Title

Supplying not electrified island with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines

This is a pre-print of a paper published in “Energy”, Volume 202, 1 July 2020, 117670.

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1 Introduction

Universal electrification by 2030 was set as the 7th target under the UN’s Sustainable Development Goals (SDGs) framework [1]. Low-carbon technologies such as renewable energy (RE) are important means for achieving SDG7 [2], because environmental and social sustainability are implicit aspects of the SDG framework [3]. Rural and remote areas require electricity for socio-economic development although causal relationships are site specific and complex [4]. Additionally, providing access to electricity is of particular importance to the overall SDG framework as it positively correlates and facilitates advancing towards other SDGs [5].

Strategic energy access planning is required to advance toward SDG7 and utilize resources most efficiently [6]. Advanced software tools are needed to allow for energy access planning [6] and several examples of such tools have been developed and presented in the scientific literature [6], [7]. The presented tools allow for deriving key information for energy access planning, among other the electrification type (grid connection, mini-grid, stand-alone), system design, power generation costs and dispatch of off-grid systems, distribution grid network design and additional upstream generation requirements [6]. Results of such tools allow for different depth-of detail [6]: Prefeasibility studies indicate optimal electrification solutions for areas and customers clustered in raster cells of different sizes (e.g. km²). Examples have been presented for Sub-Saharan Africa [8], [9], Nigeria [10], Ethiopia [11] and Kenya [12]. Intermediate analysis tools add a further level of detail since individual villages or populated places are taken into account, grid network designs are retrieved and further technological constraints are considered. Such tools have been applied to Nigeria [13], [14] and Ghana [15] among other. Finally, tools considering detailed generation networks and designs provide the maximum level of detail by including detailed village grid layouts and introducing a large variety of technological constraints for power system design. Ciller and Lumbreras (2020) [6] identify only one existing tool providing such detail but do not present peer-reviewed articles. Geospatial software has been applied as essential and integrated part of many of the aforementioned tools or was utilized for gathering data (e.g. population distribution, renewable resources). This includes several tools applied for Africa on the prefeasibility level [7], [16], [17]. Furthermore, geospatial analysis was used for case studies in Timor Leste [18] and Nigeria [14] on the intermediate analysis level. The presented tools and case studies focus mainly on Sub-Saharan Africa given the large need for energy access interventions there. However, thereby the tools neglect other regions in need of energy access interventions like Southeast Asia and disregard the local specific conditions e.g. the large number of islands. A combined approach of geospatial analysis and energy system modelling was applied on a global scale to study the feasibility of RE integration into island grids [19] and for a classification regarding the RE potential on islands [20] but not specifically for the strategic planning of providing energy access. In the Philippines, the case study country of this paper, similar combined approaches were utilized to quantify the potential for upgrading diesel based island systems with RE [21] and to project costs for submarine cable connection [22]. However both studies consider pre-electrified islands. Overall these findings highlight that electrification planning tools are rarely designed and applied to regions outside Africa which reflects a research gap. Furthermore, a review study formulates research needs for the improvement of electrification planning tools including adding multi-criteria optimization, including more detailed year by year planning, adding further power generation technologies, improving grid network design and addressing uncertainties of input parameters [6]. Our study contributes to the research field with a detailed assessment of the not electrified island landscape of an understudied country, the Philippines, and a simulation of 100% RE based electrification pathways. Thereby, we address the identified research gap by focusing on a region outside Africa and address some of the research needs for improving electrification planning tools outlined earlier. We present a novel and combined approach based on geospatial data and energy system modelling which is replicable to case studies with similar boundary conditions. The approach can be assigned to the intermediate level as defined by [6] as single islands are considered and system designs are simulated based on a set of technical constraints. Finally, we develop and present an integrated geospatial and energy system analysis tool which is fundamental for effective electrification planning and facilitates to derive key information for large geographic areas [11]. We base our approach on similar studies presented for landlocked countries as presented in [8], [10–12], [18] and contribute with a methodological adaptation to the insular context of the Philippines.

In the Philippines universal electrification by 2022 was announced as target in the Philippine Energy Plan published by the Department of Energy [23]. Nevertheless, household electrification was at 89.6% as reported for 2016 with more than 2.36 million households lacking access to electricity [24]. More recent statistics for 2019 state the electrification rate of the Philippines at >95% reflecting a population of 5.2 million without access to electricity [25]. Reaching out to the remaining 5% and the “last mile” is challenging, given the heterogeneity of the country which is comprised of more than 7,600 islands [26]. Additionally, key information for energy access planning e.g. population statistics and resource availability is missing for many of the remote areas and small islands.

Currently islands which are supplied with electricity but not connected to the two centralized electricity systems are mostly supplied with diesel generators [21]. This leads to long power cuts due to the high costs of diesel power generation [27] and is therefore not a feasible solution for the electrification of the entire archipelago [28]. Furthermore, the Philippine economy, as a net importer of crude oil products, is sensitive to global market developments and a rising oil price negatively affect the national economy [29]. As a consequence renewable energy sources need to be utilized to supply an ever increasing demand and to comply with climate change mitigation objectives [30]. This is especially relevant since the Philippines are the most vulnerable country [31], in a region largely affected by climate change [32]. Therefore, providing sustainable energy access to remote and marginalized communities is crucial for improving living conditions [33] and strengthening resilience to climate change [34]. In conclusion sustainable electricity access planning should consider only RE technologies as supply source.

In order to reach the last mile electrification with renewable systems, an effective island electrification plan needs to be derived. This study presents a combined approach based on geospatial analysis and energy system modelling to reduce data paucity and the uncertainty regarding the number and location of not electrified islands and renewable energy potential. The approach enables to identify populated islands without electricity access, to derive information for energy modelling and to simulate 100% RE systems. Thereby, we address the following research questions:

A) Where are not electrified populated islands located?

B) What are specific population and renewable resource characteristics of the not electrified islands and how can the islands be grouped for energy access planning?

C) What are the techno-economically optimal supply options for certain island groups considering an 100% renewable combination of solar power, wind power and battery storage?

We introduce the research approach and methods in chapter 2. In chapter 3 we present the main findings of our consecutive approach separately for each step starting with geospatial analysis, cluster analysis and energy system modelling analysis. We discuss our approach and results in chapter 4 and conclude the paper with conclusions and policy recommendations in chapter 5.

2 Material and methods

This study applies a three-step approach for addressing the research questions as outlined in the introduction section. First, we conduct a geospatial analysis to identify not electrified islands. Second, we apply explorative cluster analysis to classify islands and to identify representative case study islands per cluster group. Third, we utilize open source energy system modelling to assess the potential for 100% RE systems for the case study islands.

2.1 Geospatial analysis

First, we determine islands lacking power supply by analysing transmission grid data and statistics on isolated island energy systems. Therefore, we apply geospatial analysis as it has been extensively applied for electrification planning in scientific studies [8], [11], [12], [18], [35]. Other researchers used spatial information on transmission grid extension and power plant location in comparable approaches for identifying not electrified areas [9], [10], [14]. Second, we apply novel and openly available geospatial data which allows for accurate population mapping and renewable resource assessment in remote and rural areas and has been applied by other scholars for similar purposes [36], [37]. The applied population data is utilized for energy access planning in land-locked countries [38] and for estimating island populations for assessing the potential of hybrid energy systems [39]. We conduct all geospatial analyses by using the open access geospatial software *QGIS* [40].

2.1.1 Identification of not electrified islands

We define islands without connection to the Philippine transmission grid and/or islands without power generation on site as relevant for the scope of this study. We consider such islands as "not electrified" although small-scale and informal electrification schemes such as solar-home systems (SHS) or small diesel/gasoline generators might be implemented on household scale. Our approach builds up on available information on grid extension and location of power plants: A geospatial dataset of the island contour for the entire Philippines provided by the National Mapping and Resource Information Authority of the Philippines (NAMRIA) serves as base map and provides information on the spatial extent of single islands [41]. This dataset reflects the most extensive inventory of land masses in the Philippines and contains more than 17,834 polygons each reflecting an island. However, a large number of those islands are uninhabited small rocks and other tiny land masses of few square meters. This explains the contrast to other stated quantities for Philippine islands e.g. 7,107 islands [42] or 7,641 islands [26]. Spatial data on the extent of the operational transmission grid network is derived from the grid operator (National Grid Cooperation of the Philippines) and digitalized for further analysis [43]. Spatial data on the location of power plants and island grids is taken from the Philippine Department of Energy (DoE) and digitalized for further analysis [44], [45]. Subsequently, all islands from the spatial island (polygon) dataset are selected and removed which are intersecting with the grid (line) dataset and/or with the power plant (point) dataset and can therefore be considered as supplied with electricity. The remaining islands are considered as "not electrified" and as relevant for further analysis.

2.1.2 Assessment of population and renewable resource availability

Following the identification of not electrified islands we quantify the inhabitants per islands as key information for electrification planning. We assess the population of not electrified islands by using population raster datasets. We apply the High Resolution Settlement Layer (HRSL) dataset [36], [46]. This dataset is based on population census and satellite imagery for the year 2015 and provides a specific population value for each raster cell (extent of 30 to 30 m). For the quantification of inhabitants per island we summarize the raster cell values for the extent of each island polygon using geospatial software "raster-statistics-for-polygons" function. Beside the population per island we assess the renewable resource availability for solar and wind power. For solar power we apply global horizontal irradiation (GHI) datasets providing mean kWh/m²/year for the period of 2007 - 2018 [47]. For wind power we apply datasets for wind speed in m/s at 50 m hub height for the period of 2008-2017 [48]. Both datasets are provided on a pixel scale of ~ 250 m. We derive the mean value of all raster cells covering a specific island using geospatial software “raster-statistics-for-polygon” function.

2.2 Cluster analysis

We apply cluster analysis as it is a widely applied method for pattern recognition in large datasets [49]. The objective of cluster analysis is to minimize intra-cluster variation and maximise the difference to other clusters. Different types of partitioning clustering methods are presented in the scientific literature: For example partitioning around medoids (PAM) [50] enabled to classify islands according to bioclimatic characteristics [51]. The widely applied k-means cluster analysis approach [52] was used for classifying islands according to their RE potential [20], economic potential for smart grids [53] and for assessing feasibility for smart energy systems on Philippine islands [54].

2.2.1 Partitioning clustering using PAM

We consider PAM as most appropriate for the scope of our study. In PAM each cluster is represented by the most central observation (medoid) with lowest average dissimilarity to all other observations in the cluster. In contrast to the k-means approach the cluster assignment per data point is based on the dissimilarity to the medoid and not the mean value of a cluster. Thereby, PAM is more robust to outliers and the medoids reflect the most representative observation for a cluster and serve as case study for its respective cluster.

PAM cluster analysis is implemented by using the open access statistical software package *R* [55], [56]. Prior to the main analysis the geospatial dataset is transformed for compatibility with *R.* Key parameter for clustering are population, mean GHI and mean WS per island given the objective of exploring the island landscape with regard to the aforementioned parameter. Since cluster analysis can be sensitive to missing values we eliminate all observations with one or more missing values. Subsequently, all values are transformed to z-scores to compensate for the differences in value ranges. We apply euclidian distance for measuring distances between data points. For identifying the optimum number of clusters we compute the average silhouette values and cluster sums of squares for each cluster solution in a cluster range between 1 and 10. Finally, we implement the cluster segmentation indicated by both indices. We then assign each island to its respective cluster group and identify the medoids for case study development.

2.3 Energy system simulation

We apply energy system modelling to assess the techno-economic potential of 100% RE systems for case study islands represented by the medoids of cluster groups. Energy system modelling is widely applied for simulating RE based electricity systems [57]. A variety of software tools exist to model hybrid energy systems [58], [59], which are considered as the most appropriate energy supply solution for islands [27], [60], [61]. HOMER Energy is a commonly used hybrid energy system assessment tool which has been applied for case studies all over the world [62–65], for the island context [66–70] and as well for the Philippines [71]. Other energy system simulation models were applied to cases studies in the Philippines, e.g. to assess the potential of RE for household electrification [72], to study the potential for RE integration in diesel based energy systems [21] and to compare the feasibility of supplying power to islands through submarine cable or hybrid energy systems [22]. We apply the open source energy system simulation tool Offgridders [73], [74] since HOMER is a proprietary software and does not allow for customisation of its internal computation method and requires license fees [58], which contradicts the scientific criteria of replicability, accessibility and reproducibility of research results and approaches [75]. However, we apply HOMER for the validation of the applied simulation tool.

2.3.1 Simulation model

The applied Offgridders energy system simulation tool founds on the python based Open Energy Modelling Framework (oemof), which allows to model various energy systems [75] in a transparent and replicable way [76]. The tool is available online including open access to the source code [77] and the model has been applied for large scale energy system modelling for Europe [78] as well as for a smaller case study for Nepal [79]. The energy model implemented categorizes the assets into three main groups: Sources which have output flows (PV, wind, shortage), sinks which have input flows (demand) and components which have both input and output flows i.e. transformers and battery storage. All parts are unilaterally connected through energy flows to balanced energy busses, i.e. an AC and DC feeder. The outline for the model applied for this study is illustrated in Figure 1.

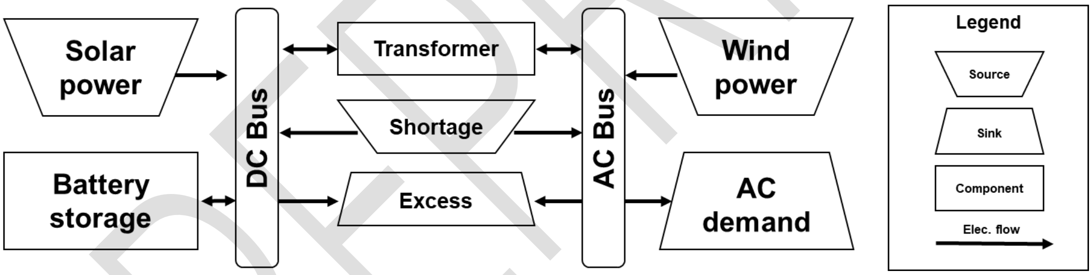

Figure 1: Sketch of energy system model, own illustration based on [74], [75].

Each oemof component is described by technical (efficiencies, constraints) and economic parameters (capital expenditures, operational expenditures, lifetime) presented in subsection 2.3.2. The energy model with the defined sources, sinks and components is transposed to a linear equation system, which is then solved using the *cbc* solver [80] with the objective to minimize annual energy supply costs. For that, both the asset capacities and their dispatch are optimized, the general concept of the tool is presented in more detail in [79].
The identification of the cost-optimal system configuration is based on the minimization of the annual electricity supply costs (Equation 1).

$$min\ Annual\ supply\ costs = \sum_i CAPEX_i * CRF_i + OPEX_i(t)$$

Equation 1: Applied formula for calculation of annual electricity supply costs.

In equation 1, CAPEX stands for capital expenditures for a source (USD), CRF stands for capital recovery factor, OPEX stands for operational expenditures (USD/kW/y, USD/kWh/y), i for each source considered (solar, wind, battery) and t for hourly time steps of the simulation period of one year.

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1}$$

Equation 2: Applied formula for the calculation of the CRF per technology.

In equation 2, the capital recovery factor per technology (CRF) is calculated based on the weighted average cost of capital (WACC) and individual component lifetime (N).

$$LCOE = \frac{\min Annual\ supply\ costs}{E_{supplied}}$$

Equation 3: Applied formula for calculation of the LCOE.

In equation 3, the levelized cost of electricity (LCOE) are calculated based on minimal annual supply costs (Equation 3), divided by the supplied electricity ($E_{supplied}$) per year.

$$E_{PV}(t) + E_{Wind}(t) + E_{Batt,out}(t) \cdot \eta_{out} + E_{short}(t) - E_{inv}(t) - E_{Batt,in} - E_{ex}(t) = E_D(t)$$

Equation 4: Dispatch function for energy system modelling.

Equation 4, describes the dispatch of assets which have to be utilized in such way to balance the electricity bus. In the equation E_i stands for energy flow from asset i [kWh], $E_{Batt,out}$ for battery discharge after discharge losses [kWh], $E_{Batt,in}$ for battery charge before charge losses [kWh], η for conversion efficiency, E_{short} for curtailed energy flow to balance out supply shortage [kWh], E_{ex} for energy flow into dumbed to balance out excess generation [kWh], E_D for energy demand (kWh).
We apply a temporal resolution of one year in hourly time steps. Thereby we take into account seasonal variation in resource availability and electricity demand (see subsection 2.3.2).

2.3.2 Input parameter

Renewable resource data (solar and wind), electricity demand and technical/economic parameter per component are required for the simulation of the case studies.
Renewable resource data is derived from the renewables.ninja project [81] which provides open access to hourly solar and wind resource data. For each case study island the island's centroid serve as location for the resource data download. The data provides hourly power output for solar and wind power plants for the reference year of 2014. Solar and wind resource data is based on weather datasets and satellite observations [82–84] and power outputs are calculated by a conversion model for solar power outputs [85] and a conversion model for wind power outputs [86]. For deriving hourly solar power outputs we apply a system loss of 10%, tilt angle of 10° and azimuth angle of 180° [87], [88]. For calculating hourly wind power outputs we apply a hub height of 30 meters for the XANT M21 turbine model given its suitability for micro grids.
Detailed forecasting of electricity demands is of high importance for appropriate electrification planning [89]. The temporal resolution of electricity demands is equally important to the overall electricity consumption due to the intermittence of renewable resources. Researchers have introduced models for projecting electricity demands based on statistics and/or household surveys to face the uncertainty of electricity demands in not electrified areas [14], [71], [90–92]. As extensive household surveys are

out of scope of this study we apply reported electricity demands and load profiles from the scientific literature. Lozano et al. [71] conducted a household survey for a small Philippine island to estimate electricity demands for a techno-economic assessment of a hybrid energy systems and finds an electricity demand of 0.43 kWh/day per island resident. Similar values of 0.34 kWh/day are found for a comparable RE based hybrid system in the Philippines [93], [94]. We apply the value of 0.43 kWh/day per island resident for estimating overall electricity demands since the reported case study reflects a small Philippine island. The daily electricity demand per case study is calculated based on the specific island population. The resulting energy demand per island is then distributed over load profiles reported for small island communities in the Philippines [21], [71] and a seasonal variation for the three main regions of the Philippines is incorporated as provided in [21].

Investment costs for RE technologies and battery storage systems have been falling significantly and are projected to decrease further [95], [96]. Nevertheless, uncertainty regarding investment costs remains high especially when considering to implement such technologies in remote island locations. We address this uncertainty by applying conservative cost assumptions and a variety of sensitivity analysis. Solar photovoltaic plants and wind power plants are characterized by capital expenditures, operational expenditures, lifetime and resource availability. The applied cost values for both technologies are based on recent RE power cost reports [97], however we consider lower costs for solar deployment since it is easier to ship to and assembly on remote islands. For the battery storage system we consider lithium-ion battery technology given the high efficiency, robustness and projected substantial future cost reductions [95], [98], [99]. Despite the promising projections we apply more conservative costs formerly reported for a study of Philippine islands [21] which are meeting the lower boundaries of cost projections in [100]. Additional parameters for lithium-ion batteries applied are a C-rate of 1, maximum depth of discharge of 80%, charging and discharging efficiencies of 97%, operational expenditures of 5 USD/kWh installed and component lifetime of 10 years [98]. Weighted average costs of capital (WACC) are an important factor especially with regard to high upfront costs required for RE development. Here, we find a value of 3.5% applied for a similar study [71]. However for our base case scenario we apply a higher value of 8% anticipating that financial institutions would assess high risks for financing the development of RE systems on remote islands. Finally, we apply a project lifetime of 20 years (all values are provided in Table 1).

Table 1: Applied input parameter for describing cluster characteristics and system components.

Parameter	**Unit**	**Value**	**Source**	**Parameter**	**Unit**	**Value**	**Source**
PV CAPEX	USD/kW	1500	adapted from [97]	Wind CAPEX	USD/kW	2500	adapted from [97]
PV OPEX	USD/kW/y	15		Wind OPEX	USD/kW/y	62.5	
Lifetime	years	20		Lifetime	years	20	
Battery capacity CAPEX	USD/kWh	250	[21], [100]	Max. depth of discharge (DoD)	%	80	[21], [100]
Battery power CAPEX	USD/kW	450		Charging efficiency	%	97	
Battery OPEX fix.	USD/kWh/y	5		Discharging efficiency	%	97	

C-rate (kW/kWh)	Ratio	1		Lifetime	years	10
WACC	%	8	[71]	Project lifetime	years	20

2.3.3 Energy system model validation and sensitivity analysis

We validate our energy model with the widely applied HOMER Energy software [101] by investigating a solar-battery system for an island selected randomly from the dataset. The island centroid serves for the resource download and the default community load provided in HOMER is applied excluding seasonal variation. The technical and economic parameter as presented in Table 1 are applied apart from OPEX which are excluded to enhance the comparability of validation results.

We apply sensitivity analyses to address uncertainties in RE technology investment costs, battery technology investment cost and capital cost (as WACC). This includes a variation of initial CAPEX in a range of -80% to +100% and 20% steps for solar, wind and battery CAPEX. Since capital costs are expected to significantly impact the economic potential we apply a wider range of 1.6% to 16% capital costs in 1.6% steps. Furthermore, we incorporate several reliability levels and assess the effect of power generation costs under annual supply shortage scenarios. We consider an annual electricity shortage range of 0 to 10% in 0.5% steps.

3 Results

3.1 Geospatial analysis

We identify 171 islands with connection to the electricity grid or power plants based on the geospatial approach outlined in subsection 2.1.1 and exclude these islands from further investigation. For the remaining more than 17,600 polygons reflecting land masses we assess the population as described in subsection 2.1.2. Thereby we identify 1920 islands as populated (population > 0) with an overall population of more than 734 thousand. This population reflects approx. 14% of the not electrified population of the Philippines taking into account recent estimations [25]. A more detailed overview on number of islands and overall population is provided for different population classes in Figure 2.

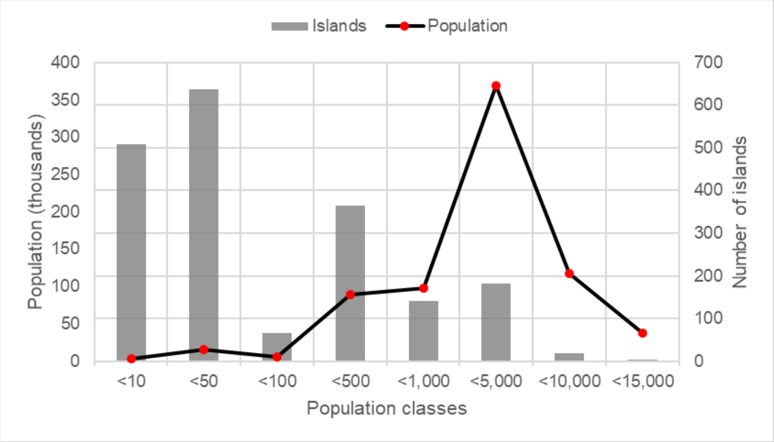

Figure 2: Overview on overall population and number of islands for not electrified Philippine islands.

A large number of more than 1,200 islands (population classes <10 to <100) have a very small population which summarize up to 23 thousand. The population classes of <500 to <5,000 comprise the bulk of the not electrified population on a smaller number of islands. Especially, focusing electrification efforts on islands between <1,000 and <5,000 can lead to considerable progress in providing energy access given the relatively high overall population. A significant share of the population lives on only 21 islands larger 5,000 inhabitants. More than 59% of the identified islands have a population lower than 50 (n = 1,146). We exclude these islands prior to the cluster analysis, since we consider SHS as more appropriate for the electrification of islands with very small populations and the focus of this study on 100% RE micro grid development. Through excluding the aforementioned islands the number of overall islands decreases to 774. However, the overall population only decreases by 2.4% to 716 thousand. For the remaining 774 islands the mean GHI and mean wind speed per year are calculated as outlined in section 2.1.2. No values can be derived for 125 islands due to data gaps. Finally, a dataset comprised of complete population and renewable resource information for 649 islands and a population of 650 thousand is consigned to the cluster analysis.

3.2 Cluster analysis

By applying the cluster analysis approach as outlined in subsection 2.2.1, we find four cluster as the optimal solution indicated by both indices through calculating average silhouette width and cluster sum of square for the applied cluster solution range of 1 to 10 clusters. The results for both indices are illustrated in Figure 3. Subsequently, we apply the suggested partitioning of the dataset into four clusters and assign each island to its respective cluster taking into account the distance to cluster medoids. Figure 4 presents the cluster partition through a cluster plot. Cluster one, three and four are more homogenous than cluster two, while cluster four shares characteristics of the other three clusters.

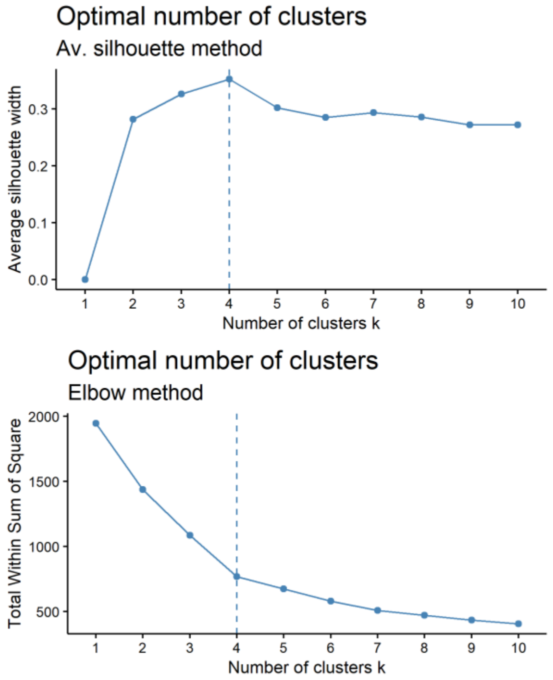

Figure 3: Results of average silhouette width (left) and cluster sum of square (right) for cluster solution between 1 10.

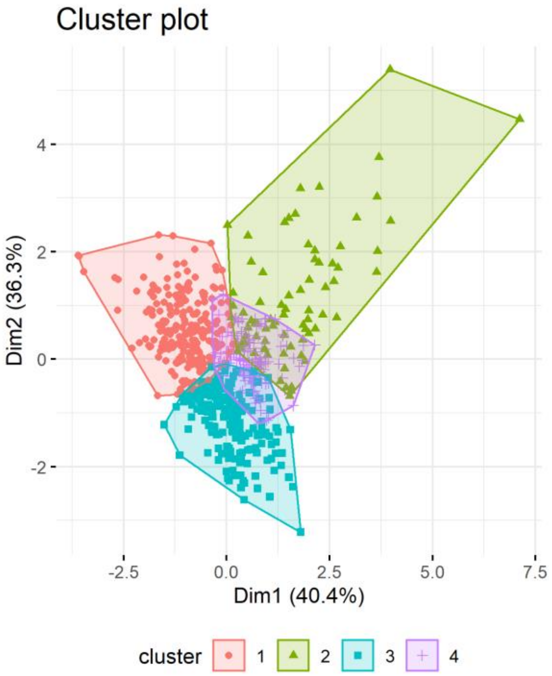

Figure 4: Cluster plot showing four cluster solution.

Table 2 provides information on number of islands and overall population per cluster group as well as population statistics and renewable resource data for the medoids islands. Cluster 1 groups the most islands (227) with a higher overall population (142 thousand). In contrast to that cluster 2 comprises only 76 islands but a much larger overall population of 314 thousand. Cluster 3 and 4 are characterized by comparable values in terms of number of islands (186 to 160) and overall population (96 thousand).

Table 2: Key characteristics of the three proposed cluster groups.

Cluster			**Medoid**					
Cluster (#)	N (#)	Total pop. (#)	Island name	Inhabitants (#)	Wind speed (m/s)	GHI (kWh/m²/y)	Lat.	Long.
1	227	142,888	Manipulon	471	5.4	1905.1	11.64	124.88
2	76	314,856	Talampulan	3454	3.7	1860.2	12.12	119.84
3	186	96,328	Poro	511	4.3	1776.2	11.64	124.88
4	160	96,032	Bunabunaan	479	2.9	1879.7	4.95	119.98

Cluster one, three and four comprise islands with smaller populations but clusters are distinguishable in resource availability: The first cluster represents the renewable resource richest islands with high average wind speed and high mean GHI. Cluster three islands are less rich in renewable resources and are characterized by the lowest mean GHI values. The fourth cluster is defined by the lowest mean wind speed values but holds higher mean GHI values. The second cluster group is more heterogeneous in renewable resource availability as it primarily groups islands with larger populations.

Figure 5 shows the distribution of the island clusters and medoids (which are presented as case studies) in the Philippines. On a geographical scale islands of cluster 1 are predominantly located in the Central and Northern parts of the Philippines. Islands of cluster 3 are distributed over the country with a small bias towards the East. In contrast to that islands of cluster 4 are mainly located in the South of the country. This reflects the difference between available wind power resources in the northern part and lower availability of such resources in the southern parts as GHI values differ in a small value range. The islands of cluster group 2 are spread over the entire archipelago as population is the key criteria for assigning islands in this cluster group. Finally, we select the island representing the cluster medoid as case study for more detailed analysis in the energy system modelling approach. Case studies for cluster 1 and 3 are located in the Visayas region in the central Philippines. The case study for cluster 2 is located north of Palawan in the western part of the Philippines and the case study of cluster 4 is found in the Sulu Sea in the most southern part of the country.

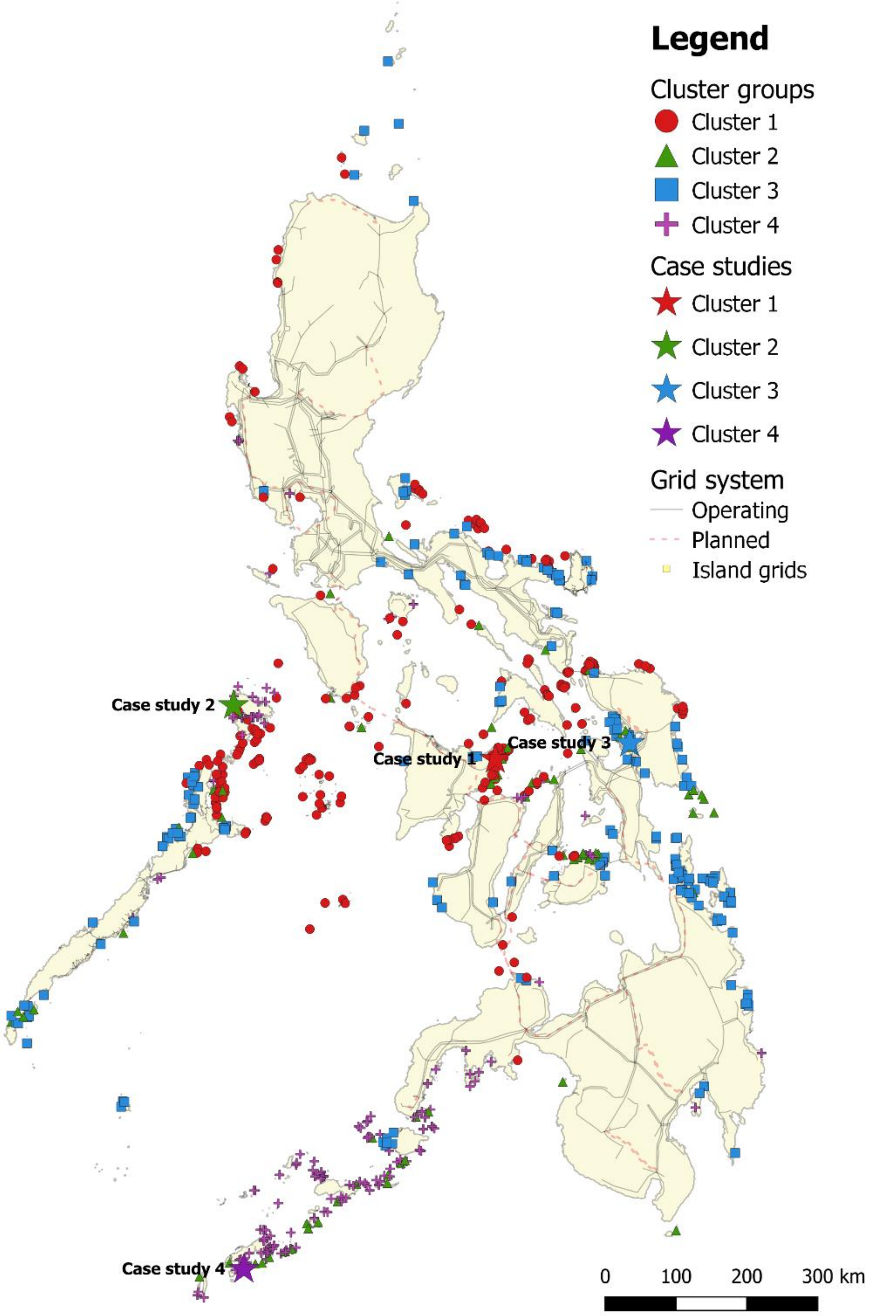

Figure 5: Overview map showing island per cluster group, case study islands, and grid infrastructure.

3.3 Energy system simulation

3.3.1 Validation of energy system tool

Prior to applying the Offgridders energy system model we conduct a validation with HOMER as described in 2.3.3. We limit the considered technologies to solar power and battery storage to ease the comparison of both tools. Additionally, we implement a default community load with a distinctive evening peak of 12 kW and derive solar resource data for one randomly selected Philippine island. The results of the validation are presented in Table 3 and reveal that cost-optimized system design and power generation costs for both models are in a close range. The Offgridders tool indicates a slightly larger capacity which leads to slightly higher LCOE. A difference between both models can be found in the battery storage dispatch: A larger amount of generated electricity is charged and discharged to and from the battery storage in HOMER while the share of excess electricity is higher in Offgridders. However, we conclude that the difference in both models is acceptable and that Offgridders delivers sufficient results for our approach.

Table 3: Validation of the applied Offgridders simulation tool with HOMER.

Parameter	Unit	HOMER	Offgridders	Difference (%)
Annual demand	(kWh)	62,050	62,050	0.0%
Peak demand	(kW)	12	12	0.0%
PV capacity	(kWp)	118.9	124.0	4.1%
PV output	(kWh)	167,951.5	175,166.5	4.1%
Battery capacity	(kW/kWh)	136.0	137.0	0.7%
Battery discharge	(% of PV output)	0.19	0.18	-0.8%
Battery charge	(% of PV output)	0.21	0.19	-1.8%
Excess electricity	(%)	0.59	0.62	3.0%
LCOE	(USD/kWh)	0.522	0.536	2.6%

3.3.2 Input parameter

We present the derived resource data for the four case study islands in Figure 6 in mean power output in kWh/kWp per day over one reference year. We can observe that the case study islands for cluster 1 to 3 have very similar profiles in contrast to cluster 4. For cluster 1 we find the highest resource availability with 1,296 kWh/kWp/y for solar power and 2,193 kWh/kWp/y for wind power. Followed by cluster 2 (1,379 kWh/kWp/y and 2,032 kWh/kWp/y) and cluster 3 (1,294 kWh/kWp/y and 1,928 kWh/kWp/y). The derived resource data reflect the tendencies found in the cluster analysis although cluster 2 holds higher resources than predicted. Probably the use of different datasets or different hub heights for wind speed assessment causes these deviations. For the wind power resources of all three cluster it is noticeable that resources are very low for considerable periods of the year. For the case study for cluster 4 we notice the high solar resource availability (1,325 kWh/kWp/y) and absence of wind power resources despite short periods of the year (969 kWh/kWp/y).

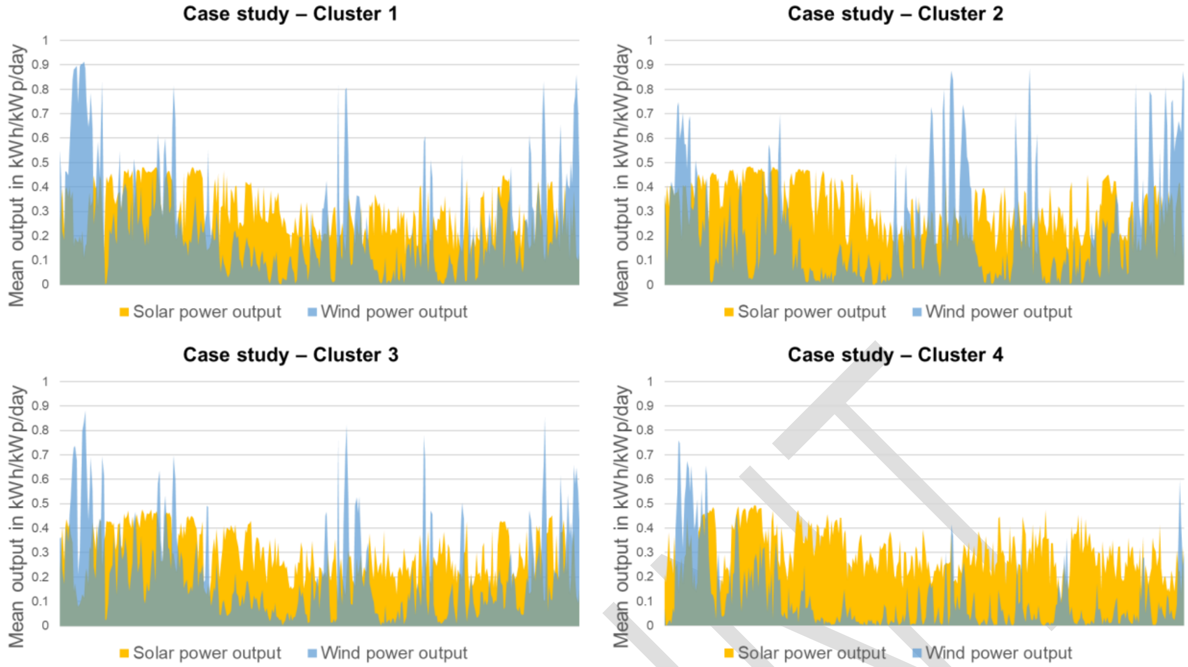

Figure 6: Solar and wind mean power output in kWh/kWp per day for the four applied case study islands.

The electricity demands applied for assessing 100% RE energy system potential are visualized in Figure 7. We apply the load profile presented by Lozano et al. [71] for the case study islands of cluster 1, 3 and 4 since the island populations are very small. For the case study island of cluster 2, we apply a load profile presented by Bertheau and Blechinger for islands with a peak demand larger 100 kW [21]. Since islands of cluster 2 have a larger population and more economic activity can be expected there. Finally, we append the daily load profiles to yearly load profiles and add seasonal variation in demands for different regions of the Philippines as presented by [21]. All load profiles peak in the evening hours which is typical for rural electricity loads [91]. Average demands are low for case study 1, 3 and 4 with 0.52 of the peak load whereas cluster 2 islands have a higher average demand of 0.69 based on higher economic activity and island area.

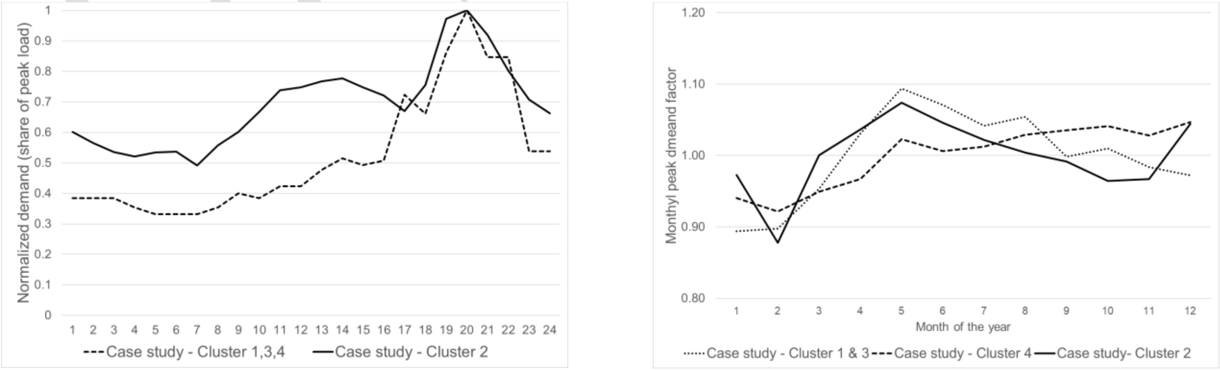

Figure 7: Normalized electricity demand (left) applied for case study islands based on [21], [71] and monthly variation in peak demands applied for each case study island based on [21].

3.3.3 Simulation results

For each case study island we apply the scenarios and sensitivity analyses outlined in subsection 2.3.3 with the input parameters presented in subsection 2.3.2. Table 4 provides the energy system simulation results for each case study island. We find LCOE in a range of 0.53 to 0.61 USD/kWh. This would allow for interruption-free and entirely renewable power supply on the islands and would comply with the SDG#7 targets. The reliability of the 100% RE systems comes at a considerable price: Since the energy system components are dimensioned to supply the demand even in the worst-case-scenario of the year (low RE resources and high demand) the power capacities are oversized compared to the typical daily electricity demand. Consequently, a considerable share of the generated electricity is dumped (range of 55% to 61%). However, the costs are still below retail costs charged for environmentally harmful diesel power reported in the scientific literature [71], [102]. In terms of the technology share we find solar power in combination with battery storage as the essential components of the cost-optimal system configurations. Solar power capacities to be installed are in a range of 6 to 8 above the peak demand and battery capacities are in a range of 0.79 – 0.85 of the daily energy demand. Wind power capacities are a part of the cost-optimized solution although capacities are small compared to the other technologies. However, the effect of such small capacities on power generation costs in a 100% RE system can be significant and offsets up to 0.2 USD/kWh compared to solar-battery systems. The economic advantage of wind power is the replacement of substantial battery storage capacities and thereby the reduction of power generation costs. A disadvantage of wind power lays in the seasonality of wind resources (as presented in subsection 3.3.2) which limits wind power to a supplementary power source. The concurrence of solar and wind power capacities is a decisive factor for the system design and results in lower wind power capacities for case study 1 (higher concurrence) than expected compared to case study 4 (lower concurrence) although higher wind resources are available.

Sensitivity analyses reveal the effect of cost variation on LCOE and installed capacities: A variation in Solar CAPEX of -80% to +100% shows a significant impact on LCOE with a spread of -0.18 to +0.22 USD/kWh since solar power is the essential part of 100% RE systems (Figure 8). With increasing CAPEX the solar capacities decrease while battery capacities significantly grow. Lower solar CAPEX have a lower effect on system capacities and solar capacities increase only for case study 2 and 4 replacing wind power capacities. Variation in Wind CAPEX affects the LCOE in a smaller range of +/- 0.05 USD/kWh as wind capacities have a supplementary role and solar capacities generate the bulk of required electricity. Wind power capacities change little with CAPEX variation apart from the 80% reduction scenario which affects a large growth of wind capacities replacing a part of solar capacities in case study 1 and 2 (Figure 9). A large LCOE spread between -0.28 to +0.24 USD/kWh is found for the battery CAPEX sensitivity analysis (Figure 10). Hence, battery CAPEX is the most influential parameter on LCOE as large capacities are required in a 100% RE system to shift generated electricity to the time of demand. Additionally periods of low renewable resource availability need to be bypassed with large capacities. Rising battery CAPEX have no effect on the installed capacities. Lower battery CAPEX show similar results as for increasing solar CAPEX: Larger battery capacities are part of the cost-optimized system while solar capacities decrease. Figure 11 shows the effect of different WACC to the LCOE, which is affecting each case study in a similar way. The difference in costs range is large with -0.19 to +0.30 USD/kWh. The effect on capacities is very low and only change the system design for case study 1 above a WACC of 14.4% (lower solar capacity – larger battery capacity). We apply sensitivity analysis for reliability levels in a range of 100% to 90% to study the impact on LCOE and installed capacities (Figure 12). The lowest reliability level of 90% allow for LCOE reduction between 0.17 – 0.22 USD/kWh. The cost reduction is realized as much lower capacities need to be installed in a range of -33% to -45%. The sensitivity analysis further reveals that a reduction of the reliability level by 0.5% has the largest impact with an average LCOE reduction of 16%. Reducing the reliability level further by 0.5% to a 99% reliability level allows for an additional average LCOE reduction of 3.4%. With further steps the LCOE reduction potential increases in a slower pace. This finding indicates that the optimal solution between reducing costs and maintaining high supply reliability levels can be achieved by applying a 99% reliability level.

Table 4: Findings for base scenarios applied to the four case study islands.

Case study	LCOE (USD/kWh)	Annual supply costs (USD)	Peak demand (kW)	Annual demand (kWh)	Solar capacity (kW)	Wind capacity (kW)	Battery capacity (kWh/kW)	Reliability (% of demand)	RE share (%)	Solar power yield (kWh)	Wind power yield (kWh)	Excess electricity (% of total)
Cluster1	0.60	44,493	17.6	73,842	149.3	3.0	169.1	100	100	193,489	6,653	61.8%
Cluster2	0.53	286,884	95.7	542,105	850.5	48.7	1177.7	100	100	1,172,706	98,923	56.1%
Cluster3	0.56	45,186	18.8	80,201	125.5	11.3	187.7	100	100	162,540	21,872	55.2%
Cluster4	0.61	45,983	17.3	75,282	124.9	18.2	175.9	100	100	165,685	17,665	57.7%

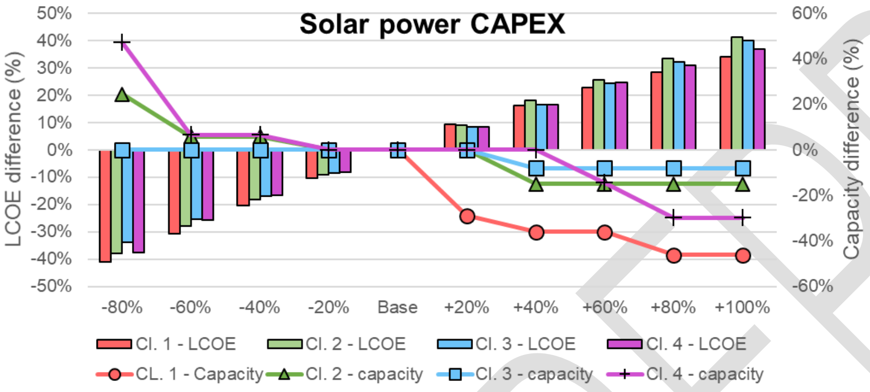

Figure 8: Sensitivity analysis for Solar CAPEX.

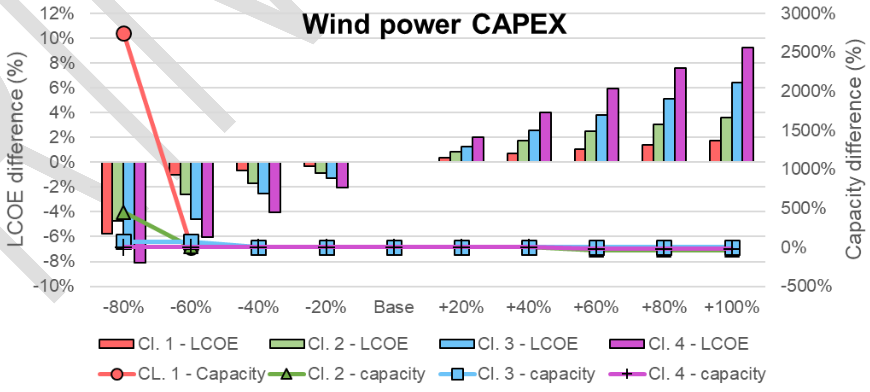

Figure 9: Sensitivity analysis for Wind CAPEX.

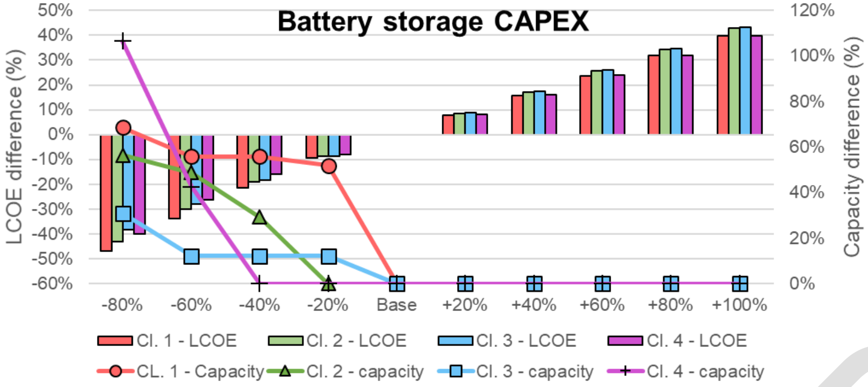

Figure 10: Sensitivity analysis for Battery CAPEX.

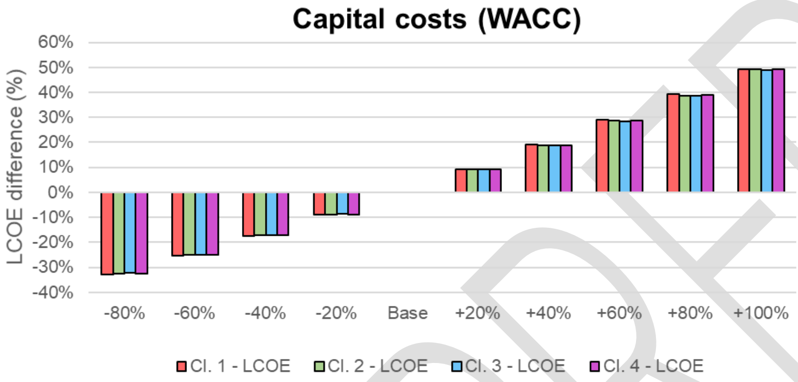

Figure 11: Sensitivity analysis for capital costs.

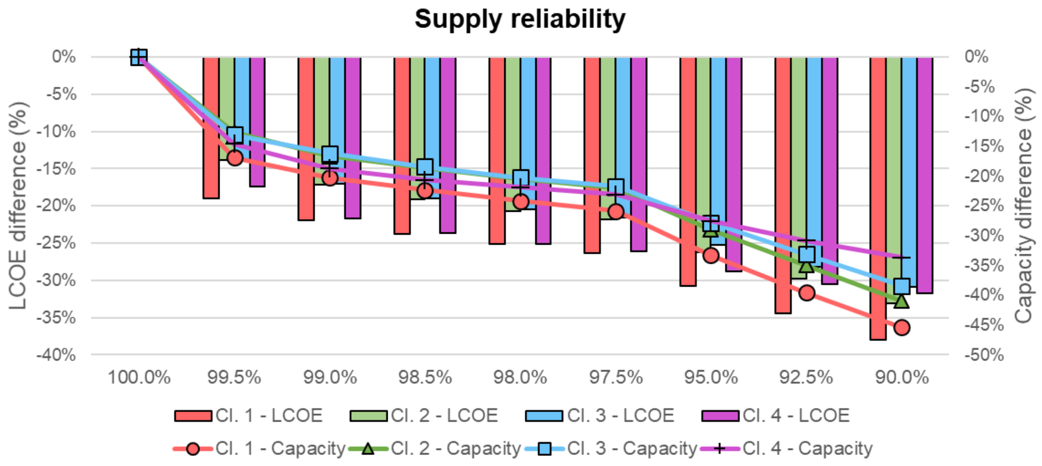

Figure 12: Sensitivity analysis for reliability in terms of annual supplied electricity.

For a 99% reliability level we find power generation costs in a range of 0.43 -0.47 USD/kWh which are significantly lower than for the 100% reliability level and are closer to the cost range for utility scale diesel power generation costs taking into account diesel fuel growth projections [21], [103]. The technology composition is affected by reducing reliability levels: When applying a reliability level of 99% the PV capacities are reduced in a range of 25% to 45%, whereas battery capacities are reduced only by 3% to 10%. Wind power capacities have more diverse patterns as capacities are reduced by 8% and 12% for case study 2 and 3. Whereas for the more extreme case study 1 (high wind resources) the capacities increase by factor 3 and case study 4 (low wind resources) the capacities shrink by 75%. By allowing a 99% reliability level the seasonality of wind resources is not as disadvantageous anymore in cluster 1 and affects the split between solar and wind capacities. Whereas lower wind capacities are required to overcome the short periods of the year with low solar resource availability for case study 4. Practically, a reliability level of 99% would lead to power curtailment in 205, 203, 211 and 163 hours of the year for case study 1 - 4 respectively. However, for an average share of 26% of that period the curtailment is lower than 30% of the hourly demand so that critical loads could potentially still be supplied. Hence, we consider the 99% reliability level as acceptable for this study as it would still improve the status quo of few service hours on many islands [21], [28], [71], [102]. The share of excess electricity is reduced to 39% - 42% which increases the economic feasibility. Nevertheless, the share of excess electricity remains high and future research should focus on how to utilize excess electricity e.g. for water purification or water desalination.

Table 5: Scaling of case study results to not electrified island landscape.

Medoid	Solar capacity/ capita	Battery capacity/ capita	Wind capacity/ capita	Cluster	Total pop. (#)	Solar capacity required	Battery capacity required	Wind capacity required
(#)	(kWp)	(kWh)	(kWp)	(#)	(#)	(kWp)	(kWh)	(kWp)
Case study 1	0.17	0.34	0.02	1	142,888	24,669	48,752	3,026
Case study 2	0.18	0.31	0.01	2	314,856	57,110	96,635	4,095
Case study 3	0.18	0.34	0.02	3	96,328	17,051	32,437	1,873
Case study 4	0.19	0.35	0.01	4	96,032	18,720	34,061	900
Sum					650,104	117,550	211,886	9,894

Finally, we apply the required per capita capacities to achieve universal and 100% RE based electrification at a 99% supply reliability level and scale the capacity requirement to the entire not electrified landscape of the Philippines. Based on our approach and the applied input parameter we project a required power capacity of at least 117 MWp solar capacity, 211 MWh battery storage capacity and 9.8 MWp wind capacity to provide energy access to the considered islands (Table 5).

4 Discussion

Our results for generation costs, supply shortage levels and share of excess electricity are in line with findings of other researchers: Lozano et al. [71] find LCOE of 0.39 USD/kWh for 100% RE systems with excess electricity of 39.3% and a shortage level of 91.4%. Katsaprakakis and Voumvoulakis [103] compute power generation costs of 0.29 EUR/kWh for a 100% RE scenario on the Greek island Sifnos considering pumped-hydro storage as cost-efficient electricity storage option. Another case study for a Greek island finds a 100% RE system possible at costs of 0.61 EUR/kWh [104]. Lau et al. [105] simulate cost of 0.64 USD/kWh and an excess electricity share of 30% for the simulation of a 100% RE system on a Malaysian island case study. It need to be taken in consideration that costs largely depend on the applied economic and technical parameters:

The sensitivity analysis revealed the following most important tasks for improving the economic feasibility of 100% RE systems on islands: (1) Decreasing battery storage costs, (2) lowering capital costs, (3) allowing power rationalization and (4) utilizing excess electricity.

For 1, battery storage costs are projected to decrease substantially [95] and would reduce investment costs significantly. However, for 2 the lack of access to finance is a specific challenge for RE development in the Philippines [94] and high risks of RE development increase capital costs in developing countries [106]. Therefore, de-risking investments for the electrification of small islands is a major task for Philippine policy makers and investments should be partly shouldered by government funds in case of low interest of the private sector. For 3, allowing supply shortages through intelligent demand side management and dropping of non-critical loads holds potential to reduce costs [107]. Operational models for reducing loads through demand response have been presented in the scientific literature [108], [109]. Implementing such models as well as weather and load forecasting models can allow for pre-scheduling of load shedding in the proposed energy systems [110].

For 4, the utilization of excess electricity as deferrable loads can increase the viability of a 100% RE system and provide further benefits to island communities. Examples for potential utilization of electricity in the island context are water purification, water desalination, cold storage or ice making as researchers find high household expenditures for clean portable water [71] and fishing as main source of income of many households on remote Philippine islands [94]. Additionally, such appliances can potentially replace or reduce battery storage capacities [111]. Future studies should focus on the feasibility of integrating such systems and the impact on costs and potential revenue streams.

Despite the promising findings the specific implications of wider deployment of the proposed energy system solutions need to be taken into consideration carefully: Availability of land for RE development can be a challenge especially on small islands

[71], [112]. Furthermore, the impact of providing access to electricity to the island communities is complex [4] and communities should be integrated into the development and design process [94]. Although 100% RE systems are clearly advantageous over diesel fuel systems with regard to life cycle assessment [113], the environmental impact of RE micro grids especially with substantial Li-ion battery storage capacities as presented here need to be further investigated [99], [114]. Nevertheless, Aberilla et al. [112] identified household scale PV installations in combination with community-scale wind power and Li-ion batteries as most environmentally sound solution for rural communities in the Philippines. Finally, RE system design need to account for the occurrence of frequent extreme weather events in the Philippines [115]. Future studies should consider the resilience of system designs [116] and investigate into the feasibility of containerized solutions for robustness, capability to shelter sensible components in extreme weather events, multifunction (energy supply and water purification units), transportability and cost reduction potential [117].

The overall research approach could be improved through including more detailed input data if available and considering further RE technologies. In the following key assumptions are listed which could increase the robustness of the results and should be considered in future studies:

- First, a number of the considered islands may be already supplied with electricity through small community networks or household solutions. Official statistics about such systems covering the entire country would improve the database for this approach. Potentially, the analysis of recent and high-resolution night light satellite imagery could facilitate to gain a more accurate overview on not electrified islands.
- Second, cluster analysis depends on complete datasets and adding or removing relevant missing values potentially affects the cluster split and assignment. Filling the missing values with accurate data could improve the research findings.
- Third, for the energy system modelling approach we limit the technology selection to solar and wind power in combination with battery storage. Taking into account further low-carbon technologies (e.g. biomass) could enhance the findings and improve the implications for policy makers. Especially, the integration of less intermittent and more schedulable renewable generation technologies such as biogas from agricultural residues [118] could reveal further development options.

5 Conclusion

Finally, we can state that the research questions outlined in the introduction chapter have been addressed: We find 1,920 not electrified and populated islands of which we select 649 with a population larger 50 and complete resource datasets for further analysis. PAM cluster analysis indicates an optimal split of four island groups. Three cluster groups comprise the majority of islands (88%) and are characterized by small populations of around 500. These cluster groups differ in resource availability: While the first cluster group shows both high solar and wind resource availability, the second cluster is characterized by lower solar resources and the last cluster by lower wind resources. The fourth group consists of 76 islands with a larger population and average resource availability. Cluster medoids serve as case study for assessing the feasibility of 100% RE systems. Here, we find power generation costs in a range of 0.53 to 0.61 USD/kWh for systems with a 100% reliability. Solar power in combination with battery storage is the essential component of cost-optimal system configurations while wind power capacities are supplementary. Variation in battery CAPEX and WACC affect power generation costs stronger than variation in solar and wind CAPEX. Reducing the reliability level can reduce power generation costs significantly as required capacity and the amount of excess electricity decrease. The findings for the four case studies are generalizable to not electrified island landscape of the Philippines as we can assume little differences in cost and demand parameters and we found a large homogeneity in solar resource availability. For a 100% RE based electrification on a 99% reliability level a capacity of 118 MWp solar power, 212 MWh battery capacity and 10 MWp wind capacity is required. Total investments would sum up to 350 million USD under the applied cost assumption but would only require 537 USD on a per capita basis.

Finally, we conclude with the following key findings for the rapid electrification of the Philippine archipelago: First, 100% RE systems are a suitable option for electrification and could allow a high energy autonomy and little operational costs. Since huge upfront investments are required low capital costs are key to wider deployment. This problem needs to be urgently addressed by policy makers and financing institutions. Especially development loans with lower interest rates and lower revenue expectations are required. Second, allowing for electricity shortages enables significantly lower costs while maintaining a reliability level above the status quo. Consequently, micro grids need to be equipped with intelligent management software to observe short-term resource availability and facilitate power rationalization in the event of shortages. Third, 100% RE systems are characterized by a high share of excess electricity. The usage of such excess electricity offers an opportunity for further cost reduction and improvement of the operational model. Future policy and research efforts should focus on economic aspects (financing products), technical aspects (power rationalization) and operational aspects (use of excess electricity) for the development of 100% RE systems.

Acknowledgement

The author thank the Reiner Lemoine-Foundation for co-financing this research work. Additionally, the author also thanks Philipp Blechinger, Martha Hoffmann, Karoline Gerbatsch and Setu Pelz for methodological support and proof-reading.

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