

Article

Decentralized versus Clustered Microgrids: An Energy Systems Study for Reliable Off-Grid Electrification of Small Islands

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Abstract: Philippine off-grid islands are mostly electrified by diesel generators, resulting in costly electricity that is interrupted by fuel supply disruptions. The archipelagic nature of the country also impedes off-grid electrification due to the high capital cost of grid extension. Transitioning from diesel-only systems to hybrid renewable energy systems and interconnecting the island microgrids can solve these problems while promoting cleaner energy production. In this work, a comparative study on decentralized and clustered hybrid renewable energy system microgrids in the Polillo group of islands in the Philippines, using HOMER Pro, was performed. Microgrids comprising solar photovoltaics, lithium-ion battery energy storage, and diesel generators were designed on each island. Clustered systems encompassing multiple islands in the island group were simulated by also considering the least-cost interconnection paths. The techno-economics of each decentralized or clustered system and the four-island system were evaluated based on the levelized cost of electricity (LCOE). Reliability was assessed using the change in LCOE upon the failure of a component and during weather disturbances. Transitioning from diesel-only systems to hybrid systems reduces generation costs by an average of 42.01% and increases the renewable energy share to 80%. Interconnecting the hybrid systems results in an average increase of 2.34% in generation costs due to the cost of submarine cables but improves system reliability and reduces the optimum solar photovoltaic and lithium-ion storage installations by 6.66% and 8.71%, respectively. This research serves as a framework for the interconnection pre-feasibility analysis of other small off-grid islands.

Keywords: diesel; solar photovoltaics; lithium-ion; decentralized microgrids; clustered microgrids; renewable energy

1. Introduction

Off-grid islands are remote islands that are difficult to connect to the main grid due to the high cost of interconnection. These islands can be found globally, but the Philippines has attracted researchers' attention due to the numerous islands in the country that may be used in case studies. The electrification of these islands has been the priority of the Philippine Department of Energy (DOE) to promote inclusive socio-economic development in these areas [1,2]. Off-grid islands are often electrified by diesel power plants, which in the Philippines are operated by the National Power Corporation-Small Power Utilities Group (NPC-SPUG) [3]. Diesel plants, however, offer high electricity rates and an unreliable power supply due to price volatility and the logistics of fuel transport [4]. They are also

detrimental to the environment due to oil spills, noise pollution, and greenhouse gas emissions [5]. Researchers have therefore investigated the implementation of hybrid renewable energy system (HRES) on these islands.

HRESs are composed of at least one renewable energy (RE) source and may include conventional generation sources, such as diesel generators [6]. RE generation reduces the fuel requirements, while conventional generation addresses the intermittency of RE sources. Energy storage is included to meet peak load demand and to address the mismatch between RE generation and the peak load [7]. HRES is becoming more attractive due to the decreasing cost of solar photovoltaic (PV) and energy storage [8,9]. The decreased reliance on diesel consumption also mitigates economic risks from fuel price shocks [10]. A summary of HRES feasibility studies is presented in Table 1. These works have shown that a transition to a HRES provides more sustainable generation while decreasing the levelized cost of electricity (LCOE).

Table 1. Summary of studies in hybrid renewable energy systems (HRESs) in off-grid islands.

Location	Components				Remarks	Ref.
	PV	Wind	Diesel	Battery		
Philippines	✓		✓	✓	HRES provides 20% lower LCOE than diesel	[4]
Philippines	✓		✓	✓	HRES is a cost-effective solution for most islands	[11]
Philippines	✓		✓	✓	Analyzed the HRES potential of 132 diesel-based grids	[12]
Philippines			✓		Diesel consumption in off-grid islands can be reduced by coupling with biodiesel	[13]
Philippines	✓	✓	✓	✓	Reducing the reliability of a 100% RE system also reduces the LCOE	[14]
Philippines	✓	✓	✓	✓	Identified 137 islands wherein solar PV and wind installations are feasible	[15]
Global	✓	✓	✓	✓	Identified around 1800 islands with high potential for solar PV and wind generation	[16]

The reliability of an energy system must also be considered in areas with severe weather events. For example, Typhoon Mankhut forced several diesel generators in Philippine off-grid islands to shut down to prevent damage from distribution line disturbances [17]. System reliability is often quantified based on the failure probability of the energy components [18–22] but may also be measured in terms of cost differences when comparing two energy systems [23]. It is generally observed that HRESs composed of solar PV, energy storage, and diesel generators offer increased reliability [21]. Solar PV and energy storage can power the system when conventional sources, such as diesel generators, are nonfunctional [23]. Bertheau et al. notes, however, that increased reliability often comes with increasing costs [14], so cost optimization must be performed. Nevertheless, an HRES provides lower costs than installing additional diesel generators [19]. A review of the studies on energy system reliability is presented in Table 2.

Table 2. Summary of studies about energy reliability.

Location	System	Remarks	Ref.
New York, USA	Residential building	<ul style="list-style-type: none"> Compared systems with combinations of electric grid, natural gas, solar PV, and battery. Proposed framework wherein reliability is evaluated based on preparedness, robustness, recovery, and adaptation. PV + battery + grid systems were the most reliable. 	[19]
India	Police control room	<ul style="list-style-type: none"> Considered a hybrid system with solar PV, wind, battery, and generator. Evaluated reliability using a fault-tree analysis. 	[20]
Iran	Off-grid area	<ul style="list-style-type: none"> Proposed an optimization algorithm that considered reliability. PV + wind + battery + diesel systems had the lowest costs and highest reliability. 	[24]
Poland	Household	<ul style="list-style-type: none"> Compared on-grid and off-grid hybrid systems. Assessed reliability using probability of failure and the ratio of system downtime to customer demand time. Off-grid systems had higher capital costs, but higher reliability. 	[21]
New York, USA	Buildings	<ul style="list-style-type: none"> Quantified reliability as the savings gained when an energy system survives a power outage. Solar PV + battery + diesel provides better reliability than diesel alone. 	[23]
Texas, USA	Harris County	<ul style="list-style-type: none"> Developed a probabilistic method to assess the reliability of a power system against hurricanes. 	[22]

Many studies on HRESs focus solely on decentralized microgrids, which are designed to supply energy to a single off-grid island only [11]. Decentralized electrification, however, has a low investment potential due to the high capital cost and revenue uncertainty [25]. Main grid interconnection has also been investigated. For example, Meschede et al. identified off-grid islands in the Philippines that are viable for main grid interconnection [26]. Cader and Bertheau considered an extreme case wherein all islands are interconnected in the main grid [11]. It was revealed, however, that main grid interconnection is viable only for larger islands [11]. A clustered microgrid, in which the HRESs of multiple islands are interconnected, is proposed as an alternative option. This setup offers increased energy security, reduced energy storage requirements and capital costs per island, and flexibility for RE penetration [27]. Table 3 summarizes studies about interconnection either to the main grid or between islands. Many of these suggest that interconnection decreases generation costs [28–32], but little is known about its impact on reliability. Moreover, the small amount of related literature implies that the economic aspects of interconnection require further study.

Table 3. Summary of studies about clustered HRESs.

Location	LCOE Reduction	Remarks	Ref.
Philippines	✓	Main grid interconnection delivers least-cost electricity supply for larger islands.	[11]
Canary and Balearic Islands	✓	Interconnection decreases the generation costs among the connected islands.	[27]
Greek Islands	✓	Interconnection decreases the generation costs and CO ₂ emissions.	[28,29]
UK–France	✓	Interconnection decreases the generation costs and CO ₂ emissions. The intermittency of solar PV and wind is managed better.	[30]
Ireland–Great Britain	✓	Interconnection decreases the generation costs and CO ₂ emissions.	[31]
Malta and Sicily		Interconnection does not necessarily decrease the generation costs. Effect depends on fuel costs, business models, and installation capacities.	[32]

From the previous studies, the techno-economics and reliability of decentralized HRESs in island systems have been studied extensively. However, there exist research gaps on clustered HRESs. In this work, a comparative study between decentralized and clustered HRESs is conducted using the Polillo group of islands in the Philippines as a case study. The analysis of the study was divided into two parts. The techno-economic aspects of clustered and decentralized HRESs are compared in terms of the LCOE. The reliability of the HRES was evaluated by observing the change in LCOE upon the introduction of a disturbance. This study gives insights for private companies and investors for investing in clustered microgrids. Moreover, it provides a simple framework for the modeling of interconnected off-grid islands for pre-feasibility purposes.

2. Materials and Methods

2.1. General Approach

This study considers HRESs consisting of solar PV, lithium-ion (Li-ion) energy storage, and diesel generators only, as this yields a lower LCOE than diesel-only configurations as shown in Appendix A. The optimum sizes and LCOE of an HRES is determined by the HOMER Pro microgrid optimization software. The techno-economic parameters used in the simulations are presented in Appendix B, while the existing generation capacities and generation and demand profiles are in Appendix C. The length of the cables that connect the islands is determined using bathymetric data and the A* algorithm. Decentralized HRESs, which consist of one island only, can be readily optimized by HOMER Pro. Clustered HRESs, which comprise multiple islands, will also require the cable lengths. The techno-economic aspects of the configuration, consisting of all four islands, are evaluated by combining results from the decentralized and clustered HRESs that power the islands. The reliability of an HRES is determined by introducing disturbances into the simulations. Figure 1 summarizes the general approach.

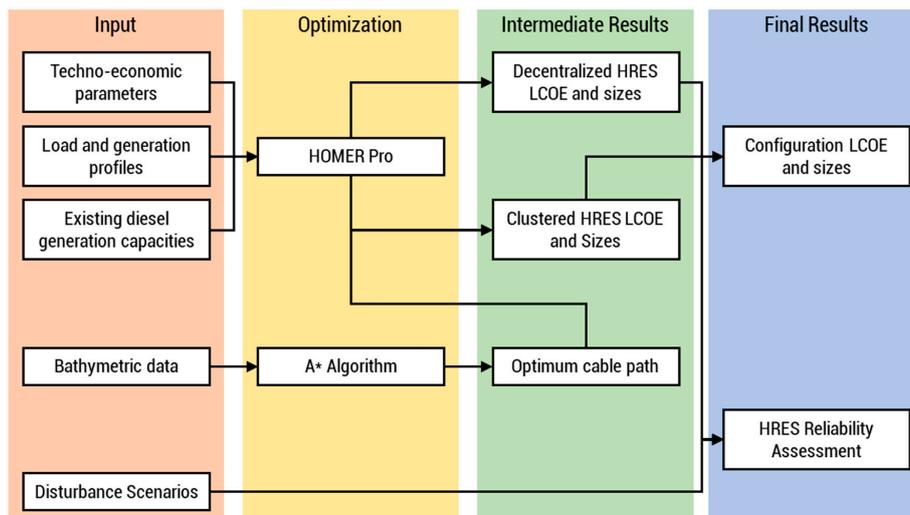


Figure 1. Flowchart of the general research approach.

2.2. Case Study

The Polillo group of islands comprising Polillo, Palasan, Patnanungan, and Jomalig Islands in Quezon Province, Philippines was considered as the case study (Figure 2). In 2015, the islands registered a total of 53,906 inhabitants and 12,083 households, with Polillo Island constituting approximately 57% of the figures followed by Patnanungan, Jomalig, and Palasan, respectively [33]. The islands are located within the typhoon belt, making them very vulnerable to disasters.

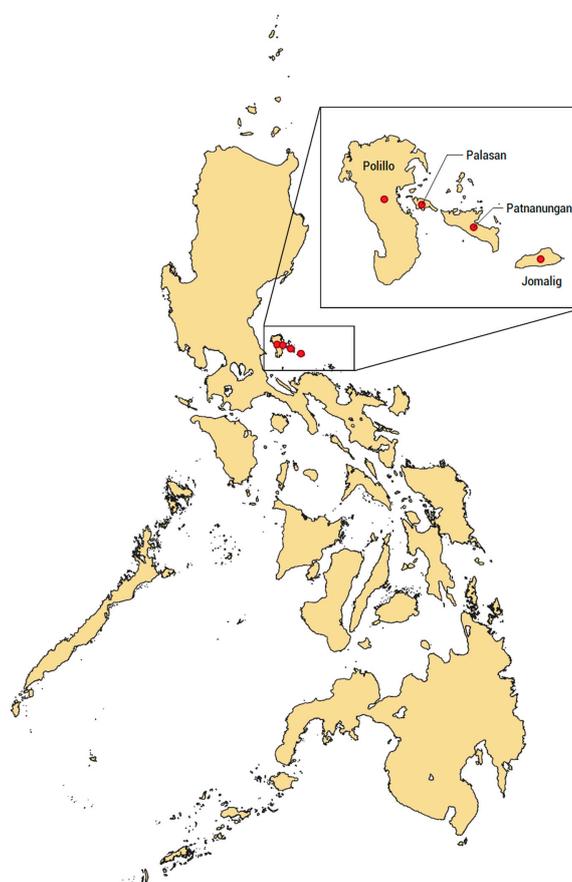


Figure 2. Location of the selected islands.

2.3. HRES Calculations

2.3.1. A* Algorithm

Island interconnection is performed using submarine and land cables (Table 4). The voltage rating is selected based on the peak load passing through the cable. Due to the linear geographic arrangement of the islands, it was also assumed that the possible connections are only between Polillo and Palasan, Palasan and Patnanungan, and Patnanungan and Jomalig (Figure 3). The path of least cost was obtained using the A* algorithm [34] implemented in Python 3. The A* algorithm determines the path between two points that minimizes a given penalty, which in this case is the cost of the interconnection cables. Note that the path of least cost may be different from the shortest path (i.e., a straight line) due to differences in land and submarine cable costs. The algorithm was selected because it accounts for elevation differences due to the terrain. Bathymetric data in 15 arc-second intervals were obtained from the database of the General Bathymetric Chart of the Oceans [35].

Table 4. Techno-economic parameters of interconnection cables [11].

Cable	Parameter	Unit	Value
Submarine	CapEx (13.2 kV; 200 kW)	USD/km	350,000
	CapEx (34.0 kV; 1 MW)	USD/km	500,000
	CapEx (69.0 kV; 5 MW)	USD/km	750,000
	CapEx (138 kV; 10 MW)	USD/km	1,000,000
	CapEx (230 kV; >10 MW)	USD/km	1,500,000
	OpEx	USD/y	0.005% of CapEx
Land	CapEx	USD/km	12,000
	OpEx	USD/y	0.05% of CapEx

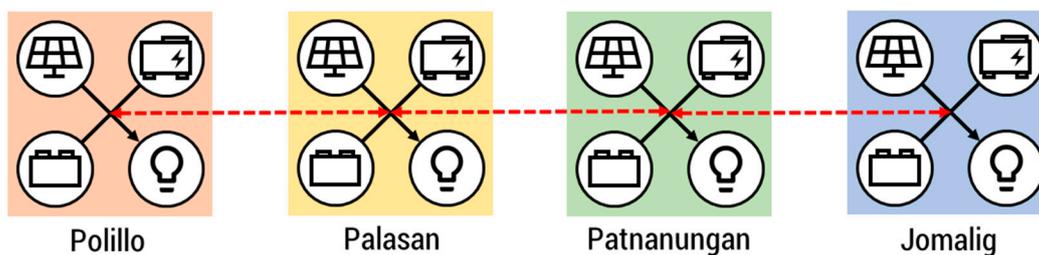


Figure 3. Architecture between the possible interconnections between the selected islands.

2.3.2. HOMER Pro

HOMER Pro accepts the techno-economic parameters, the existing diesel generator capacities, the global horizontal irradiance (GHI) profile, and the load profile at a given site as input. The outputs are the solar PV and Li-ion sizes that minimize the LCOE ($LCOE$, Equation (1)). In this equation, d is the discount rate, N is the project lifetime (y), NPC is the net present cost (NPC) of the energy system (USD), and E_{yr} is the annual energy demand at the given site (kWh). Details about the calculation of the NPC and other economic data are presented in the HOMER Pro User Manual [36].

$$LCOE = \frac{d(1+d)^N}{(1+d)^N - 1} \times \frac{NPC}{E_{yr}} \quad (1)$$

Decentralized HRES cover only one island (i.e., one site) and can be optimized directly in HOMER Pro (Figure 4). In contrast, clustered HRESs comprise multiple islands, so the multiple sites must be aggregated into one hypothetical site. If the interconnection losses are neglected, the sum of the load profiles of each island $P_{ld,i}(t)$ can be taken as the load profile of the clustered HRESs $P_{ld,m}(t)$ (Equation (2)). The GHI profile of the clustered HRESs $G_m(t)$ is approximated as the average GHI profiles of the

connected islands $G_i(t)$ (Equation (3)). The existing generators in each island are modeled individually (Figure 4). In the equations below, M is the set of islands i connected by the clustered HRESs and n is the number of connected islands or the cardinality of M . The costs of the interconnection cables are emulated in HOMER Pro by specifying these as the capital or operating costs of the project.

$$P_{ld,m}(t) = \sum_{i \in M} P_{ld,i}(t) \quad (2)$$

$$G_m(t) = \sum_{i \in M} G_i(t) / n \quad (3)$$

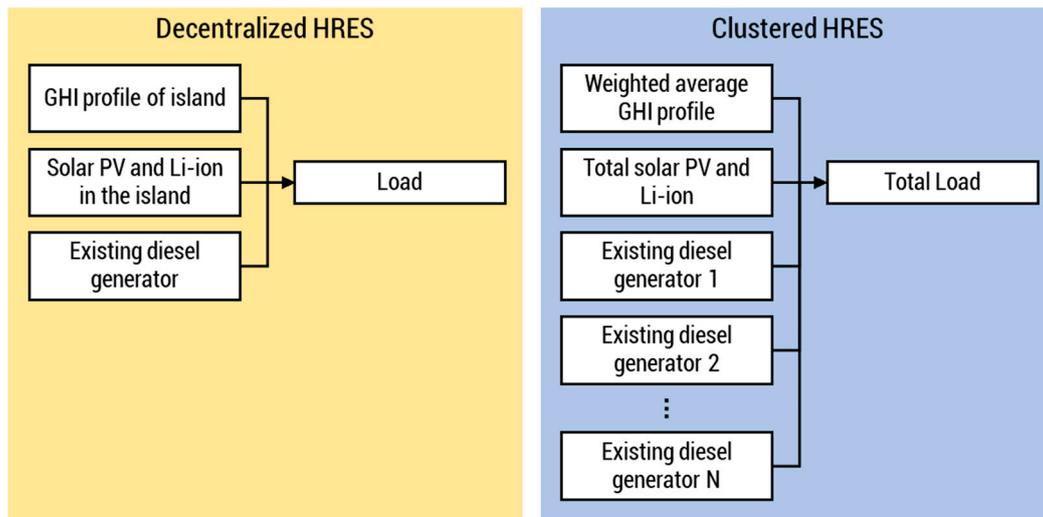


Figure 4. System architecture simulated in HOMER Pro for decentralized (**left**) and clustered (**right**) HRESs.

The optimum sizes and LCOE of a decentralized HRES are taken as those of the island. Meanwhile, the optimum solar PV and Li-ion battery sizes of a clustered HRES are interpreted as the optimum total capacity among the connected islands. The results do not specify the location of the solar PV and Li-ion installations, and are valid even if the capacity is split among the islands because the models are linear with respect to installation size [36]. The impact of interconnection is evaluated by comparing the optimum sizes and LCOE of the clustered HRESs with those of the islands if they were not interconnected. The solar PV size $S_{PV,nc}$ (kW), Li-ion size $S_{Li,nc}$ (kWh), and LCOE $LCOE_{nc}$ (USD/kWh) of the non-interconnected islands are given by Equations (4)–(6), respectively. $S_{PV,i}$, $S_{Li,i}$, $LCOE_i$, and E_i are the solar PV size, Li-ion size, LCOE and annual consumption (kWh) of island i , respectively. The form of Equation (6) is justified in Appendix D.

$$S_{PV,nc} = \sum_{i \in M} S_{PV,i} \quad (4)$$

$$S_{Li,nc} = \sum_{i \in M} S_{Li,i} \quad (5)$$

$$LCOE_{nc} = \frac{\sum_{i \in M} E_i \times LCOE_i}{\sum_{i \in M} E_i} \quad (6)$$

2.4. Configuration Calculations

The optimum solar PV S_{PV} (kW) (Equation (7)) and Li-ion S_{Li} (kWh) (Equation (8)) sizes of the configuration (i.e., all four islands) are the sum of the solar PV $S_{PV,m}$ (kW) and Li-ion $S_{Li,m}$ (kWh) sizes of each HRES, respectively. In the following equations, T is the set of HRES m that encompass the four islands.

$$S_{PV} = \sum_{m \in T} S_{PV,m} \quad (7)$$

$$S_{Li} = \sum_{m \in T} S_{Li,m} \quad (8)$$

The LCOE of the configuration $LCOE$ is the average LCOE weighted by the annual consumption of each HRES (Equation (9)). $LCOE_m$ and E_m are the LCOE (USD/kWh) and annual consumption (kWh) of HRES m . A justification of this equation is provided in Appendix D.

$$LCOE = \frac{\sum_{m \in T} E_m \times LCOE_m}{\sum_{m \in T} E_m} \quad (9)$$

2.5. Reliability

The reliability of an HRES r is assessed by recording the percent change in LCOE when a disturbance is introduced $LCOE_{m,d}$, in comparison to the HRES LCOE when the disturbance is absent $LCOE_{m,0}$. This is summarized by Equation (10).

$$r = \frac{LCOE_{m,d} - LCOE_{m,0}}{LCOE_{m,0}} \quad (10)$$

The disturbance scenarios considered in this study and their physical interpretation are summarized in Table 5. Energy component failure is simulated in HOMER Pro by excluding it from the input. The effect of weather disturbances is emulated by setting the GHI values to zero at the given time.

Table 5. Summary of interconnection scheme of the four-island cluster.

Disturbance	Interpretation
Half of solar PV fails All solar PV fails	Delamination, solder corrosion, and encapsulant discoloration [37]
Li-ion battery fails	Degradation [38], thermal runaway [39]
Large generator fails Medium generator fails Small generator fails Medium and small generator fails	Engine failure, lack of fuel or lube oil, and circuitry failure [40]
3 days of no sun (min. sun period) 1 week of no sun (min. sun period) 3 days of no sun (max. sun period) 1 week of no sun (max. sun period)	Weather disturbances

3. Results

3.1. HRES Results

3.1.1. A* Algorithm

The least-distance and least-cost interconnection cable paths are compared in Table 6. The large difference between the least-cost and least-distance paths justifies the use of the algorithm. The cable routes follow the same path regardless of the number of interconnected islands.

Table 6. Comparison of least-cost path generated by A* (top) and shortest path (bottom).

Connection ¹	Power	Voltage	Distance (km)		Cost
	(kW)	(kV)	Land	Water	(10 ⁶ USD)
Po–Pa	5000	69	19.48	4.96	3.96
			15.94	5.86	4.58
Pa–Pt	1000	34	28.23	0.59	0.64
			26.16	0.93	0.78
Pt–Jo	1000	34	10.66	12.36	6.30
			8.63	13.40	6.80

¹ Po–Polillo, Pa–Palasan, Pt–Patnanungan, Jo–Jomalig.

In the case of the four-island interconnection, the total peak demand of the islands exceeds the peak demand limit and subsequently changes the voltage level of all the submarine cables to be used. A higher cable voltage level slightly increases the interconnection cost as shown in Table 7.

Table 7. Summary of interconnection scheme of the four-island cluster.

Parameter	Unit	Value
Peak Load	kW	2943
Power Rating	kW	5000
Voltage Rating	kV	69
Distance	km	76.29
Cost	10 ⁶ USD	13.98

Figure 5 shows the optimized submarine and land cable routes for interconnecting the four islands. The algorithm optimizes the route to avoid costly submarine cables.

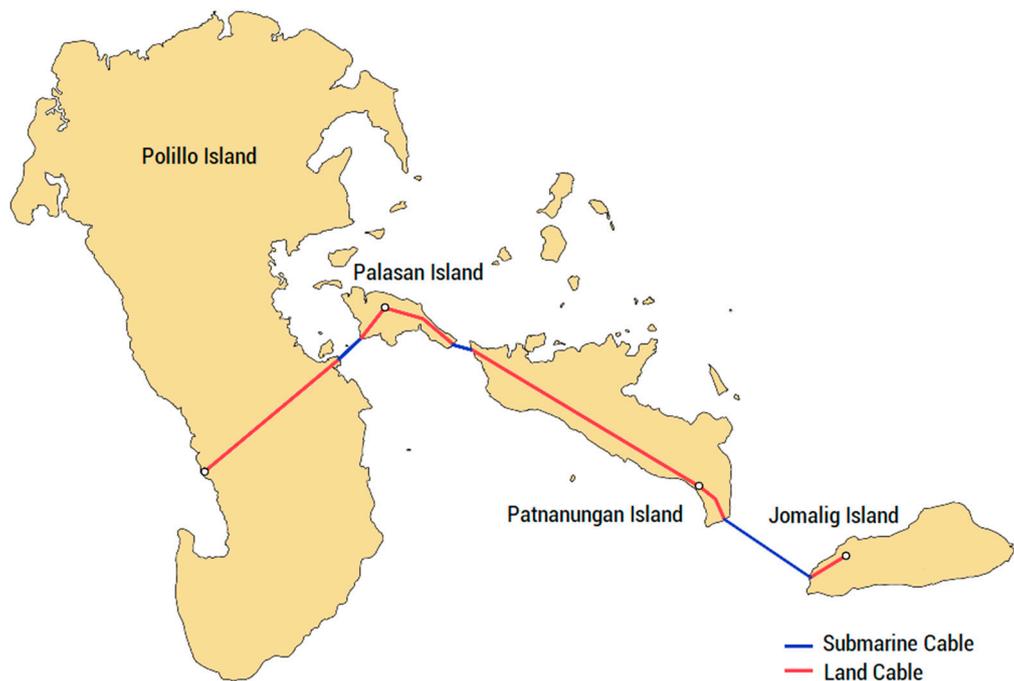


Figure 5. Optimized land and submarine cable routes between islands.

3.1.2. HOMER Pro

The LCOE generally increases after interconnection (Table 8) due to the capital cost of the cables. The average LCOE increase in all the clustered HRES is 5.71%. However, interconnecting Polillo–Palasan–Patnanungan reduced the LCOE by 1.04% due to the short length of submarine cables.

Table 8. LCOE of the decentralized and clustered HRES simulations from HOMER Pro.

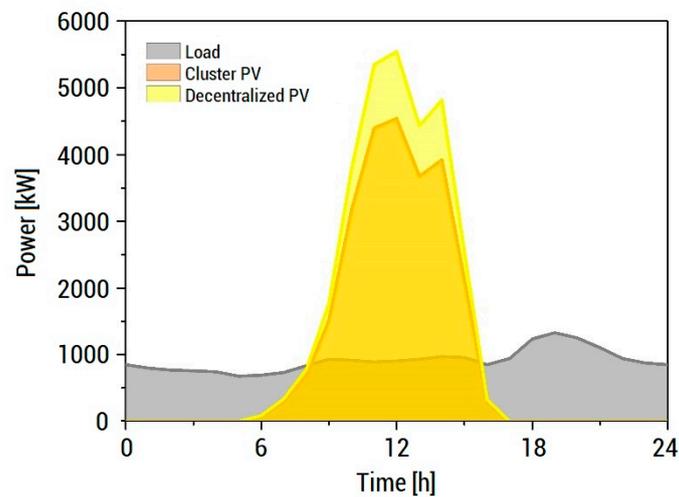
Connection	LCOE (USD/kWh)		LCOE Increase (%)
	Not Connected	Interconnected	
Po		0.421	
Pa		0.392	
Pt		0.423	
Jo		0.420	
Po–Pa	0.420	0.462	10.07
Pa–Pt	0.420	0.454	8.10
Pt–Jo	0.422	0.426	1.07
Po–Pa–Pt	0.421	0.416	−1.04
Pa–Pt–Jo	0.420	0.477	13.72
Po–Pa–Pt–Jo	0.421	0.430	2.35

In contrast, the installation requirements of solar PV and Li-ion battery decreased by 14.56% and 14.45%, respectively, on average (Table 9). The Polillo–Palasan cluster of islands has the highest decrease for both solar PV and Li-ion. Installation requirements decreased upon clustering because excess generation can be sourced from other islands as opposed to increasing the generation capacity. This is justified in Figure 6, wherein the power flow of the Polillo–Palasan cluster and the sum of power flows of the decentralized Polillo and Palasan islands are compared. Larger islands benefit more from this effect because they tend to have more excess generation.

Table 9. Optimum sizes of the decentralized and clustered HRES simulations from HOMER Pro.

Connection	PV (MW)		Decrease (%)	Li-ion (MWh)		Decrease (%)
	NC ¹	Int ²		NC ¹	Int ²	
Po	8.74			25.72		
Pa	0.19			0.61		
Pt	2.16			6.16		
Jo	1.35			3.99		
Po–Pa	8.93	7.92	19.48	26.33	20.76	21.13
Pa–Pt	2.35	1.91	18.71	6.77	5.81	14.09
Pt–Jo	3.51	2.92	16.68	10.15	8.86	12.78
Po–Pa–Pt	11.09	10.39	6.30	32.49	28.76	11.49
Pa–Pt–Jo	3.70	3.27	11.75	10.75	9.74	9.42
Po–Pa–Pt–Jo	12.44	10.64	14.47	36.48	29.99	17.80

¹ NC—Not connected; ² Int—Interconnected.

**Figure 6.** Power flow of the Polillo–Palasan clustered HRES vs. the sum of the power flows of Polillo and Palasan if they were not connected.

3.2. Configuration Results

The configuration wherein Polillo, Palasan and Patnanungan islands are interconnected while Jomalig island has a standalone energy system (i.e., Po–Pa–Pt Jo configuration) was determined to be the least-cost configuration (Figure 7). The component sizes and LCOE of this configuration are presented in Table 10. It is also observed that a higher degree of interconnection generally leads to smaller component sizes. The configuration wherein all four islands are connected has the lowest solar PV and Li-ion installation requirements.

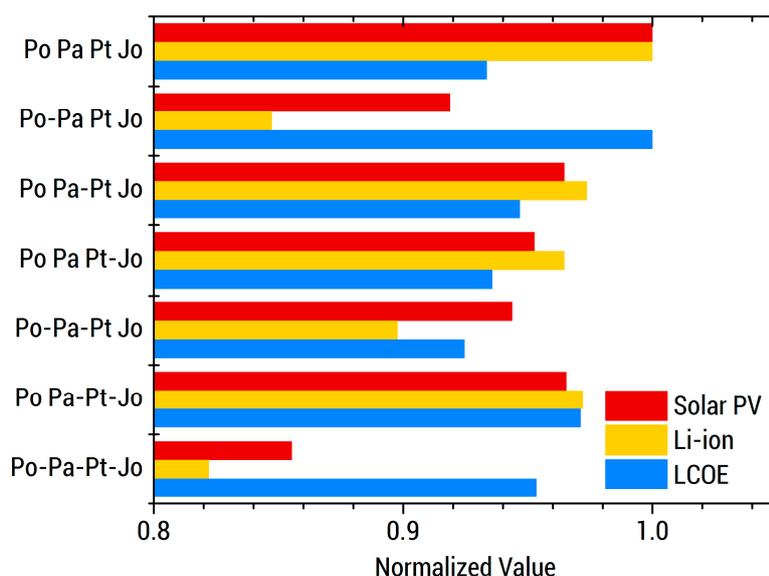


Figure 7. Optimum sizes and LCOE of different interconnection configurations normalized with respect to the highest value.

Table 10. Details about the least-cost Po–Pa–Pt Jo configuration.

HRES	Solar PV	Li-ion	Diesel
	(MW)	(MWh)	(MW)
Po–Pa–Pt	10.39	28.68	4.26 (large) 1.06 (medium)
Jo	1.35	3.99	0.62 (small)

3.3. Reliability

The reliability of each HRES comprising the least cost configuration (i.e., the clustered Po–Pa–Pt HRES and the decentralized Jo HRES) was analyzed. The extreme case wherein all four islands are interconnected was also considered to demonstrate the effects of interconnection. The system disturbances and the corresponding LCOE response are summarized by Figure 8.

The lower LCOE changes of the island clusters compared to the standalone energy system demonstrates the advantage of interconnection in terms of reliability. In particular, the clustered HRES, wherein all four islands are interconnected, is the more reliable system. The clustered islands can still provide enough energy when the small or medium generators fail, showing the additional reliability gained from clustering. The HRES fails, however, when the large generator fails because the power generation is insufficient. Storage system failure also alters the LCOE because the system is dependent on Li-ion batteries as seen in the power flow (Figure 9). The component sizes and LCOE of the more reliable HRES are shown in Table 11

The highest LCOE increase of 105.81%, 73.86% and 33.97% of the Jo, Po–Pa–Pt, and Po–Pa–Pt–Jo HRESs, respectively, is obtained when both solar PVs fail. The increased diesel consumption during the failure of solar PV causes the increased LCOE. This is evident when comparing the power flow during the partial failure of solar PV (Figure 10) with that of the no-disturbance scenario (Figure 9).

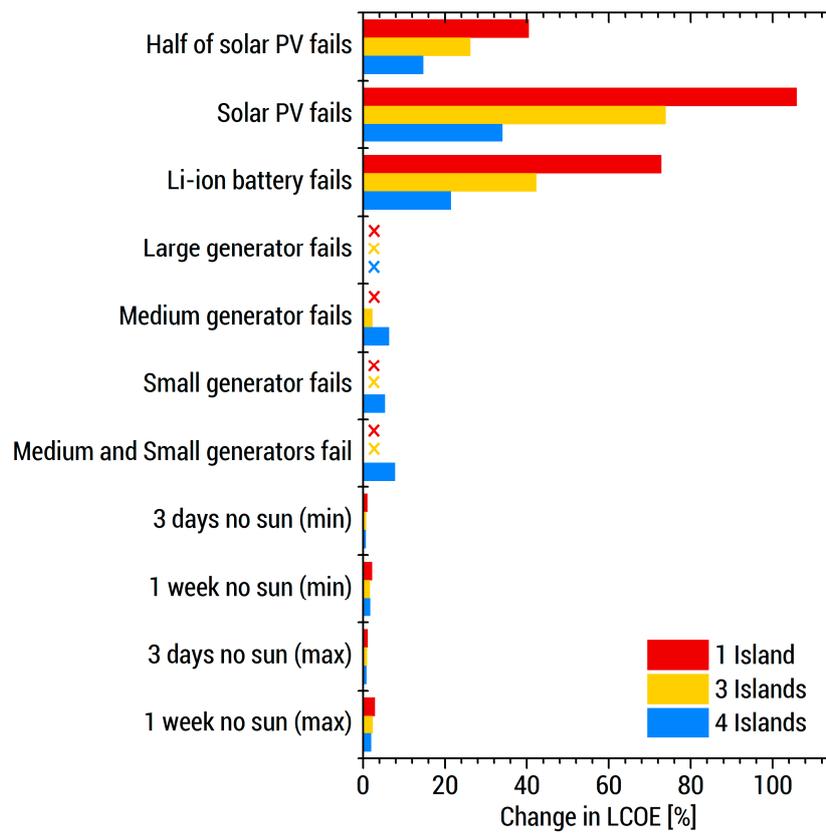


Figure 8. Change in LCOE when a disturbance is applied to Jomalig decentralized HRES (1 island), the Po–Pa–Pt clustered HRES (3 islands), and the Po–Pa–Pt–Jo clustered HRES (4 islands). An × mark indicates a technically infeasible system.

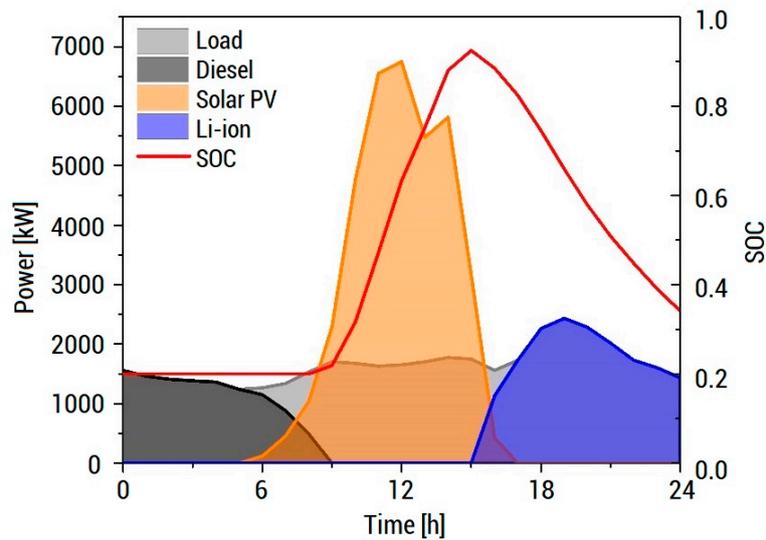
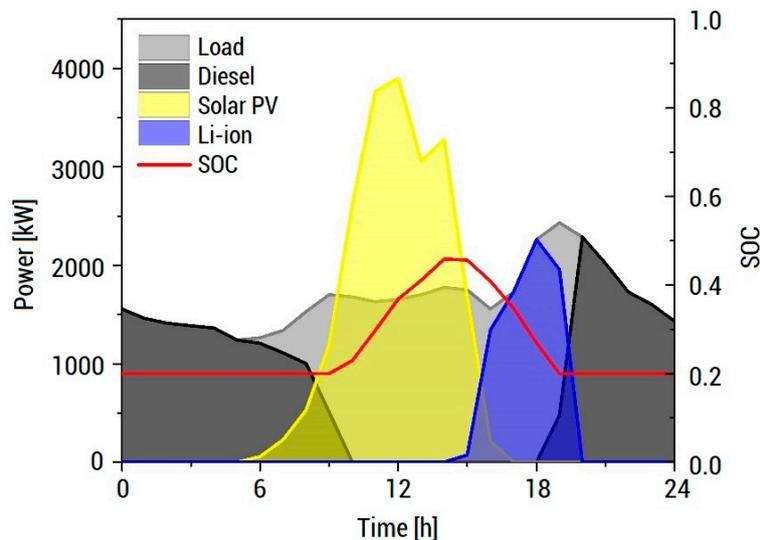


Figure 9. Power flow of the more reliable HRES without disturbances.

Table 11. Details about the more reliable HRES.

HRES	Solar PV	Li-ion	Diesel
	(MW)	(MWh)	(MW)
Po–Pa–Pt–Jo	10.64	29.90	4.26 (large) 1.06 (medium) 0.62 (small)

**Figure 10.** Power flow of the more reliable HRES when half of the solar capacity fails.

4. Discussion

The Po–Pa–Pt Jo configuration was determined to be the least-cost configuration with an LCOE of 0.417 USD/kWh. In contrast, the more reliable Po–Pa–Pt–Jo configuration with an LCOE of 0.430 USD/kWh offers a better balance between cost and reliability. The LCOE of both configurations, however, is much greater than the 0.1882 USD/kWh, 0.1638 USD/kWh, 0.1664 USD/kWh and 0.2258 USD/kWh power rates charge of QUEZELCO II in Polillo, Patnanungan, Jomalig, and mainland Philippines, respectively [41]. However, the diesel power plants in Patnanungan and Jomalig only operate 16 h a day from 1 p.m. to 5 a.m. [42,43], while the proposed HRES can provide 24/7 access to electricity. It is suggested that Polillo and Patnanungan islands are chosen as the location of the two PV installations due to their large available land areas [44,45].

Electricity generation costs decreased upon transition from diesel-only systems to HRESs. An average LCOE decrease of 42.01% was observed in the Polillo islands. Clustering the HRESs may further decrease the LCOE if the islands are separated by shorter water distances. For example, the Po–Pa–Pt Jo configuration provided a 0.95% decrease in the configuration LCOE. It is more likely, however, that interconnection will increase the LCOE due to the higher capital cost of interconnection. The average configuration-level LCOE increase in the Polillo group of islands is 2.34%. In contrast, installation sizes of solar PV and Li-ion decreased sharply after interconnection. The average decrease was 6.66% and 8.71%, respectively, while the Po–Pa–Pt–Jo configuration yielded a 14.47% and 17.79% decrease, respectively. Higher decreases in generation costs and installation sizes are observed in larger islands [26–32].

Increasing the degree of interconnection generally increases the generation costs but results in a more reliable system. The standalone Jomalig system failed without the small generator, while the four island Po–Pa–Pt–Jo cluster still provided 24/7 energy access without the small and medium generators. Periods without sun have a minimal effect on generation cost. The failure of solar PV, however, increases the generation costs by 33.97% due to increased diesel reliance. Clustered HRESs

can operate despite component failure because power can be drawn from other components instead. However, this mode of operation will require an appropriate control strategy [46].

The results of this study show that it is economical to hybridize and interconnect large islands. This observation is consistent with the state of small island electrification projects in the Philippines. For example, FP Island, owned by the First Philippines Holdings Corp., will operate a total of 1.52 MW of solar PV in Garchitorena, Lahuy and Haponan islands in Caramoan, Camarines Sur [47,48]. WEnergy Global Fund also invested in a 1.4-MW solar PV, 2.4-MWh battery storage, and 1.2-MW diesel generator system in Cabuyagan island, Palawan [49]. Though the number of HRES projects continues to rise, such as that proposed by Siemens Gamesa in Puerto Galera Island, Mindoro [50], funding is still inaccessible [51] due to the low economic returns of off-grid projects [52]. Interconnecting nearby islands can decrease the capital costs per islands, thereby reducing the barrier to energy access [53].

The study provides several insights for future projects. Transitioning to HRESs can improve rural electrification by providing 24/7 access to electricity. Investing in the decentralized hybridization of larger islands is more feasible as it is easier to hybridize. A clustered HRES is another viable option, especially for islands that are close together and are separated by shorter water distance, since it also adds to the system reliability. Reliability slightly increases the cost of electricity; however, it provides greater energy security for the islands. To maximize the potential of the off-grid investment, cost consideration is still crucial [52].

5. Conclusions

In this work, a framework for the modeling of island interconnection was proposed. The framework can be easily adapted into existing microgrid simulation software, HOMER Pro. Interconnection between the Polillo group of islands was analyzed, and the following observations were found:

- Interconnection generally increases the system reliability and decreases installation sizes in exchange of a higher LCOE due to the high interconnection costs. If the islands are closer together, however, then the LCOE may decrease.
- The Po–Pa–Pt Jo configuration provides the lowest costs because the long Pt–Jo interconnection line is excluded. This configuration also yields a lower LCOE than the decentralized Po Pa Pt Jo configuration.
- The Po–Pa–Pt–Jo configuration offers better reliability and has the lowest required installations of solar PV and Li-ion due to the higher degree of interconnection. However, the LCOE is slightly higher than the decentralized configuration.
- The Po–Pa Pt Jo configuration has the lowest cable capital cost, which may be viable if cable capital costs were higher than estimated. The reduction in installation requirements is higher, however, due to the low degree of interconnection.
- Among the selected islands, Palasan is the best place to start investing in HRESs due to the low LCOE. The HRESs installed here can be expanded to the neighboring islands.

The expansion of this analysis to hundreds of Philippine off-grid islands will be performed in future work. A sensitivity analysis on the cost of submarine cables should also be performed. Lastly, the application of the proposed framework can be extended to any small off-grid islands worldwide.

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Nomenclature

CapEx	Capital Expenditures
DOE	Department of Energy
GHI	Global Horizontal Irradiance
HRES	Hybrid Renewable Energy System
LCOE	Levelized Cost of Electricity
NPC	Net Present Cost
NPC–SPUG	National Power Corporation–Small Power Utilities Group
OpEx	Operating Expenditures
PV	(Solar) Photovoltaic
RE	Renewable Energy
Po	Polillo Island
Pa	Palasan Island
Pt	Patnanungan Island
Jo	Jomalig Island

Appendix A

A comparison between the LCOE of diesel-only systems and HRESs is presented in Table A1. The transition from diesel generation to hybrid energy generation yields reduced generation costs and a high contribution of renewable energy. This justifies the sole consideration of HRESs in the study.

Table A1. Comparison of diesel-only systems and HRESs.

System	LCOE (USD/kWh)		Reduction (%)	RE-Share (%)
	Diesel	HRES		
Po	0.739	0.421	43.07	83.40
Pa	0.567	0.392	30.89	81.70
Pt	0.806	0.423	47.57	84.30
Jo	0.785	0.420	46.52	84.30
Po–Pa	0.879	0.462	47.41	82.60
Pa–Pt	0.878	0.454	48.29	83.50
Pt–Jo	0.907	0.426	53.03	84.60
Po–Pa–Pt	0.650	0.416	35.93	81.30
Pa–Pt–Jo	0.589	0.477	18.89	79.40
Po–Pa–Pt–Jo	0.581	0.430	25.97	77.20

Appendix B

The techno-economic parameters of the energy components are shown in Table A2.

Table A2. Techno-economic parameters used in the simulations.

Component	Parameter	Unit	Value
Solar PV ¹ [54]	CapEx	USD/kW	1800
	OpEx	USD/kW-y	140
	Efficiency	%	80
	Lifetime	y	25
Li-ion ¹ [54]	CapEx	USD/kWh	300
	OpEx	USD/kWh-y	0.10
	RT efficiency ²	%	90
	Max. DOD ³	%	80
	C-rate	kW/kWh	1
	Lifetime	y	15
Diesel ¹ [54]	CapEx	USD/kW	150
	OpEx	USD/kW-y	0.11
	Fuel Price	USD/L	1
	Lifetime	h	15,000
Project [55]	CapEx	USD	0
	OpEx	USD/y	0
	Discount rate	%	3.19
	Lifetime	y	20

¹ Adjusted to 2020 using price reduction rate from Bloomberg. ² Roundtrip efficiency. ³ Maximum depth of discharge.

Appendix C

Appendix C.1. Generation Profiles

The monthly average GHI profiles used by HOMER Pro are presented in Figure A1.

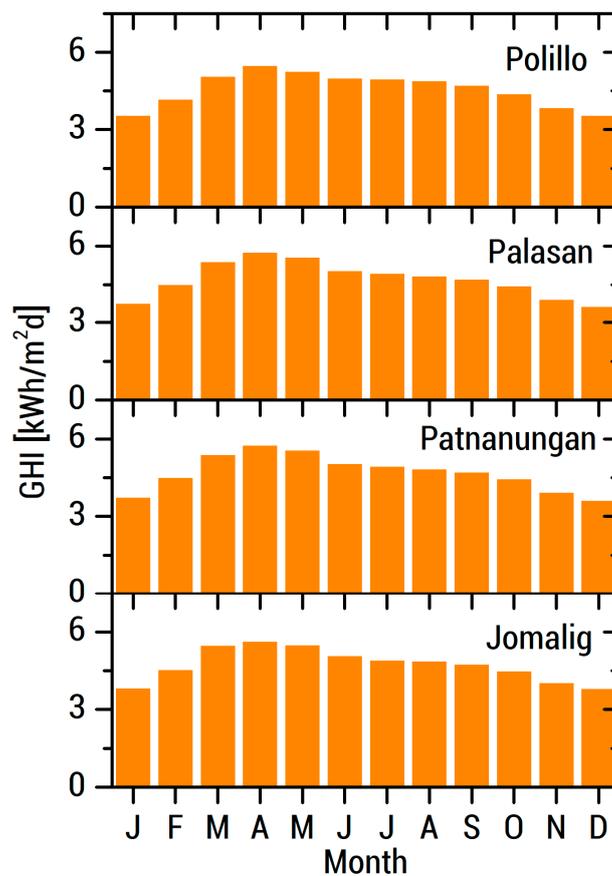


Figure A1. Monthly average global horizontal irradiance (GHI) profiles in the selected islands.

Appendix C.2. Demand Profiles

The peak demand from 2017 was extrapolated to 2020 at a load growth rate equal to each island's population growth rate. This was increased by 15% to account for power line losses [56]. The derived peak loads and a summary of each island are shown in Tables A3 and A4, respectively. To generate the load profile, a generic load profile (Figure A2) is scaled up to meet the peak load

Table A3. Forecasted peak loads of the islands and their respective population growth rates.

Island	Pop. Growth		Peak Load (kW)	
	Rate (%)	2017	2020	2020 + Losses
Polillo	1.61%	1708	1791	2060
Palasan	1.91%	41.24	43.71	50.27
Patnanungan	1.00%	427.61	440.62	506.71
Jomalig	1.43%	271.30	283.14	325.61

Table A4. Relevant parameters about each island.

Island	Coordinates	Existing Diesel (kW)	Peak Load (kW)	Annual Load (MWh)
Polillo	14.87° N; 121.94° E	4263	2061	10,236
Palasan	14.86° N; 122.04° E	0	50	250
Patnanungan	14.79° N; 122.19° E	1059	507	2517
Jomalig	14.70° N; 122.38° E	616	326	1617

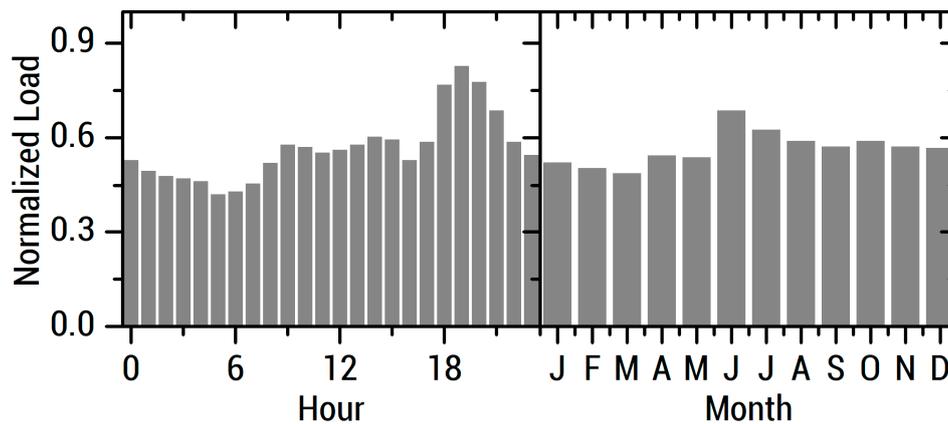


Figure A2. Daily and monthly average of the normalized load profile.

Appendix D

Consider an agglomeration T of HRES m each with an annual energy consumption E_m and an LCOE of $LCOE_m$. It is desired to determine the LCOE of the agglomeration $LCOE$ (Equation (A1)) in terms of the parameters given earlier. In Equation (A1), NPC and E refer to the NPC and annual energy consumption of the agglomeration.

$$LCOE = \frac{d(1+d)^N}{(1+d)^N - 1} \times \frac{NPC}{E} \quad (A1)$$

The NPC of the agglomeration is the sum of the net present cost of each HRES NPC_m (Equation (A2)). Similarly, the annual consumption of the agglomeration is the sum of the annual consumption of each HRES E_m (Equation (A3)).

$$NPC = \sum_{m \in T} NPC_m \quad (A2)$$

$$E = \sum_{m \in T} E_m \quad (A3)$$

The NPC of an HRES is related to its LCOE (Equation (A4)).

$$NPC_m = E_m \times LCOE_m \times \frac{(1+d)^N - 1}{d(1+d)^N} \quad (A4)$$

Substitute Equation (A4) into Equation (A2) to yield Equation (A5).

$$NPC = \frac{(1+d)^N - 1}{d(1+d)^N} \sum_{m \in T} E_m \times LCOE_m \quad (A5)$$

Finally, substitute Equation (A3) and Equation (A5) into Equation (A1) to yield Equation (A6). This equation states that the LCOE of an agglomeration is the average LCOE of each HRES weighted with respect to the annual energy consumption.

$$LCOE = \frac{\sum_{m \in T} E_m \times LCOE_m}{\sum_{m \in T} E_m} \quad (A6)$$

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