Exploring requirements for sustainable energy supply planning with regard to climate resilience of Southeast Asian islands

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Abstract

Southeast Asia is one of the regions most affected by impacts of climate change underlying the urgency to build resilience especially for remote and isolated island communities. Moreover, these islands face the problem of expensive and unreliable electricity supply. The large number of island communities further magnifies the difficulty of reaching universal sustainable electricity supply. Off-grid electrification technologies promise to tackle this challenge entailing high investments yet also market potential. Currently both aspects – electricity access and climate resilience - are barely linked in electrification planning. Energy planning in a region highly affected by climate change requires integrative planning considering these risks. Here, to enhance integrative planning, we study the status quo of energy access and risk exposure of non-electrified Southeast Asian islands. We identify 1,932 islands with a population greater than 21 million having limited access to electricity. Our study reveals three risk-specific island archetypes, which need different technical measures to enhance climate resiliency of future electricity systems. We conclude that future energy planning in Southeast Asia requires climate resilience as an additional planning dimension. The identified cluster groups serve as a blueprint for decision makers to support measures improving energy systems’ resilience avoiding expensive re-investments in the future.

1 Introduction

Southeast Asia is one of the regions most affected by the impacts of climate change [1]. This is especially true for remote communities located on the numerous small islands in the region. The latest world risk report identified Southeast Asia as one of the five global hot spots of disaster risk [2]. Besides floods, droughts, landslides, cyclones [1] and sea-level rise [3], the alteration of weather patterns like the monsoon poses a big threat to the livelihoods of Southeast Asian nations [4]. As a consequence Asia and Southeast Asia account for most of the world's disaster related fatalities [5]. Five of the eleven Southeast Asian countries have a very high world risk index (rank 3 Philippines, rank 8 Brunei, rank 12 Cambodia, rank 13 Timor Leste, rank 25 Vietnam) and two a high index (rank 36 Indonesia, rank 64 Myanmar) [2].

The National Intelligence Council (NIC) states in their report "Southeast Asia and Pacific Islands: The Impact of Climate Change to 2030" that the region is exposed to sea-level rise, severe coastal erosion, projected increases in cyclone intensity, rising surface temperatures and increased precipitation or droughts [6]. The magnitude of these challenges varies within the region: During the period 1993-2001 for example, the largest increases in sea-level (15-25 mm per year) occurred near Indonesia and the Philippines, while only moderate changes (0-10 mm per year) occurred along the coasts of Thailand, Cambodia and Vietnam [6].

Most Southeast Asian countries (except Laos) encompass long coast lines or are island states. The NIC report emphasizes that coastal regions are amongst the most at-risk areas for the impacts of climate change due to their prevalence and high population density [6]. Especially, highly urbanized areas along the coastline are under threat [7]. Ecosystems that helped to protect coastal areas and their inhabitants, such as mangroves and coral reefs are themselves highly impacted by climate change [6]. Indonesia and the Philippines as the two archipelago states have a high number of people at risk from sea-level rise [3]. Projections show that the number of people at risk will dramatically increase by 2050 (Indonesia from 13.0 Million to 20.9 Million; Philippines from 6.5 to 13.6 Million) [3].

In addition, Southeast Asian islands face the problem of limited and unreliable supply of electricity [8]. Looking at the issue of electricity access in Southeast Asia we can see two main dimensions: the first is that 65 million people currently have no access to electricity and the second is that many millions only have access to sub-par connections, relying on costly and polluting diesel generators to provide power [9]. Both situations hinder the ability to achieve the sustainable development goal (SDG) 7: Access to sustainable energy supply [10]. Regional policy makers have recognized this problem and put strong efforts on improving the supply situation on remote islands. Even in its conservative New Policies Scenario, the International Energy Agency (IEA) estimates that all countries in Southeast Asia will achieve universal access by the early 2030s [9]. To reach this goal it is expected that $14 billion need to be spent [11]. On the technical side it is estimated that 40% of the population will be connected via grid extensions, one third via mini-grids and the remainder via small-scale off-grid solutions such as solar home systems [9]. The two island states Indonesia and the Philippines will reach about 75% of their off-grid population with mini-grids [11]. All energy sources play crucial roles, but renewables are of special importance for electrifying remote areas, providing a viable alternative to expensive diesel generators [9]. These facts underlie the region's high market potential and upcoming investments to connect Southeast Asia's last mile.

Renewable energy (RE) holds significant potential on islands given the limited access to conventional sources due to the many islands' remoteness, small land area and degree of isolation [12]. Kuang et al. (2016) underline that hybrid electricity systems based on RE technologies are one of the most feasible solutions for supplying islands with electricity [12]. However, small scale island systems are fragile and require a robust design to increase resilience to natural or economic impacts [13]. Neves et al. (2014) presented an overview of hybrid electricity system case studies in which different RE and conventional technologies were applied and underline the necessity of more comprehensive and integrative energy access planning [14]. Additionally, the feasibility of energy systems with high RE shares has been studied for several island case studies to showcase the ability to adapt and mitigate to climate change by decarbonizing the energy sector [15]. A high techno-economic potential of RE based hybrid systems, was identified for the focus region by Blechinger et al. (2016) and were confirmed by Meschede et al. (2016), who applied a cluster analysis for highlighting the RE potential for islands on a global scale [8], [16].

Given that both climate change impacts and the electrification challenge are crucial issues for Southeast Asian islands, it becomes obvious that integrated planning is necessary for the region’s sustainable development. The National Intelligence Council of the United States for example states that the “[electric power] sector is itself vulnerable to projected changes in climate” [6] and the “[…] Electric power in Asia and the Pacific is […] a vulnerable sector in a vulnerable region” [6]. If electrification planning is to withstand current and future climatic changes, it is necessary to consider these changes in technical designs and integrate social structures and adaptation needs on the islands into the planning procedures [17]. According to the Asian Development Bank (ADB) “Electric power investment decisions have long lead times and long-lasting effects, as power plants and grids often last for 40 years or more. This explains the need to assess the potential impacts of climate change on such infrastructure, to identify the nature and effects of possible adaptation options and to assess the technical and economic viability of these options” [18].

It is therefore a significant weakness that both aspects – electricity access and climate resilience - are barely linked to current adaptation and electrification strategy planning. The missing link becomes clear while screening current literature. A review on the topic compiled by Perera et al. (2015) concludes that “only a few” documents contained “evidence demonstrating the link all the way through from access to energy to adaptation and building resilience to climate change and climate variability” [19]. Ebinger et al. (2011) also emphasize the importance of integrated-risk based planning processes e.g. in the energy sector to address occurring climate change impacts and build resilience [20]. At the same time they state that the knowledge base is still nascent [20]. Another review conducted by Schaeffner et al. (2012) reveals the various impacts of climate change on energy systems and underlines that “[…] climate impacts research is fundamental in developing tools to assist energy planners and policy makers to avoid unexpected surprises and overcome potential energy systems’ bottlenecks […]” even though little research has been conducted on this subject [21]. We validate these findings and research gap for our research area (Southeast Asian island communities) through conducting an own review of electrification case studies for Southeast Asian islands. We identified 17 island electrification case studies, of which only one mentions the topic climate change (the mitigation potential of switching to renewable energy sources) [22]. Climate change induced impacts are not yet considered in energy planning and the optimization is mostly based on a least cost approach. More details of our review can be seen in annex 1.

Investments into initial energy infrastructure are often combined with subsidies and favouring regulations. Policy makers need to incentivise climate resilient supply systems according to the respective risks for electrification projects in Southeast Asia. The complex task of electrification policies and optimized planning has therefore a new dimension: climate resilience. This leads to the main objective of our paper, which is to shed light on climate resilient electricity access planning in Southeast Asia as guidance for policy makers. In order to achieve this, we need to better understand where the regions with the most non-electrified island communities are and what climate risks – e. g. sea-level rise, cyclones – affect them the most. Understanding these risks and identifying typical island archetypes is crucial to derive technical recommendations which can be translated into concrete action plans for policy makers and planners. These steps translate into the following research questions:

- On which islands live people with no or limited electricity access in Southeast Asia?
- What island archetypes can be identified regarding climate risk patterns?
- What technical design aspects need to be considered for electrifying those archetypes?
- How can such technical aspects be translated into policy making?

The questions are addressed by spatial analysis using Geographic Information System (GIS) which gives an overview of different climate change impacts and extreme weather phenomena relevant for Southeast Asian islands, highlighting their vulnerability. Cluster analysis of these climate risks supports the identification of island archetypes. Literature review serves to develop technical recommendations to electrify those island archetypes. Finally, our study highlights the importance of integrating climate change impacts in energy planning in order to sustain positive effects of electrification in the long run. Our paper thus shows the missing but important connection between two main challenges of Southeast Asian island communities: first access to reliable and sustainable electricity supply and second increasing impacts of climate change.

2 Background on Climate Change Resilience, Energy Access and Energy Planning

Our study includes three main research fields: resilience (including risks and vulnerability), energy supply with focus on electricity access and energy planning and policy making. In order to foster a well-informed interdisciplinary discussion, we discuss in this background chapter the impacts of anthropogenic climate change, its terms and definitions, the options to provide electricity access and basic principles of energy planning.

2.1 Climate Change Impacts: Risk, Vulnerability and Resilience

The process of anthropogenic climate change and global warming leads to large-scale shifts in the world's climate, economic and societal systems. Thereby this global change is rapidly redesigning the realities and livelihoods of humankind, who are simultaneously affected and driver of such changes [23]. The negative impacts of those changes requires systems, societies and individuals to be capable of quickly adopting to them, favouring those with the highest resilience [24]. It is therefore crucial to discuss measures and options to improve the resilience of areas, communities and their vital infrastructures most at risk.

In order to assess a community's risk, three main elements are identified that influence this risk (see Figure 1, [25]). The first one are weather and climate events and stresses that occur either within a natural variability or because of the aforementioned anthropogenic climate change [25]. This element can only be influenced through mitigation measures relating to the change. The second element is the exposure of a community towards these events and stresses and is only addressed by migrating to other places, which is often the last resort. The third element is the community's vulnerability. The vulnerability can be improved though various measures that are strengthening the community's resilience towards the impacts of climate change [26]. Measures are manifold and include the development of proper disaster risk management and building adaptive capacity. In summary, disaster risk emerges from the interaction of weather or climate events (the physical contributors to disaster risk) with exposure and vulnerability (the contributors to risk from the human side) as displayed in Figure 1 [25].

Figure 1: Climate and Development Effects, own visualisation based on [25].

Resilience is often considered the flipside or even the positive connotation of vulnerability. Resilience defines how individuals, communities or societies continue to thrive and develop under shocks and stresses [27]. The exact definition and concept of resilience depends on the sector using the term. Climate resilience means the strength to prepare for, withstand and recover from stresses and disasters caused by the impacts of climate change. While talking about climate resilience it is first of all important to define the context

("Resilience of what?") and the cause of potential disturbances ("Resilience to what?") [28]. Figure 2 visualizes the concept of resilient capability: Every individual, community or society has a certain capacity to deal with the disturbance depending on their exposure, sensitivity (or vulnerability) and adaptive capacity. These factors then influence how the individual or group reacts to and gets out of the disturbance [29]. Recent research shows a low environmental resilience of Southeast Asian countries [30].

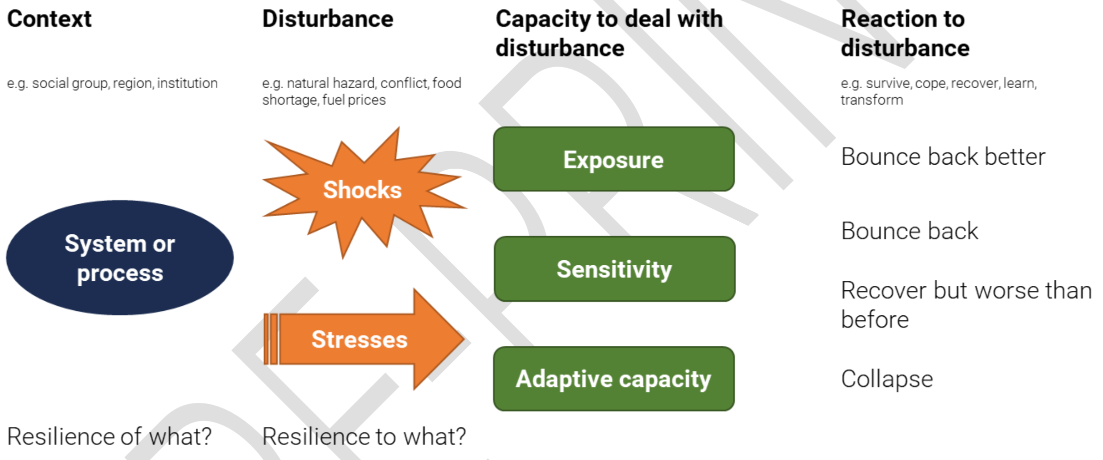

Figure 2: Four elements of resilience, based on [31].

The context for our research are the Southeast Asian island communities with no or limited access to electricity and their (future) electricity infrastructure (context: "Resilience of what?"). With regard to disturbances we focus on climate change induced shocks and stresses these islands communities and more specifically their (future) electricity infrastructure are facing. Stuart et al. (2017) and Schaeffner et al. (2012) identified four main climate change induced stresses that are affecting energy systems ("Resilience to what?") [32], [21]:

- temperature increase
- precipitation fluctuation (droughts, torrential rains, floods)
- extreme weather events (storms, cyclones)
- sea-level rise.

These stresses are affecting different dimensions of energy supply systems having impacts on:

- Technical components: There are impacts on the technical components (grid, generation units etc.) due to e.g. land slides and flooding caused by heavy rainfall or rising sea-level or due to storm surges [33], [21].
- Output and efficiency: The output and efficiency of energy systems are influenced by e.g. temperature and/or water stresses. For example, limited water resources will pose risk to hydropower, bioenergy, solar and thermal power plants [33].
- Demand and peak loads to be supplied: E.g. increasing temperatures will lead to higher cooling demands and therefore rising demands as well as peak loads [33], [21].

The exposure to shocks and stresses is difficult to influence for the island communities as relocation is the only viable option and is thus not further considered. The sensitivity is the likeliness to experience adverse consequences while being exposed to hazards and the ability to cope and recover [34]. The adaptive capacity refers to factors that allow communities to anticipate and plan effectively for change, to learn from experiences of previous hazards and to act based on the lessons learnt of that experience [34]. Various aspects to strengthen the adaptive capacity are improved by sustainable electricity access as it contributes to many vital functions of a community [29]. A simple example is the opportunity to use information and communication technology for which electricity access is a prerequisite. If electricity supply is guaranteed, the affected communities are empowered to access relevant information such as weather forecasts and communicate with important institutions in case of emergency.

It becomes obvious that a holistic approach and integrated planning of community and energy access development is needed in order to create and sustain positive correlations between sustainable energy access and building adaptive capacities.

2.2 Energy Access, Electrification Options and Planning

Access to electricity is a top priority for policy-makers in Southeast Asia. Countries across the region have made great progress in addressing the issue, with electrification rates rising by 28% since 2000 and is now at 90% [9]. The large number of communities situated on remote and difficult to access islands makes the challenge to reach the last mile more difficult. Despite the above-mentioned efforts, it is estimated that 65 million people still lack access to electricity in Southeast Asia [9]. The three common electrification options are small stand-alone systems (e.g. solar-home systems), decentralized mini-grids (run on diesel generators and/or renewable energy technologies and/or storage) and grid extensions. An overview of these options and their applicability is given in Table 1.

Table 1: Electrification approaches and their application [35].

Electrification Option	Electricity consumption	Population density	Distance to grid	Complexity of terrain
Grid extension	high	high	close	easy
Mini-grids *(supplied by fossil fuels, renewables or hybrid models)*	medium to high	medium to high	medium to far	medium
Small stand-alone systems *(e.g. Solar home systems)*	low	low	far	complex

To reach the remaining off-grid islands in Southeast Asia grid extension is usually very costly and due to the high distance to the next grid connection point onshore often not feasible. Bertheau et al. (2019) for example analyse the cost to electrify the remaining off-grid islands in the Philippines through submarine cable grid extensions (more than 3 billion USD) and compares this with electrification via decentralized mini-grids (700 million USD) [36]. The study finds renewable energy based hybrid systems most feasible for the majority of islands and submarine cable interconnection more promising for a few larger islands [36]. Kuang et al. (2016) analyses the renewable energy development on islands globally and states that hybrid electricity systems, based on one or more renewable energy technologies combined with battery storage solutions and/or diesel back-up generators, are one of the most feasible solutions [12]. Solar home systems however are often applied in very sparsely populated areas with a high distance to the grid and low electricity consumption [37]. It becomes clear, that RE-hybrid mini-grids and solar home systems play a crucial role to reach the last mile on Southeast Asia's remote islands.

The three electrification options are not equally prone to be affected by the impacts of climate change. In this paper we are focusing on island electrification only, which implies that grid extension is applied by installing submarine cables to connect the islands. These cables are usually not affected by the above mentioned hazards [38]. The infrastructure on the island is then limited to substations, transmission and distribution lines which are also components of the second electrification option (mini-grids). Small stand-alone systems such as solar home systems are usually mobile systems and their users are able to position them according to their preferences. In case of hazards these systems can be easily uninstalled and stored in a safe environment to protect them. Therefore, depending on the users and their mindfulness, the climate resilience of small stand-alone systems is high [17]. Small standalone systems and submarine grid extension are not further considered in this paper because of their low vulnerability to the impacts of climate change. Mini-grids however combine generation, transmission and distribution on the island and are designed to cover the local demand. All these technical components are risk prone and additionally the local demand is influenced by impacts of climate change [32], [21]. In our study we focus on electricity infrastructure on the islands considering solar, wind and diesel as main sources for mini-grid power supply.

Electrification planning defines areas for electrification through grid extension, mini-grid development or stand-alone systems (compare Table 1). The state of the art for energy access planning are GIS based spatial least cost planning tools, showcased for several geographic contexts, e.g. Ethiopia [39], or Nigeria [40]. The combination of geospatial analysis and electricity system modelling is then delivering most suitable electrification options for the pre-defined areas on project level.

Current energy planning processes are following either a least-cost approach (optimizing on purely economic criteria) or a multi-sector approach (optimizing on economic criteria including a qualitative dimension e.g. human development or environmental impact) [41]. These require solid input data such as demand, available energy resources and technologies and, if regulated, qualitative criteria e.g. climate resilience or environmental impact. On governmental level electrification processes are always dependent on proper energy policy and planning as they require favourable legal and institutional frameworks. Investments into initial energy infrastructure as discussed in this paper are usually high and are often combined with subsidies and favouring regulations. Policy makers guide the planning and implementation process through their regulatory frameworks and definition of incentive systems for different electrification options. That is why energy planning considering the increasing impacts of climate change on policy level is of special importance to Southeast Asia as climate change affected region.

3 Material and Methods

We apply a two-step consecutive approach for this study: First, we utilize geospatial analysis to assess the island landscape and derive key information for population and climate risks. Second, we apply a risk cluster analysis to explore and identify similar patterns and island archetypes with regard to climate risks. The research steps are illustrated in Figure 3.

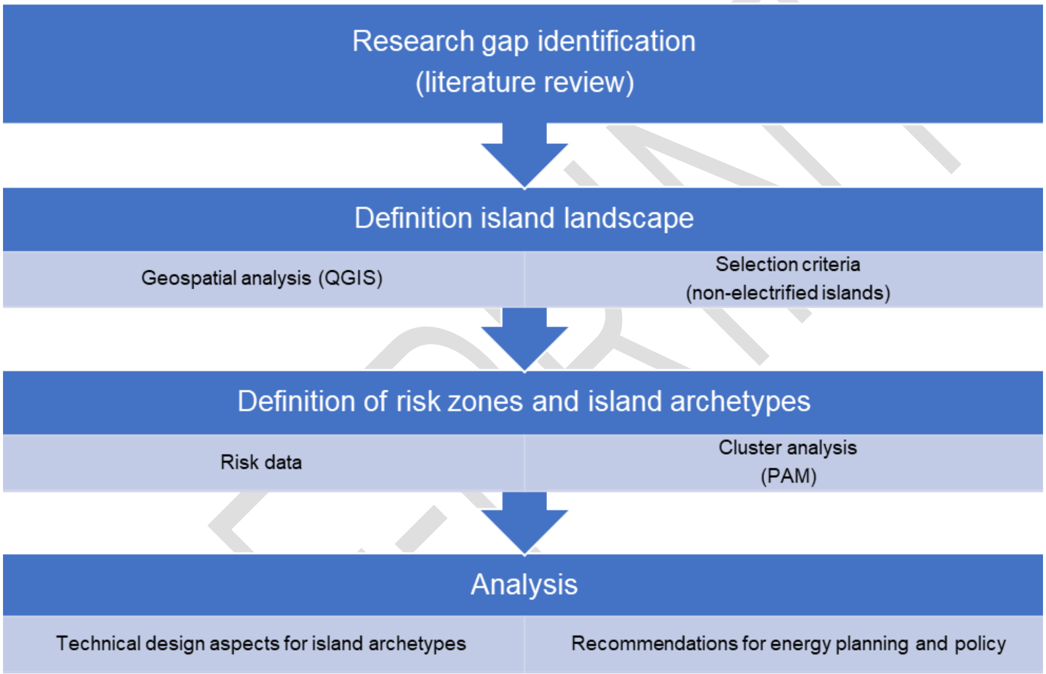

Figure 3: Flow chart of research approach.

3.1 Definition of the Island Landscape

To identify islands of interest we apply the Global Administrative Areas database (GADM) version 3.6 [42] using the open access software QGIS 3.4. [43]. Subsequently we limit the dataset to our case study countries and exclude the non-insular parts (e.g. “Mainland” Southeast Asia). For the remaining islands we calculate the population based on WorldPop datasets [44], [45], individually for each county (applying the 2015 values) by using geospatial raster statistic algorithms. Additionally we derive the extension of the national transmission grids by digitalizing grid maps provided from [46]. Since we focus on currently not electrified or undersupplied islands in this study which require significant and climate resilient electricity infrastructure investments in the near future, we limit the island selection by applying three main criteria:

- **Exclusion of islands below 100 inhabitants**

  We define that remote islands below 100 inhabitants will be electrified by isolated solar home systems [47]. These systems are to a high extent resilient towards climate change inducted impacts as they are mobile, can be decommissioned easily and stored in a shelter during extreme weather events [37].

- **Exclusion of islands above 1,000,000 inhabitants**

  We also define that islands with a population above 1,000,000 have already significant energy supply infrastructure and are thus not part of our focus group. Such islands are more likely to be integrated in regional electricity systems [48].

- **No transmission grid**

  As there is a certain probability that islands within the range of 100 – 1,000,000 inhabitants are electrified we also excluded those having a transmission grid installed as this makes electrification of the island very likely.

The applied datasets are summarized in Table 2. Additionally, the size of the islands and mean elevation is calculated by GIS tools.

Table 2: List of applied geospatial datasets.

Parameter	Description	Unit	Source
Population	The applied dataset provides the number of inhabitants on a raster scale. Pixel resolution is~ 100 m. The population is summarized for the identified island.	#	[44], [45]
Area	Island size is calculated in square kilometre.	km²	GIS calculation
Grid	Geographical coverage of national transmission grids		Digitalized from [46]
Elevation	Digital elevation model (DEM) of the NASA Shuttle Radar Topographic Mission (SRTM) is applied for deriving the mean elevation of an island.	m	[49]

3.2 Definition of Climate Risk Zones

To understand the different hazards to the islands and their infrastructure, we apply datasets reflecting the four climate stresses and shocks affecting energy systems identified by Stuart et al. (2017) and Schaeffner et al. (2012) [32], [21]:

- Cyclone risk

  provided by the Global Risk Data Platform created by UNEP/ UNISDR for the Global Assessment Report on Risk Reduction [50–52].

- Sea-level rise

  provided by the Centre for Remote Sensing of Ice Sheets who created datasets for different sea-level rise scenarios (1-6 m) [53], [54]. We take into account the most conservative scenario expecting a 1 m sea-level rise.

- Fluctuation in precipitation patterns and temperature

  provided by WorldClim – Global Climate Data who created a platform to access free climate data for ecological modelling and GIS [55]. We consider the data of version 1.4 which provides current data (interpolations of observed data, representative of 1960-1990) and future data (downscaled global climate model data from the Coupled Model Intercomparison Project Phase 5 for the Firth IPPC Assessment for the year 2050) and calculate the difference (in this case the absolute change to keep the actual value of precipitation in- or decrease in mm) between both to get trends for increased likelihoods of floods (positive values) and droughts (negative values).

In order to select the most suitable future dataset from WorldClim for temperature and precipitation, we followed Kamworapan et al. (2019) and used the CNRM-CM5 Global Climate Model [56]. In order to respect international agreements to keep global warming below 1.5 °C, we applied the data deriving from the Representative Concentration Pathway 26 (rcp26) emission scenario as it is the only scenarios were we stay likely below 1.5 °C [57].

Table 3 provides a documentation of the applied datasets, characteristics and processing steps relevant for the climate risk zone definition.

Table 3: List of applied datasets, characteristics and processing steps for climate risk zone definition.

Parameter	Description	Unit	Source
Sea-level rise	Raster data is provided covering areas flooded by a sea-level rise of 1 meter. The data is polygonised and total	per cent (%)	[53], [54]

	flooded area per island calculated. The division of $\text{area}_{\text{flooded}}$ and $\text{area}_{\text{total}}$ provides area flooded by sea-level rise (%). Pixel resolution is ~ 1 km.		
Cyclone risk	This raster dataset includes an estimate of the global risk induced by tropical cyclone hazard. Unit is estimated risk index from 1 (low) to 5 (extreme). Pixel resolution is ~ 10 km.	#	[50]
Temperature	The fluctuation in temperature is calculated based on WorldClim datasets. Comparing the difference between the mean values of the current historical dataset (interpolations of observed data, representative of 1960-1990) and the future projections dataset (downscaled global climate model (GCM) data from CMIP5 IPPC Fifth Assessment, 2050). Positive values indicate a temperature increase, negative values indicate a temperature decrease. Unit is °C. Pixel resolution is ~ 1 km.	°C	[55]
Precipitation	The fluctuation in precipitation is calculated based on WorldClim datasets. Comparing the difference between the mean values of current historical dataset (interpolations of observed data, representative of 1960-1990) and future projections dataset (downscaled global climate model (GCM) data from CMIP5 IPPC Fifth Assessment, 2050). Positive values indicate a precipitation increase (absolute change), negative values indicate a precipitation decrease (absolute change). Unit is mm. Pixel resolution is ~ 1 km.	mm	[55]

3.3 Cluster Analysis

Cluster analysis is a commonly used method for unsupervised pattern recognition in large datasets [58]. The goal is to partition the dataset in the most possible homogenous group by minimizing intra-cluster variation while maximising the variation to other clusters. Cluster analysis has been widely applied and presented in the scientific literature: K-means cluster analysis approach was applied e.g. for classifying islands according to their RE potential [16], economic potential for smart grids [59] and for assessing feasibility for smart energy systems on Philippine islands [60]. Partitioning around medoids

(PAM) analysis for example allowed to cluster islands according to bioclimatic characteristics [61]. For both approaches a predefined cluster solution *k* (number of cluster) is required whereas other type of cluster analysis e.g. hierarchical cluster analysis do not require to specify the cluster solution [58].

We apply PAM cluster analysis for this study as it is the most robust approach to outliers which might occur in our datasets given the many islands considered. In contrast to k-means approach each cluster is represented by a medoid which is the most central data point for a cluster with lowest average dissimilarity to all other data points in the cluster. Cluster assignment is based on the dissimilarity to the medoid and not the mean value of a cluster (k-means cluster approach). We implement PAM cluster analysis by using the statistical software package *R* [62], [63]. The dataset (summarized in Table 3) is scaled (z-transformation) applying the "scale" function within R to compensate for the differences in value ranges. Euclidian distance is used for measuring distances between data points. In order to determine the optimum number of clusters, we compute the average silhouette values and cluster sums of squares for a range between 1 and 10 clusters [64]. Finally, the suggested cluster solution is implemented based on the distance to cluster medoids (PAM method). In order to visualize the cluster results we apply the "fviz_clust" function in R which is automatically applying a principal component analysis if more than two observations shall be shown in the cluster plot.

4 Results: Climate Risks of Southeast Asian Islands

4.1 Spatial Identification of Islands with limited Electricity Access

Based on the approach explained in the previous section, we identify 13,388 islands with a population of more than 385 million and an accumulated area of more than 2.4 million km². The discrepancy in island quantities to other information, e.g. more than 7,700 islands for the Philippines [65] or 17,500 for Indonesia [66], are due to simplifications of the GADM dataset. However, since these simplifications result only in the merge of very small islands and given that the dataset is the only one comprehensively available for all selected case study countries we decide to apply the GADM dataset. Figure 4 provides an overview of the distribution of islands and their population.

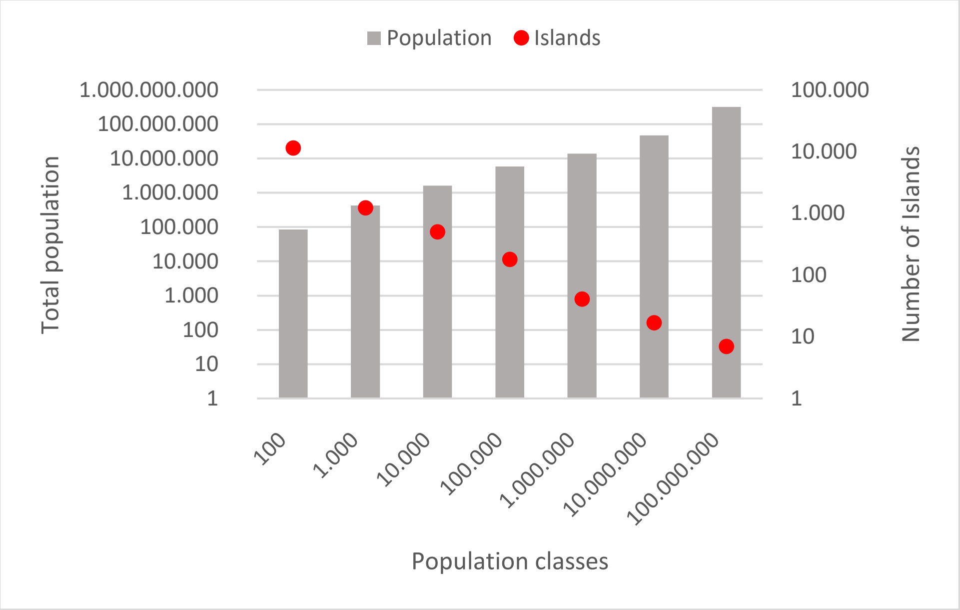

Figure 4: Overview on population classes and islands based on GADM data.

The vast majority of islands (>11,000) host very small communities, totalling to a population of less than 85,000. Most of those islands are tiny since more than

79% of all islands are not larger than one km². On the other extreme, the seven most populated islands comprise 82% of the overall population. To assess only islands that are not yet electrified and will have significant energy infrastructure installed in the near future, we apply the stepwise exclusion criteria outlined in subsection 3.1 by excluding 11,416 islands with a population below 100 inhabitants, 24 islands with a population above 1,000,000 inhabitants and 16 islands connected to a larger transmission grid. After applying this selection in our GIS analysis, 1,932 islands with a population of more than 21 million remain for further analysis.

4.2 Definition of Risk-Specific Island Archetypes

Given the objective of exploring the considered island landscape with regard to climate change induced threats, we select the four identified climate risks (see Table 3) as decisive parameter for the cluster analysis. Prior to the main analysis, islands with missing values for the four considered risks are excluded from the dataset. Since values for the parameter "cyclone risk" are missing for more than 64% of the islands we decide to entirely exclude the parameter from the cluster analysis. Finally we derive 1,478 data points reflecting islands with complete information for sea-level rise, temperature and precipitation. By applying the approach outlined in subsection 3.3 we derive average silhouette width and cluster sum of square for each cluster solution in a range of 1-10. Both indices indicate an optimal solution of three clusters (Figure 5 right side). Consequently, the cluster solution is assigned to each island by using PAM routine considering the dissimilarity of each data point to cluster medoids. Finally, we derive the most distinctive partition of Southeast Asians off-grid islands. The scatter plot of data points coloured by cluster numbers (Figure 5 left side) shows the data after an automatic principle component analysis considering the first two principle components. Those are the two dimensions that show the most variation in the data. The 47.6 % means that the first principle component accounts for 47.6 % of the variation. The second principle component accounts for 28.7 % of the variation. Together they account for 76.3 % of the variation. Cluster 1 and 3 show the largest overlap while Cluster 2 is the most distinctive with slight overlaps to Cluster 3.

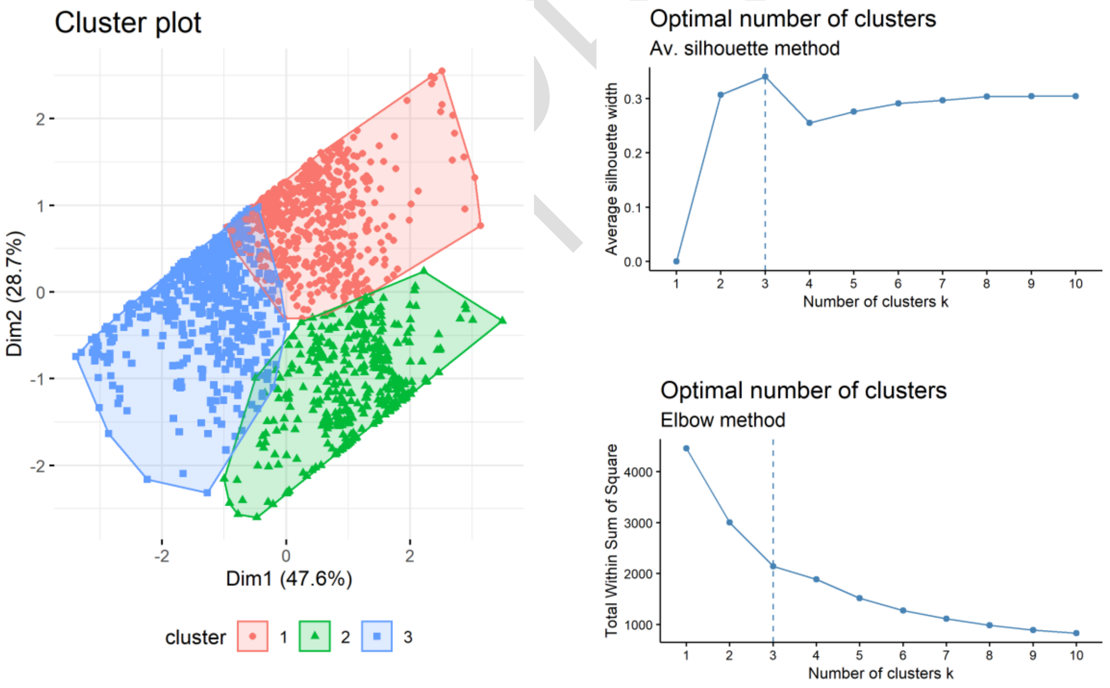

Figure 5: Cluster plot for 3 cluster solution (left) and average silhouette value and cluster sum of square indication a 3 cluster solution (right).

Table 4 presents mean values per cluster and Figure 6 shows the range of patterns per cluster through boxplots. Mean cyclone risk, even if not considered in the cluster analysis, is shown based on island data for each identified cluster (excluding NA values). Consequently, variation of cyclone risk within all clusters is relatively high (see boxplot bottom right; Figure 6). Looking at Table 4 it becomes obvious that all islands will suffer from a similar temperature increase. No island is showing a negative temperature development (see boxplot bottom left; Figure 6). Islands within Cluster 2 are additionally affected by sea-level rise (83% of their area will be flooded in case of 1 m sea-level rise) and a higher cyclone risk (2.26). Islands within Cluster 3 are mostly affected by a precipitation increase of 145 mm (+4.8% compared to current data) indicating an increased flood risk.

Table 4: Island cluster and their general characteristics.

No. Cluster	Islands	Population	Area	Elevation	Sea-level rise[1]	Temperature variation	Precipitation variation	Cyclone risk
	[#]	[total /mean #]	[mean km^2]	[mean m]	[mean %]	[mean °C]	[mean mm]	[factor]
1	570	12,466,723 / 21,871	301.9	60.7	20%	0.94	32	1.89
2	383	811,765 / 2,120	66.1	14.4	83%	0.92	52	2.26
3	534	6,357,820 / 11,906	94.3	51.9	19%	0.87	145	1.72

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[1] Share flooded by sea-level rise (1m)

Table 5: Detailed precipitation characteristics indicating flood or drought risks for each cluster.

No. Cluster	**Islands total**	**Islands with negative /positive precipitation variation**	**Precipitation variation total**	**Negative precipitation variation in cluster**	**Positive precipitation variation in cluster**
	[#]	[#]	[mean mm] / [mean %]	[mean mm] / [mean %]	[mean mm] / [mean %]
1	570	217 / 353	32 / 1.6%	-35.34 / -1.5%	75.42 / 3.5%
2	383	79 / 304	52 / 2.1%	-39.01 / -1.8%	76.03 / 3.1%
3	534	2 / 532	145 / 4.8%	-23.28 / -0.8%	146.52 / 4.9%

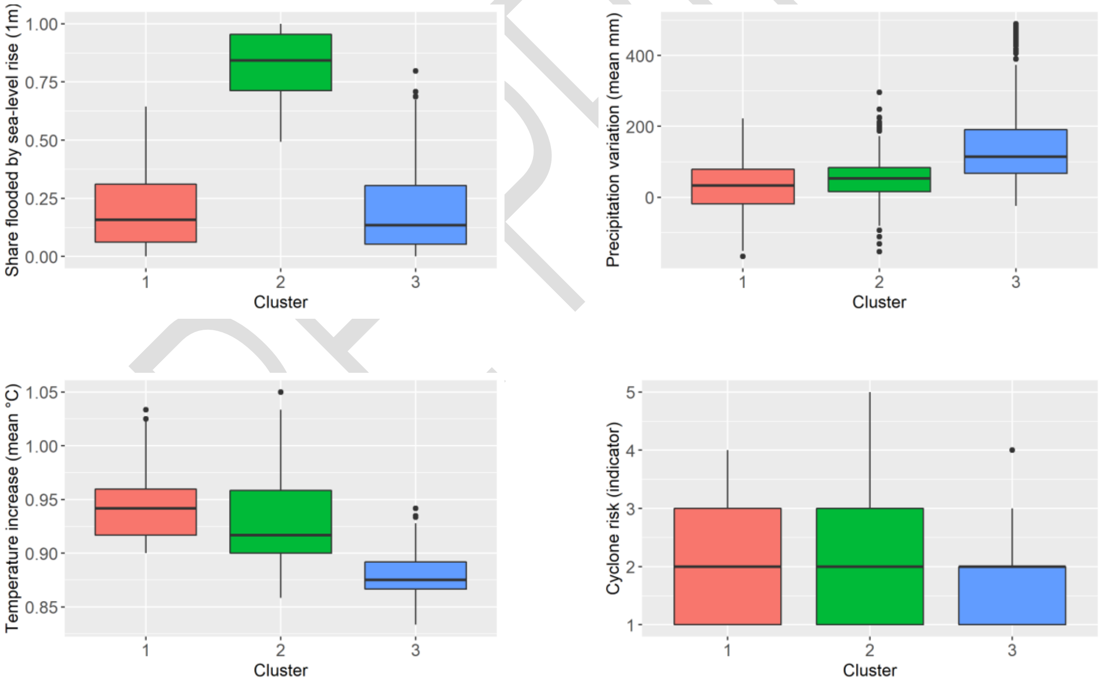

Figure 6: Boxplots for the three cluster highlighting similarities in climate risks.

The first cluster includes the highest number of islands (570) and the largest overall population with more than 12 million. In terms of climate risks this cluster is characterized by the highest mean temperature variation of + 0.94°C and lowest variation in mean precipitation of +32 mm (+1.6% compared to current value). The mean share of island area flooded by sea-level rise is at 20% for Cluster 1 and the cyclone risk is the second highest compared to the other two cluster with 1.89. A look at the boxplots (Figure 6) reveals a high number of islands showing a decreasing precipitation pattern for islands within Cluster 1 (indicating drought risk).

Table 5 summarizes the precipitation patterns for each cluster in more detail. Negative precipitation variation indicates a drought risk, positive variation indicates flood risk. 217 (out of 570) islands will face decreasing precipitation for Cluster 1 (mean -35.34 mm, decrease of 1.5%). The remaining 353 islands show a positive precipitation variation (mean +75.42 mm, increase of 3.5%).

The second cluster forms the cluster with the lowest number of islands and smallest overall population (around 800,000) and can be distinguished from the first cluster by a high mean share of area flooded by sea-level rise (83%). The range in precipitation variation is small apart from few outliers (Figure 6).

Table 5 shows 79 islands within Cluster 2 in risk of drought (mean -39.01 mm, decrease of 1.8%) and the majority of islands (304) in risk of flood (mean +76.03 mm; increase of 3.1%). Temperature increase varies largest within Cluster 2 among all clusters (Figure 6). Cluster 2 islands have a higher cyclone risk (2.26) than islands grouped in the other two cluster.

The third cluster comprises with 534 a similar number of islands as Cluster 1 but has a much smaller overall population (6.3 million). It groups islands with the highest mean variation in precipitation of +145 mm (increase of 4.9%) and the value range for this parameter (Figure 6) indicates that a significant number of islands can be affected by a higer increase in precipitation than the mean value reveals (highest value of +489.38 mm). Only two islands within Cluster 3 show negative precipitation variations. At the same time temperature variation is slightly lower (mean +0.87°C) and a small range. Risk through sea-level rise is lower compared to Cluster 2 and is in a similar range as Cluster 1. Cluster 3 shows the lowest cyclone risk (1.72) compared to the other two cluster.

Comparing the negative and positive precipitation variation of all cluster (

Table 5), it becomes obvious that Southeast Asian islands will mostly be challenged by precipitation increases indicating a higher flood likelihood. This is underlined by Southeast Asia's mostly tropical and therefore humid climate zone [67].

Geographical patterns are observable on the map provided in Figure 7. Most Cluster 1 islands are located south of the seventh latitude and comprise predominantly Indonesian islands. Islands of cluster 2 are spread most widely over the region with aggregations in the eastern and southern Philippines and eastern Indonesia. Cluster 3 islands are located mainly north of the seventh latitude and comprise most islands in the central Philippines and many Malaysian, Thai and Burmese islands facing the Indian Ocean. Grid data is also visualized in the figure below.

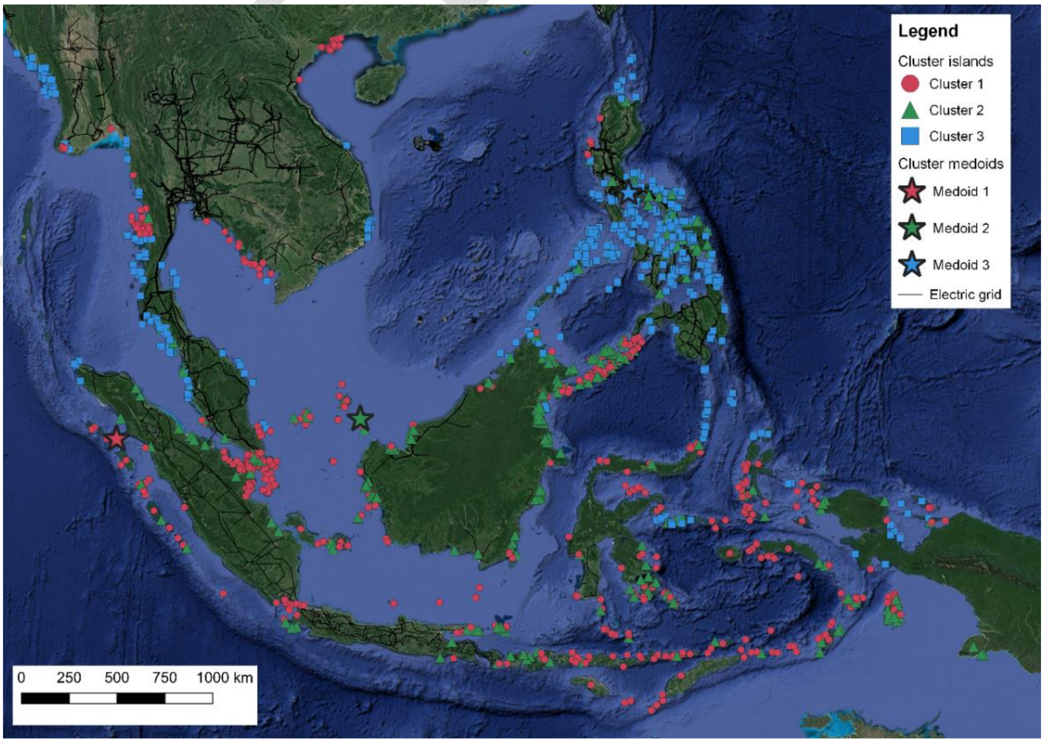

Figure 7: Visualization of cluster locations in Southeast Asia.

Table 6 summarizes the information of the medoid islands for each cluster derived from running the PAM function in R. These islands are also highlighted in Figure 7 (stars). Cluster 1 medoid island (Bangkaru Island) is situated in Indonesia (Northeast part of West-Sumatra) facing the highest temperature increase of all medoid islands also presented as general characteristic for Cluster 1 above. The medoid for Cluster 2 (Palau Subi-Besar, part of Riau Islands) is also situated in Indonesia and is one of the most northern islands of Indonesia (situated between Peninsular and West Malaysia) showing a high share of area flooded by sea-level rise (87 %) representing the characteristic of Cluster 2 islands. Cluster 3 medoid is Pagbilao Island situated in the Southern part of Luzon (Philippines) showing the highest precipitation variation of all medoid islands as analysed for Cluster 3 above.

Table 6: Island cluster medoids and their climate change induced risk and other parameters

No. clus-ter	**Country**	**Lat./ Long.**	**Area** [km²]	**Popu-lation** [#]	**Share flooded by sea-level rise** [%]	**Tempe-rature rise** [°C]	**Precipi-tation rise** [mm]	**Cy-clone risk** [factor]
1	Indonesia	2.071/ 97.123	181.3	304	20	0.94	38.65	N/A
2	Indonesia	3.033/ 108.855	2,300.5	273	87	0.93	60.31	N/A
3	Philippines	13.912/ 121.768	23.2	10,776	15	0.88	125.84	3

4.3 Combination of Technical Design Aspects and Island Archetypes

The Asia-Pacific Economic Cooperation Organization (APEC) states that "Climate change significantly affects the energy sector across many regions" [33] and highlights that especially off-grid areas are affected "due to their geographic, social and economic constraints" [33]. Southeast Asia's energy sector was for example challenged by the tsunami in 2004 (Indonesia, Thailand), floods in 2011 (Thailand, Cambodia, Vietnam) or the Typhoon Haiyan in 2013 (Philippines). APEC emphasizes the necessity of technological and political preparedness to tackle these challenges. In order to do so it is necessary to understand the region's specific risk patterns analysed in the previous chapter. Once we understand and identify these risk zones, it is possible to develop technical recommendations for future energy systems in the region and define regulations, incentives and other support mechanisms on political level to guide the process of risk-based energy access planning.

Therefore we summarize the impacts of the four risks considered in this study on electricity generation sources, grid infrastructure and demand development based on literature review in Table 7 [21], [32]. It becomes obvious that an increased temperature and precipitation fluctuation impacts mostly efficiency and output of the systems and leads to increased demand and peak loads whereas most impacts on energy systems caused by sea-level rise and extreme weather events are affecting the technical components (equipment).

Table 7: Impacts of climate change induced stresses on energy systems; adapted from [21], [32].

Energy system	**Increased temperature**	**Precipitation fluctuation**	**Extreme weather events**	**Sea-level rise**
Wind	Decreased air density may decrease energy output [32]	*No significant impact*	Alternation in wind speed may increase output variability [32], [21] Equipment damage [32], [21]	Damage of off-shore equipment [32]
Solar	Reduced solar cell efficiency [32] , [21]	Increased cloud cover and humidity decreases solar generation output [32] , [21]	Damage of equipment [32]	Damage of infrastructure through salt-water corrosion [32]
Diesel power plants	Increased temperature may decrease efficiency [32] Disruptions of production transfer and transport [21]	Disruptions of production transfer and transport [21] Heavy precipitation threatens diesel units not appropriately sheltered [32]	Equipment damage may decrease plant lifetime and output [32] Disruptions of production transfer and transport [21] Disruptions of import operations [21]	May increase risk of damage to off-shore infrastructure and coastal stations [32]
Transmission and distribution grids	Increased electrical resistance decreasing efficiency [32] Increased fire risk damaging grid lines [32]	*No significant impact*	Damage of grid lines reducing system reliability [32]	Damage of infrastructure through salt-water corrosion [32]
End-user / demand	Increased energy demand for	Increased power outages and disruptions [32]	Damage of infrastructure and power outages [32]	Increased need for desalinisation plants and

	cooling [32], [21] Reduced energy demand for heating[32], [21] Increased energy demand for irrigation [21]	Floods and droughts may require additional emergency energy capacity [32] Increased energy demand for cooling [21] Reduced energy demand for heating [21] Increased energy demand for irrigation [21]		water efficient irrigation techniques [32]

In another analysis we identify measures to reduce these impacts on energy systems based on the findings of Perera et al. (2015), Schaeffer et al. (2012) and APEC (2017) [29], [21], [33]. Thus the measures listed in Table 8 are able to address and improve an energy systems' resilience alone or in combination, depending on the hazard occurring in the specific area of installation.

Table 8: Measures to reduce the impact of climate change induced hazard on energy systems; own analysis based on [21], [33], [29].

Measure	**Explanation**	**Reduces impact of…**			
		increased temperature	**Precipitation fluctuation**	**extreme weather events**	**sea-level rise**
Diversification of energy mix and high renewable energy shares	▪ less dependency on fossil fuels (often transported from the mainland) ▪ diverse energy mix creates reduced sensitivity to shortcuts (because of		X	X	

	failure or recession of one technology) ▪ interconnecting island grids to larger supply systems via submarine cables				
Modular and distributed systems	▪ reduced need for transmission and distribution lines (both are often physically exposed and thus vulnerable to e.g. storm surges) ▪ local energy generation according to the best resource available ▪ reduced sensitivity to total system failure (if one part of the modular system fails, another part is able to operate independently)		X	X	
Containerized solutions	▪ increased flexibility of rearranging the systems position ▪ allows for reactive actions in case of changing hazard zones ▪ option to jack the system in case of frequent flooding or land slides		X	X	X
Concrete-sided buildings (instead of metal)	▪ more resistant to wind and salt-dust corrosion ▪ stays cooler than metal housing	X		X	X
Underground cabling	▪ higher resistance to wind and to a certain extend to flood surges ▪ cooling effect on cables	X	X	X	
Cooling for substations, transformers	▪ increased efficiency and lifetime span of components	X			

and storage technology					

If we apply these findings to the identified risk cluster, we are able to give technical recommendations for the implementation of future energy systems on the islands: As all islands are facing increased temperature, it will be beneficial to house the batteries, inverters and diesel generators in a cool environment (proper concrete building with air circulation or even air-conditioning) and lay cables underground to benefit from the cooling effect of the soil compared to higher air temperatures. The increase is almost 1°C for all islands. In order to evaluate the real impact of this increase in the long run, a more detailed analysis of multiple effects like efficiency decrease and demand increase as well as different system sizes and setups is recommended.

In addition to that islands grouped in Cluster 2 are highly affected by sea-level rise. In this case it is recommended to install energy supply systems in areas of high elevation far from the shorelines and technical component housing in concrete buildings resistant to salt-mist corrosion. In many cases the distance of energy infrastructure installation to shore and their elevation is limited due to space constraints (small islands, topography etc., see Table 4) [12]. In these cases containerized solutions make it easier to move the energy infrastructure to other areas if rising sea-level is endangering its operation. In addition to that containers offer the opportunity to artificially pile up the infrastructure in case of scarce land resources in high elevations. In comparison with fixed housing for energy system components, poles can easily and economically be replaced after they reached their lifetime. As sea-level is rising, the affected area of salt water mists will increase. All components of energy systems to be installed on islands within Cluster 2 shall ideally be salt water corrosion resistant.

Increased flood risk of Cluster 3 islands implies that they will benefit from a diverse energy mix as different sources are usually more reliable in terms of demand supply coverage (e.g. decreasing solar power output might be compensated by increased wind power output). In addition to that decentral system setups e.g. with several micro-grids connected to one mini-grid are reducing total system failure likelihood in case of heavy flooding in one area. Another advantage of containerized solutions installed on poles is the reduced surface affected by floods and land slide which makes them a promising solution for islands within Cluster 3. To a certain flood level it is also recommended to use underground cabling as it reduces the risk of electricity poles been flushed away.

Looking at Table 4 all cluster show at least a low cyclone risk (Cluster 2 being the most affected). To decrease the impacts of cyclones and storms on the electricity infrastructure, it may be beneficial to invest in underground cabling in landslide proof areas for distribution and transmission lines in order to reduce their exposure to storms. Deeply grounded mounting structures able to resist strong winds for solar power stations are also required. Considering vertical wind turbine technologies while designing and planning wind power stations helps to reduce sensitiveness to rapid changes in wind direction and peaks [32]. Concrete buildings to host energy infrastructure in low flood risk areas are able to protect sensitive technology from storm surges. In communities highly affected by storms and extreme weather events interconnected small energy generation units on household level able to be stored in a safe environment in case of emergency are also a promising option [68].

A diverse energy mix as well as modular and distributed systems and proper housing and cooling for sensitive components (e.g. batteries, inverter) are of great value for each of the cluster as they enhance energy security by eliminating reliance on one source and one system and lead to higher system stability [32]. The interconnection of several islands or to the mainland via submarine cables also increases supply security as it adds to the diversification of electricity sources in case of system failure [69]. However, the investment of these interconnections are high and a more detailed cost benefit analysis is required [36].

In an island context as discussed in this paper it is also recommended to pay attention to install salt-water corrosion resistant components and infrastructure, because they must withstand the corrosive environment of coastal areas [70].

5 Conclusion and Policy Implications

5.1 Discussion and Recommendations for Energy Planning and Policy

Our results identify three main climate risk archetypes for Southeast Asian islands showing different risk patterns and exposure. In summary, the risk analysis has shown, that all islands will be affected by increased temperatures while the other risks such as flooding, sea-level rise and cyclones are more site specific. With exacerbating climate change, accounting for climate change related risks will become increasingly crucial for energy planning and related policies.

The cluster analysis serves as a first approach to climate risk assessment as input for energy planning processes. We are focusing on energy access planning, meaning new electricity infrastructure installations. The stresses mentioned above can be addressed proactively if integrated into energy planning and management of these new systems. Effects on the technical components lay mainly with the design and sizing of the systems and are therefore easier to address for not electrified areas than for existing systems which would need to be refurbished. The specific technical design implications are addressed in section 4.3 and should serve as first overview for climate resilient energy planning. Climate change impacts on efficiency and output of the energy system as well as demand and peak loads are noticeable. Nevertheless, they are mostly covered by effective energy and demand management of running systems [33]. In order to install resilient electricity systems, knowledge of risks and the technical options to manage these risks are required as mentioned. In order to implement these, political guidance and suitable regulations are needed to fulfil the shift from pure least-cost to integrative resilient planning. We observe an increased attention for connecting climate action and energy access, but the recommendations stay superficial and rather focus on mitigation or the general strengthening of local communities as adaptation measure [71], [72]. Policy makers and energy planners should familiarize themselves with the respective climate risks and countermeasures in their region.

We therefore recommend integrating climate risk assessments into new electrification projects on Southeast Asian islands. The introduction of initial energy infrastructure is often fully or at least partly supported by public investments and financing. Thus, policy makers have the power to outline the rules for public tenders of such systems. Similar to social and environmental impact assessments we suggest that climate risk assessments become mandatory for island energy supply planning [73]. Prior to island's supply system being built, a risk assessment including temperature increase, sea-level rise, flooding and cyclones must be conducted following the risk types presented in this study. Based on such assessments, the tenders and system designs can be specified to address the site-specific risk types. The initial risk identification as presented above can guide policy makers in this process. They are enabled to identify the prevailing risks based on the applied data sets and therefore introduce a more resilient planning approach.

The technology, design and setup of electrification projects on islands can be selected based on Table 8 and the recommendations given in section 4.3. The suggested measures may serve as input to define minimum requirements for each specific climate risk zone to be considered in either regulations or tender specifications. We understand the limitations of this simplified table and see our work as a first approach to introduce climate resilient energy planning. We call for future research on planning tools, which enable more complex sizing and designing of supply systems based on identified risks. These tools shall consider site-specific risks and adjust technical design options according to their impacts on each component.

Another challenge of climate resilient planning is that most options to improve the electricity systems' resilience are coupled with higher upfront investments [33]. On the long term, however, these investments are expected to pay off as they lead to reduced maintenance and replacement cost in the face of increasing climate change induced risks in the region [33]. Still, specific support schemes need to be introduced to finance climate resilient infrastructure for electricity access. Here is even an opportunity for Southeast Asian countries to attract support from international climate funds to implement energy access measures as resilient energy supply systems connect both fields, climate adaptation and energy access [74], [75]. Thus, future planning tools need to integrate economic comparison of common versus more resilient system setups in order to support policy makers to adapt their incentive mechanisms and requirements and facilitate the access to international funding to cover the extra-cost of resilient energy infrastructure.

Financial incentives can be given to project developers or operators to introduce adequate climate resilient technologies. Therefore governments or development banks should provide low interest loans or even grants to support the implementation of such systems as a way forward to improve climate resilient energy access. The structure of such financial support mechanisms varies based on many regional and site specific factors. The most common approach for energy access is result-based financing [76],[77]. In such an instrument, the grant or financial support is linked to the successful implementation of the project in combination with additional requirements, for example minimum level of service. For our case the consideration of resilient technology and system designs may serve as one requirement for funding. To facilitate the evaluation of all these dimensions (climate resilience, economic, technological, social and environmental factors) it is recommended to use multi-criteria decision methods as already defined as future research need [78], [79].

The APEC also sees a strong urgency to mainstream energy resiliency and follow an integrated approach when designing policies, regulations and laws, setting up institutional arrangements, programs and projects as well as financing mechanisms [33]. Increasing energy resiliency requires action on national, sectoral and project level [18]. On project level we advise considering the technical recommendations underlined in section 4.3 for each identified cluster group. For the national and sectoral level, it is important to assess the current and planned energy infrastructure within the context of climate change induced risks in a standardized way. Mapping of climate risks based on climate models as well as energy infrastructure and local resources as initiated in Chapter 4 form the basis to support these processes. The integration of energy resiliency into national development plans (e.g. National Adaptation Plans) helps to trigger integrated planning processes on national, regional and local level. The Philippines as one of the most affected countries for example declared sustainable energy as one of their priority sectors emphasizing climate-proofing and rehabilitation of energy systems infrastructure in their climate change action plan (2011 – 2028) [80]. The implementation foresees a climate change risk vulnerability assessment for energy and transport system infrastructure to initiate a programme to increase the resiliency of such infrastructure [80]. Implementation however is still in an early stage and other countries in the region lag behind.

In conclusion, the integration of climate risk assessments to energy planning processes in form of a multi-sector approach and a shift from current least-cost to result-based or integrative planning is highly recommended. Large infrastructure projects already require environmental impact assessments, which should be expanded to climate risk assessments. These assessments enabled through political frameworks are needed in order to select the most suitable location as well as best technology and system setup for each specific case. Depending on the location, the specific impacts of flooding, sea-level rise, temperature increase and cyclones need to be assessed and targeted by implementing the respective strengthened energy supply system.

Our work has identified the missing link in energy planning and climate resilience and gives an overview on the prevailing risks and technical design implications on Southeast Asian islands. Limitations can be found in the risk related data, where still gaps exist for many islands and proxies were used in our study. Here, we recommend to invest into more detailed climate risk maps of Southeast Asia as important input parameter for climate resilient planning. In addition, the technical measures to address these risks need to be specified in future research activities. This could be combined with the development of specific decision-support tools for climate resilient system design. Therefore, future research needs exist in developing multi-dimensional decision support tools including climate resilience as mentioned above. These tools are able to identify the most suitable technology and system setup for different islands in different country contexts. Other limitations remain in the approach of clustering islands for deriving broad recommendations which are not island or country specific. Thus, we recommend to other researchers to build upon our analysis and increase the granularity to country level to derive more specific recommendations for local policy makers to identify climate resilient electrification options considering the local political, regulatory and socio-economic characteristics. Addressing the urgent issues of climate resilience and energy access calls for a trans-disciplinary collaboration between researchers and policy makers to find effective solutions. Despite the aforementioned limitations we lay out a pathway for more resilient systems in our work via identifying the most common climate risks and their occurrence on Southeast Asian islands and combining them with appropriate technical measures to reduce their impact.

5.2 Conclusion

With our research we address four main questions. Firstly, we target to understand which islands consist of populations with no or limited electricity access in Southeast Asia. We identify 1,932 islands with a total population of more than 21 million which are assumed to have no or only limited access to electricity. Those islands are very relevant for planning of future energy systems. Therefore, we identify three main climate risk archetypes for Southeast Asian islands showing different risk patterns and exposure with the help of a cluster analysis as the second research step. Island cluster groups are identified based on three specific risks: Share flooded by sea-level rise, temperature variation and precipitation variation. Cyclone risk is excluded from the clustering due to the lack of sufficient data coverage. The results of the PAM method clustering show three cluster groups. The first is comprised of 570 islands which are mainly affected by increased temperatures, while the other risks are relatively low. The second cluster group includes 383 islands. The related risks are temperature increase and especially land loss through sea-level rise which might make them even uninhabitable in the mid future. In addition, islands in this cluster have the highest cyclone risk. The third cluster group includes 534 islands which are affected again by temperature increase and increased precipitation variation which can lead to increased flooding.

For the third research question, we focus on technical design considerations for the respective electricity supply systems of the different island clusters. On islands in Cluster 1, measures especially combatting increased temperatures should be implemented such as cooling for substations, transformers and storage technology, concrete-sided buildings (instead of metal) or underground cabling of the distribution and medium voltage grid. These measures also apply to Cluster 2 and 3. For Cluster 2 containerized solutions can help to react to sea-level rise as they allow for easy re-allocation and piling up of systems. To decrease the impacts of cyclones and storms on the electricity infrastructure, it may be beneficial to invest in underground cabling in order to reduce their exposure to storms. Deeply grounded mounting structures, vertical wind turbine technologies and concrete buildings for sensitive equipment are also recommended in storm prone areas. Decentral system setups are also beneficial for communities situated in high cyclone risk areas. Cluster 3 suffers under an increased flooding risk which requires a diversification of energy mix and high renewable energy shares as well as modular and distributed systems enhancing overall energy security. The previously mentioned measures to protect against temperature increase and piled up container solutions also apply to this cluster. In addition, salt-water corrosion resistant components and infrastructure are important to consider in an island context as discussed.

To answer the last research question, we study how these technical aspects can be translated into policy making. The importance of integrating climate change impact assessments in energy planning is stated out by identifying several high risk zones in the region. In order to sustain positive effects of electrification in the long run, climate impacts have to be considered in the planning phase. Our GIS work can help planners to identify the specific risks for the respective island

and adapt the energy supply systems accordingly. Energy access and resilience planning can be brought together targeting several climate change induced risks such as cyclone risk, sea-level rise, flooding and temperature increase. Tenders and support mechanisms should include climate risk assessments to ensure the appropriate design of energy supply systems. Thus, planners and project developers should use multi-dimensional decision making tools considering resilience to select the right technologies for electrifying Southeast Asian islands.

Additional financing is recommended in order to implement these measures [18]. The focus should not only be kept on least-cost options but include climate resiliency criteria according to the specific location. The cluster approach shows that risk probabilities as well as risk types need to be evaluated before formulating financing criteria as different risks and probabilities apply to different areas in the region.

We conclude that our findings and the developed methodologies are able to support policy makers in Southeast Asia facing the challenge of electrifying vulnerable remote islands. The approach of combining GIS analysis of climate and energy data with cluster development meets the needs identified by institutions and commissions such as APEC [33] or ADB [18]. We therefore strongly encourage decision makers, planners and project developers to include resilience as an additional dimension into energy planning for islands in

Southeast Asia to optimally meet the local demand and to secure investments into infrastructure in the long-run.

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Annex 1 – Island Case Studies

We started our paper in analysing the research gap. As expected we found literature stating the missing link between energy planning and climate change impact (e.g. [29], [21]). Focusing on Southeast Asian islands we wanted to crosscheck this statement in analysing case studies for this region and quickly found the hypothesis confirmed. Out of 17 island electrification case studies, only one – Surawak State - mentions the topic climate change, but only the mitigation potential of switching to renewable energy sources [22]. Climate change induced impacts are not considered in energy planning and the optimization is mostly based on a least cost approach.

For this literature review, we screened scientific publications and grey literature for island case studies in Southeast Asia dealing with island electrification.

The selection was based on the following keyword search:

- “Southeast Asia” and “Island(s)” as decisive criteria
- “Energy access” and/or “power supply”

We limited our search to Science Direct and found for the combination “Southeast Asia”, “island(s)” and “energy access” 61 matching papers and for “power supply” 299. In order to evaluate current energy planning for Southeast Asian islands, we further narrowed the selection down to case studies focusing on electrification. The criteria here were to select the case studies giving an overview on concrete locations (islands, villages etc.) and to give basic information on current or planned energy supply. We thus identified 5 studies including 13 cases (locations) out of the previously screened paper (abstract reading and keyword search). We also included 4 additional cases from the authors' personal project experience in Thailand. A detailed overview of all included case studies in given in the table below.

INDONESIA Electrification rate: 97.6 % [81]									
Island / Village	**Size** *Area and population*	**Location**	**Type of Electricity Access**	**Current Power Source**	**Electricity Tariff**	**Operator**	**Cost & Financing**	**RE Potential**	**Source**
Curugagung Village	121 connected HHs	-6.627132, 107.682756	Grid connected mini-grid (12 kW feed-in capacity)	Hydro power mini-grid Grid connection in 1991	$0.008/kWh	Project Owner: Cooperative Project Facilitator: Yayasan Mandiri	Interconnection: Loan	Hydro	[82]

Dompyong Village	40 connected HHs	-7.92623, 111.7078	Grid connected mini-grid (30 kW feed-in capacity)	Hydro power mini-grid Grid connection in 2003	$0.044/kWh	Project Owner: Cooperative Project Facilitator: ENTEC and Heksa	Interconnection: GTZ	Hydro	[82]
Seloliman Village	45 connected HHs	-7.5955, 112.59304	Grid connected mini-grid (30 kW feed-in capacity)	Hydro power mini-grid Grid connection in 2003	$0.04/kWh	Project Owner: Village Association Project Facilitator: ENTEC and Heksa	Interconnection: GTZ	Hydro	[82]
Santong Village	-	-8.39427, 116.34265	Grid connected mini-grid (40 kW feed-in capacity)	Hydro power mini-grid Grid connection in 2004	-	Project Owner: Village Cooperative Project Facilitator: Renerconsys	Interconnection: Local government	Hydro	[82]
Salido-Kecil Village	20 connected HHs	-1.24801, 100.64217	Grid connected mini-grid (668 kW feed-in capacity)	Hydro power mini-grid	$0.033/kWh	Project Owner: Developer	Interconnection: Equity and Bank Loan	Hydro	[82]

				Grid connection in 2005/6		Project Facilitator: PT AMS			
Kabupaten Mojokerto (Wat Lemah) Village	25 connected HHs	-7.59722, 112.58249	Grid connected mini-grid (20 kW feed-in capacity)	Hydro power mini-grid Grid connection in 2008	$0.04/kWh	Project Owner: Village association Facilitator: PT GMN Renerconsys	Interconnection: Village, GIF, PLN	Hydro	[82]
Sumba Island (Bakuhau MHP)	305 connected HHs	-9.69934, 119.97405	Grid connected mini-grid (37 kW feed-in capacity)	Hydro power mini-grid Grid connection in 2013	$0.039/kWh	Project Owner: Village cooperative Project Facilitator: IBEKA	Interconnection: IBEKA	Hydro	[82]
MALAYSIA Electrification rate: 100 % [81]									

Island / Village	Size	Location	Type of Electricity Access	Current Power Source	Electricity Tariff	Operator	Cost and Financing	RE Potential	Source
Juara village; Tioman Island	30 chalets (locals and resorts)	2.796247, 104.203634	-	-	-	-	-	solar radiation is estimated to be 5.21 kWh/m^2/day Wind speed 3.18 m/s Pre-feasibility study shows: 35 + 60 kW diesel OR 200 kW PV, 40 small wind turbines, 500 batteries	[83]
Pulau Perhentian		5.90097, 102.75147		200 kW diesel generators					[83]
Terumbu Layang		7.3736, 113.82872		150 kW wind turbine					[83]

Sarawak State	2.47 million, (more than half of which are indigenous groups living in rural village communities)	1.55327, 110.35921	Grid connection	peak annual energy demand 1250 MW, met by a mix of diesel, coal and natural gas generation and hydropower dams (92% fossil fuels)	for domestic customers is US $0.097/kWh while commercial customers pay US $0.068/kWh and industrial consumers pay US $0.077/kWh	operated or purchased by the state utility company SESCO		Hydro potential: State is planning 50 large scale dams (in total 20 GW) has one of the country's densest river networks and abundant rainfall; 20,000 MW of potential capacity in the state Many small scale hydro systems in remote areas installed and more potential (20 sites with high potential identified, 4.4 MW) Biomass Potential: Residues of palm oil production; 41 processing plants Two ways: empty fruit branches (EFB) biogasification and palm oil	[22]

	mill effluent (POME) biogas recovery Solar Potential: 5.00 kWh/m2/day barely developed, high potential even though it is in fact rare to have an entirely clear day even in periods of severe drought Wind Potential: is relatively poor; minimum monthly averaged wind speed is 1.51 m/s in April and the maximum is 5.27 m/s in August	
PHILIPPINES Electrification rate: 91 % [81]		

Island / Village	Size	Location	Type of Electricity Access	Current Power Source	Electricity Tariff	Operator	Cost and Financing	Renewable Energy Potential	Source
Pangan-an Island	375 households 2800 people	10.220132, 124.039032	Mini-grid & private diesel generators 42% of the households are using only less than 3 kWh/month Average: 6 kWh/month	PV (45.36 kW) /battery mini-grid (established in 1999); Some households additionally use small diesel generators	LCOE: donated system USD0.7/kWh not donated USD1.45/kWh	community cooperative: Pangan-an Island Community Cooperative for Development (PICCD)	Donation (Belgian government)	High RE potential, BUT mini-grid efficiency decreased (no funding for battery and PV panel replacement)	[84]

THAILAND

Electrification rate: 100 % [81]

Island / Village	Size	Location	Type of Electricity Access	Current Power Source	Electricity Tariff	Operator	Cost and Financing	RE Potential	Source

Bulon Don Island	81 households 300 people	6.856191, 99.593076	SHS, private diesel generators	SHS, small to medium diesel generators (3 – 7.2 kW)	12.8-63.4 USD/kWh	Family structures	SHS: Provincial Electricity Authority and Local Government Diesel generators: Family structures	PV/battery/diesel mini-grid most economically feasible electrification option (52.1 kW PV; 100kWh battery; 3x15 KW diesel)	[85]
Bulon Lae Island	79 households 170 people 11 resorts	6.829273, 99.535025	SHS, private diesel generators	SHS, small to medium diesel generators (1.76 – 8.8 kW)	-	Resorts and family structures	SHS: Provincial Electricity Authority and Local Government Diesel generators: Resorts and family structures		[86]
Jik Island	400 people 1.12 km^2	12.292714, 102.238743	Mini-Grid	PV-diesel-battery mini-grid (40 kW PV, 240 kWh battery, 50 kW diesel)	Community committee is fixing the price	Koh Jik Energy Service Company (Koh Jik ESCo)	Grand funded (Thai government)	Upgrade (19 kW PV , battery and diesel generator replacement)	[87]

Mak Noi Island	250 households 1400 people		Private diesel mini-grids	SHS, small and big diesel genrators (3 – 50 kW)	8.8 – 60.8 USD/kWh	Local entrepreneurs	SHS: Provincial Electricity Authority and Local Government Diesel Generators: Local entrepreneurs and family structures	PV/battery/diesel mini-grid most economically feasible electrification option (400 kW PV; 700kWh battery; 3x80 KW diesel)	[86]
TIMOR LESTE Electrification rate:63.4 % [81]									
Island / Village	**Size**	**Location**	**Type of Electricity Access**	**Current Power Source**	**Electricity Tariff**	**Operator**	**Cost and Financing**	**RE Potential**	**Source**
Suro Craic Village	350 households	-9.059372, 125.545073	SHS and private diesel generators	Pico-PV and small diesel generators	$0.12/kWh or $2.40/month for households consuming 20	Local entrepreneurs	Local entrepreneurs	Yearly Capacity factors: PV 0.24; Wind: 0.28; Hydro: 0.4	[88]

		kWh; the rest of the costs being subsidized	Biomass gasification: yield 2.9 ton of wood/hectares/year	