatched whenever RE is unavailable. The techno-economic potential of HRES has been demonstrated in various studies. Ocon and Bertheau (2019) showed that a transition from a diesel-only scenario to an HRES consisting of solar PV, Li-ion, and diesel generators in 215 Philippine off-grid areas can reduce the levelized cost of electricity (LCOE) by an average of 20 %.

Paper Received: 7 May 2021; Revised: 27 August 2021; Accepted: 8 October 2021
Please cite this article as: Castro M.T., Ocon J.D., 2021, Can Off-grid Islands Powered by Renewable Energy Microgrids be Operated Sustainably without Subsidies? A Techno-economic Case Study in the Philippines, Chemical Engineering Transactions, 88, 427-432 DOI:10.3303/CET2188071

While the rapidly decreasing cost of RE technologies (Schmidt et al., 2017) has accelerated the energy transition worldwide, the rate of HRES deployment in the Philippines has been rather slow. In the public sector, the Department of Energy (DOE) has plans to phase out the Universal Charge for Missionary Electrification (UCME) subsidy scheme that currently supports energy access in off-grid areas (BusinessWorld, 2019). As for the private sector, the financial viability of off-grid electrification projects has yet to be analyzed in detail. It should be noted that the lower cost of HRES with respect to diesel-only systems does not necessarily imply that the deployment of HRES is profitable.

In this work, the financial viability of installing HRES in Philippine off-grid islands was evaluated. First, Philippine off-grid islands with representative electrical demands were selected as case studies. Next, the solar and wind resource availability in each island was estimated and the techno-economic parameters describing the energy components (e.g., solar PV, wind turbines, Li-ion batteries, and diesel). The energy systems in each island was then modeled using Island Systems $\mathrm{LCOE}_{\mathrm{min}}$ Algorithm (ISLA), an in-house energy systems modeling tool. Lastly, techno-economic and profitability metrics were calculated and the financial viability of HRES in each island was discussed. This work provides insights on the financial viability of HRES projects, which has not been assessed in previous techno-economic studies.

2. Methodology

The methodology section is organized as follows. First, the process of selecting representative islands was explained. Second, the modeling of the islands was discussed, Third, the techno-economic modeling parameters were shown. Lastly, the profitability metrics used to assess the islands were presented.

2.1 Island selection

A list of Philippine off-grid islands and their corresponding peak power demand was generated so that off-grid islands with representative electrical demands could be identified. An initial list of islands was formed based on Google Maps™ and Bing Maps™. The list was then refined by removing wholly touristic islands identified by the Department of Tourism and grid-connected islands according to NPC-SPUG. Stilts, shallow communities, and non-residential islands were identified based on satellite images from Google Maps™ and were also removed. This yielded a list of 634 Philippine off-grid islands.

Next, the peak power demand of each island was determined. Some islands had available electrical demand data from NPC-SPUG. For the other islands, however, a correlation between peak demand and island population was utilized. The island population was estimated by multiplying the island area determined via geographic information systems (GIS) mapping and the population density given by the Population Density Maps from Facebook™. The correlation was then developed by determining the proportionality constant between the known peak demands of some islands and their corresponding population.

Based on the resulting peak power demands, the islands can be categorized into very small (1-10 kW), small (10-100 kW), medium (100-1000 kW), and large (1-10 MW). For a representative case study, the island in the median of each interval was selected. These islands were Patongong Island, Lapinigan Island, Balabac Island, and Sibuyan Island with peak loads of 4.42 kW, 32.5 kW, 206 kW, and 3.20 MW, respectively.

2.2 Scenario modeling

Two scenarios were considered in this study to better analyze the installation of HRES in off-grid islands. First, a diesel-only scenario was simulated wherein the electrical demand in each island was satisfied by diesel generators only. This is representative of the status quo in Philippine off-grid islands. Second, the HRES scenario was examined. The HRES consisted of solar PV, wind turbines, Li-ion, and diesel generators.

The scenarios were modeled in ISLA, an energy systems optimization software. ISLA determines the sizes (i.e., power or energy ratings) of each component such that the net present cost (NPC) was minimized under the constraint that the electrical load is continuously served. It also calculates other techno-economic metrics such as the levelized cost of electricity (LCOE), renewable energy share (RE-Share), CO_2 emissions, and capital costs. Details regarding the operation of ISLA can be found in a previous publication (Castro et al., 2020).

2.3 Techno-economic data

The optimization in ISLA will require the load profile, global horizontal irradiance (GHI), and wind speeds in each island, as well as techno-economic parameters describing each component. The load profiles were obtained by multiplying the peak demand with the normalized profiles reported by Bertheau and Blechinger (2018). The monthly average GHI and wind speeds at 10 m were obtained from the Phil-LIDAR database. The hub heights of the wind turbines were also at 10 m, so no wind speed corrections were necessary. The techno-economic assumptions used in this work are presented in Table 1.

Table 1: Techno-economic modeling parameters used as input in ISLA.

Component	Parameter	Value	Ref.	Component	Parameter	Value	Ref.
Solar PV	CapEx [USD/kW]	1,500	[a]	Diesel	CapEx [USD/kW]	500	[b]
	OpEx [USD/kW·y]	15	[a]		OpEx [USD/kW·y]	20	[b]
	Lifetime [y]	20	[a]		OpEx [USD/kWh]	0.02	[b]
Wind	CapEx [USD/kW]	Size-dependent			Lifetime [y]	10	[c]
	OpEx [USD/kW·y]	1 % of CapEx			Fuel Cost [USD/L]	0.9	[c]
	Lifetime [y]	20	[a]		CO_2 emissions [kg/L]	2.67	[c]
Li-ion	CapEx [USD/kWh]	700	[a]	Project	CapEx [USD]	0	[a]
	OpEx [USD/kWh·y]	5	[a]		Discount rate [%]	8	[a]
	Lifetime [y]	10	[a]		Lifetime [y]	20	[a]

[a] (Bertheau, 2020) [b] (Bertheau & Cader, 2019) [c] (Ocon & Bertheau, 2019)

The per-kW capital cost of wind turbines was lower for larger units based on a review of commercially available turbines, as shown in Figure 1. Small installations below 31.6 kW cost 7900 USD/kW, medium installations from 31.6 kW to 316 kW cost 5700 USD/kW, and large installations above 316 kW cost 1,300 USD/kW.

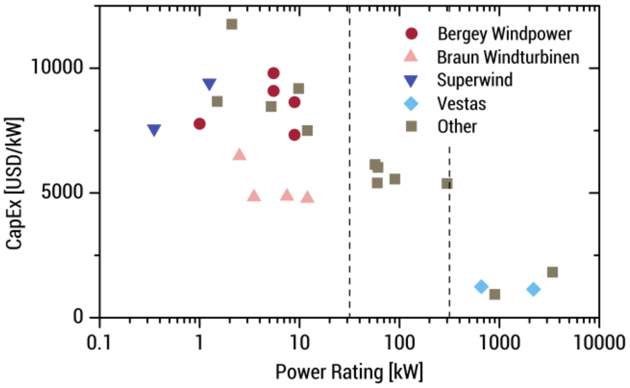

Figure 1: Per-kW capital cost of wind turbine vs. size of wind turbine.

It should also be noted that Balabac Island and Sibuyan Island have existing diesel generator capacities of 486 kW and 2.96 MW, respectively. These were assumed to have zero capital costs in both scenarios. It is possible to install an additional diesel generator in these islands, but this will incur capital costs. This analysis also quantifies CO_2 emissions solely during operation, so only the emissions of diesel generators were considered.

2.4 Profitability metrics

The financial viability of the HRES projects was assessed based on the net present value (NPV), internal rate of return (IRR), and payback period (PBP). The NPV is defined as the sum of all discounted cash flows, as given by Eq(1) (Lee et al., 2016). A positive value of the NPV indicates that the project is profitable. The IRR is the discount rate at which the NPV becomes zero, as shown in Eq(2) (Lee et al., 2016). This quantifies the growth rate of the investment, so investors are likely to choose projects with a higher IRR. The PBP is the time required for the project to break even, as given by Eq(3) (Novaes Pires Leite et al., 2019). A shorter PBP is preferrable as investors can recover their investment within a shorter timeframe.

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{C(n)}{(1+d)^n} \tag{1}$$

$$\sum_{n=0}^{N} \frac{C(n)}{(1+\mathrm{IRR})^n} = 0 \tag{2}$$

$$\int_{0}^{\mathrm{PBP}} \frac{C(n)}{(1+d)^n}\, dn = 0 \tag{3}$$

The revenue of the HRES projects is assumed to depend on the electricity rate. The mainland rate of 0.2 USD/kWh was considered as the base case, and a sensitivity analysis from 0.1 USD/kWh to 0.3 USD/kWh was performed afterwards.

3. Results and discussion

This section is divided into four parts. First, the transition from a diesel-only to a HRES scenario is discussed. Second, the techno-economic metrics of the optimized HRES systems in the off-grid islands are presented. Third, the profitability of the HRES systems is assessed. Lastly, a sensitivity analysis of the profitability with respect to electricity prices is conducted.

3.1 Diesel to HRES transition

A comparison between the techno-economic metrics of diesel-only and HRES systems is presented in Table 2. The transition to HRES was generally beneficial for off-grid islands. The lower LCOE indicated lower generation costs, while the decreased CO_2 emissions suggested a cleaner source of electricity. The normalized NPV represents the per-kWh profit, so a negative value implies that a per-kWh subsidy equal to the absolute value of the normalized NPV is required. In this regard, the transition to HRES also decreased the subsidy requirements and even made large islands profitable. The transition, however, was marked by a sharp increase in capital costs due to the installation of RE technologies. This can discourage HRES transition in marginalized communities, so strategies for mitigating capital costs should be employed (Mohapatra et al., 2019).

Table 2: Techno-economic metrics of diesel-only and HRES scenarios at a 0.2 USD/kWh electricity rate

Island	LCOE [USD/kWh]		CapEx* [USD/kWh]		CO_2† [kg/y·kWh]		NPV* [USD/kWh]	
	Diesel	HRES	Diesel	HRES	Diesel	HRES	Diesel	HRES
Sibuyan (L)	0.270	0.183	0.0044	0.0675	0.695	0.263	-0.3408	+0.01714
Balabac (M)	0.286	0.222	0.0009	0.0679	0.736	0.355	-0.3721	-0.02194
Lapinigan (S)	0.296	0.268	0.0170	0.0529	0.727	0.540	-0.3933	-0.06856
Patongong (VS)	0.296	0.261	0.0170	0.0549	0.727	0.510	-0.3933	-0.06077

*Normalized by the energy generated during entire lifespan. †Normalized by annual energy generated.

3.2 Techno-economic metrics

The techno-economic metrics of the cost optimum HRES in each island are presented in Table 3. The larger islands were more dependent on RE as indicated by the larger proportion of solar PV and wind sizes, higher RE-Share, and lower CO_2 emissions. The RE-dependent systems in larger islands had lower LCOEs than the diesel-dependent systems in smaller islands, which is consistent with the results of other researchers (Ocon & Bertheau, 2019). As for smaller islands, the prohibitively high cost of small wind turbines contributed to a higher LCOE, lower RE-Share, and increased CO_2 emissions. The lower dependence on RE, however, resulted in lower capital costs. This is advantageous for small islands, which are typically home to marginalized communities (Meschede et al., 2019) deterred by high capital costs (Mohapatra et al., 2019).

Table 3: Techno-economic metrics of the cost optimum HRES in the islands

Island	Solar PV [kW]	Wind [kW]	Li-ion [kWh]	Diesel* [kW]	LCOE [USD/kWh]	RE-Share [%]	CO_2† [kg/y·kWh]	CapEx‡ [USD/kWh]
Sibuyan (L)	2,100	4,899	700	1,400	0.183	63.3	0.263	0.0675
Balabac (M)	224.8	359.6	89.9	0	0.222	53.9	0.355	0.0679
Lapinigan (S)	28.45	0.00	3.56	42.68	0.268	27.1	0.540	0.0529
Patongong (VS)	3.868	0.000	0.967	5.801	0.261	31.1	0.510	0.0549

*Additional diesel capacity. †Normalized by annual energy generated. ‡Normalized by the energy generated during entire lifespan.

3.3 Profitability metrics

The NPV, IRR, and PBP of the cost optimum HRES under the mainland electricity rate (0.2 USD/kWh) are shown in Table 4. Among the selected islands, only the largest island was profitable. This is evident in the portfolio of energy project developers in the Philippines, which often consists of MW-scale projects in large islands. For instance, the Culna Renewable Energy Corporation (CREC) project also aimed to install a 2.8 MW solar PV, 4.8 MWh battery, and 2.4 MW diesel system in Culion Island (WERenewables, 2017). While the NPV of the HRES in the large island is positive, the IRR and PBP suggest that it is not necessarily a good investment. The IRR is close to the 8 % discount rate, which indicates a slow growth of the investment. This is supported by the long PBP, which is already more than 60 % into the lifespan of the project. As for the other islands, the magnitude of the normalized NPV indicates the subsidies required per kWh of electricity generated. The medium island is easier to subsidize than the very small and small islands.

Table 4: Profitability metrics of the cost optimum HRES in the islands at a 0.2 USD/kWh electricity rate

Island	NPV	IRR	PBP	Norm. NPV*
	[10^3 USD]	[%]	[y]	[USD/kWh]
Sibuyan (L)	+2,720	11.36	13.3	+0.01714
Balabac (M)	-280.3			-0.02194
Lapinigan (S)	-86.20			-0.06856
Patongong (VS)	-10.39			-0.06077

*Normalized by the energy generated during entire lifespan.

3.4 Sensitivity analysis

The net present revenue (NPR), IRR, and PBP of the cost optimum HRES under electricity rates from 0.1 USD/kWh to 0.3 USD/kWh are shown in Figure 2. At the 0.25 USD/kWh price point, the medium island became profitable, although the 13 % IRR and 9-year PBP may not be attractive to investors. The large island, however, gained a 20 % IRR and 6-year PBP, which is a notable improvement over the IRR and PBP at the mainland rate. The small and very small islands become profitable only at the 0.30 USD/kWh price point. The IRR and PBP are decent, however, investors may opt to invest in the large and medium islands instead.

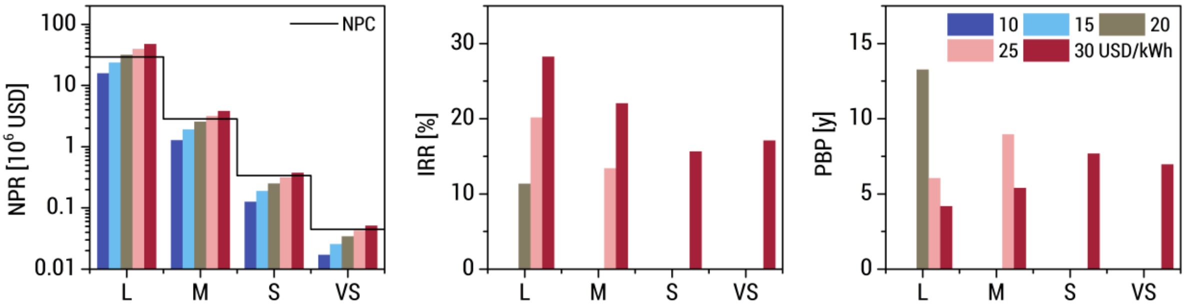

Figure 2: NPR (left), IRR (middle), and PBP (right) of the cost optimum HRES at electricity rates from 0.1 USD/kWh to 0.3 USD/kWh. NPV = NPR-NPC, so the project is profitable when the NPR surpasses the NPC.

4. Conclusions

In this work, techno-economic case studies and profitability analyses were conducted on representative Philippine off-grid islands to determine if these can be electrified without subsidies. The transition from a diesel-only scenario to HRES is economically and environmentally favorable. The techno-economic case studies suggest that larger islands have a higher dependence on RE and lower LCOE, which is in line with the findings of other researchers. This is attributed to the low cost of large wind turbines. In contrast, smaller islands depend more on diesel generators for electricity. This results in a high LCOE, but the decreased capital cost requirements are favorable for the marginalized communities in these islands.

The profitability analysis suggests that large islands will not require subsidies at the mainland electricity rate of 0.2 USD/kWh. The profitability of large islands is consistent with the fact that energy project developers have invested in MW-scale projects in off-grid islands. The IRR and PBP, however, suggest that large islands are a poor investment at the mainland rate. Increasing the electricity rate to 0.25 USD/kWh alleviates the low IRR and high PBP in large islands and even makes medium islands profitable. Only at 0.30 USD/kWh do the very small and small islands become profitable, but this is already much larger than the 0.10 USD/kWh subsidized rate that off-grid island residents currently pay for electricity.

This study serves as a guide to project developers who want to invest in off-grid islands. This is also a call to the government to rationalize the UCME scheme as subsidies are still necessary in small islands with marginalized communities. Likewise, innovations and strategies for reducing subsidy requirements should be sought after. Future work will involve extending the techno-economic case studies and profitability analysis to all 634 off-grid islands identified in this study, rather than just the representative islands.

Nomenclature

$C(n)$ – nominal cash flow at year n, y
d – discount rate, -

N – project lifetime, y

Acknowledgements

M.T.C. would like to acknowledge the Engineering Research and Development for Technology (ERDT) Graduate Scholarship. J.D.O. would like to acknowledge the ElectriPHI Program funded by the University of the Philippines Office of the Vice-President for Academic Affairs, and the CIPHER Project (IIID-2018-008) funded by The Commission on Higher Education – Philippine California Advanced Research Institutes (CHED-PCARI), The Republic of the Philippines.

References

Aziz A.S., Tajuddin M.F.N., Adzman M.R., Azmi A., Ramli M.A.M., 2019, Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq, Renewable Energy, 775–792.

Bertheau P., 2020, Supplying not electrified islands with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines, Energy, 202, 117670.

Bertheau P., Cader C., 2019, Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options, Applied Energy, 251, 113393.

BusinessWorld., 2019, DoE policy points to end of missionary electrification charge, <https://www.bworldonline.com/doe-policy-points-to-end-of-missionary-electrification-charge/> accessed 03.02.2021.

Castro M.T., Alcanzare M.T., Esparcia E.A., Ocon J.D., 2020, A comparative techno-economic analysis of different desalination technologies in off-grid islands. Energies, 13

Infranco Asia., n.d., Palawan Solar Hybrid Power, <https://infracoasia.com/our-portfolio/palawan-solar-hybrid-power/> accessed 03.02.2021.

Lee J., Chang B., Aktas C., Gorthala R., 2016, Economic feasibility of campus-wide photovoltaic systems in New England, Renewable Energy, 99, 452–464.

Manoj Kumar N., Chopra S.S., Chand A.A., Elavarasan R.M., Shafiullah G.M., 2020, Hybrid renewable energy microgrid for a residential community: A techno-economic and environmental perspective in the context of the SDG7, Sustainability (Switzerland), 12, 1–30.

Meschede H., Esparcia E.A., Holzapfel P., Bertheau P., Ang R.C., Blanco A.C., Ocon J.D., 2019, On the transferability of smart energy systems on off-grid islands using cluster analysis – A case study for the Philippine archipelago, Applied Energy, 251, 113290.

Mohapatra D., Jaeger J., Wiemann M., 2019, Private Sector Driven Business Models for Clean Energy Mini-Grids, Alliance for Rural Electrification, Brussels, Belgium.

Novaes Pires Leite G.de Weschenfelder F., Araújo A.M., Villa Ochoa Á.A., Franca Prestrelo Neto N.da Kraj A., 2019, An economic analysis of the integration between air-conditioning and solar photovoltaic systems, Energy Conversion and Management, 185, 836–849.

Ocon J.D., Bertheau 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.

Schmidt O., Hawkes A., Gambhir A., Staffell I., 2017, The future cost of electrical energy storage based on experience rates, Nature Energy, 2, 1–8.

WERenewables., 2017, Culina Renewable Energy Corporation. <www.werenewables.com/projects/culna-renewable-energy-corporation-crec/> accessed 03.02.2021.

World Bank, 2020, Access to electricity (% of population) - Philippines, <https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=PH> accessed 03.02.2021.