Climate Change Resilient Energy Systems for Southeast Asian Island Communities

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an der Fakultät III - Prozesswissenschaften
der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktorin der Ingenieurwissenschaften
- Dr.-Ing. -

genehmigte Dissertation

Promotionsausschuss:

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Tag der wissenschaftlichen Aussprache: 20. Juni 2022

Berlin 2022

Zusammenfassung

Südostasien ist eine der Regionen, die am stärksten von den Auswirkungen des Klimawandels betroffen sind. Dies gilt insbesondere für abgelegene Gemeinden auf den zahlreichen, kleinen Inseln in der Region. Die Dringlichkeit, die Resilienz dieser abgelegenen Inselgemeinden gegen die Folgen des Klimawandels zu stärken, wird immer deutlicher. Darüber hinaus sind diese Gemeinden mit dem Problem einer begrenzten und unzuverlässigen Stromversorgung konfrontiert. Der Zugang zu Elektrizität ist eine Grundvoraussetzung für viele Klimaanpassungsmaßnahmen und hat somit das Potenzial, den südostasiatischen Inselgemeinden dabei zu helfen, ihre Resilienz zu verbessern. Überraschenderweise werden beide Aspekte - Stromzugang und Klimaresilienz - in der aktuellen Energieplanung für diese Gebiete nur selten miteinander verknüpft. Die Energieplanung in einer vom Klimawandel stark betroffenen Region erfordert integrierte und multidimensionale Lösungen, die diese Risiken berücksichtigen. Meine Forschung zielt darauf ab, eine klimaresiliente Planung von netzfernen Energiesystemen zu ermöglichen, um südostasiatische Inselgemeinden bei ihren Bemühungen zur Anpassung an den Klimawandel zu unterstützen. Im Rahmen dieser Forschung wird ein erster Ansatz für eine klimaresiliente Energiesystemplanung entwickelt und angewandt, der auf Literaturrecherche, Datenanalyse und empirischer Forschung basiert. Dazu wird (i) eine Risikobewertung der Klimawandelfolgen für südostasiatische Inseln durchgeführt. Auf der Grundlage dieser Ergebnisse werden (ii) standortspezifische Anpassungsmaßnahmen ausgewählt und bei der Modellierung des Energiesystems für drei repräsentative Fallstudieninseln berücksichtigt.

Auf der Grundlage der Literaturrecherche wurden vier verschiedene mit dem Klimawandel zusammenhängende Risiken identifiziert, die sich auf aktuelle und künftige Energiesysteme auswirken: Temperaturanstieg, Schwankungen von Niederschlagsmustern (die zu Überschwemmungen und Dürren führen), Anstieg des Meeresspiegels und extreme Wetterereignisse (z.B. Zyklone). Die mit QGIS, R und Excel durchgeführte Risikobewertung des Klimawandels zeigt eine erhebliche Häufigkeit und Schwere dieser Risiken für die südostasiatischen Inseln, ihre Gemeinden und die (zukünftigen) Energiesysteme. Die vom Klimawandel hervorgerufenen Risiken sind in der Region unterschiedlich ausgeprägt, aber es lassen sich Muster und Merkmale erkennen: Es besteht ein starkes, geografisch zuzuordnendes Risiko für Zyklone, ein hohes Risiko für den Anstieg des Meeresspiegels für kleinere Inseln (die einen höheren Anteil ihres Landes verlieren) und ein höheres Überschwemmungsrisiko für Inseln außerhalb der tropischen Klimaklassifikation (Köppen-Geiger). Für alle in dieser Analyse einbezogenen Inseln wurden standortspezifische Risikoprofile und -skalen erstellt.

Basierend auf den Ergebnissen der durchgeführten Experteninterviews wird eine Auflistung von Anpassungsmaßnahmen und damit verbundenen, zusätzlichen Investitionskosten zur Verringerung der Auswirkungen der standortspezifischen Klimarisiken auf netzferne Energiesysteme und an den Klimawandel angepasste Energiebedarfe erstellt. Verschiedene Energiemodellierungsszenarien, die in HOMER ausgeführt wurden, helfen dabei, verschiedene Grade klimaresilienter Planung abzubilden und ermöglichen einen Vergleich mit gängigen Planungsansätzen für drei Fallstudieninseln. Die Auswertung dieser Szenarien, die unterschiedliche Häufigkeiten und Schweregrade von klimawandelbedingten Schäden am Energiesystem simulieren, zeigt, dass eine klimaresiliente Energiesystemplanung in den meisten Fällen von Vorteil ist: Für 6 - 8 von 9 Fällen pro Insel zeigt der Ansatz der klimaresilienten Energiesystemplanung niedrigere Elektrizitätskosten als die BAU-Systemplanung. Je höher die Häufigkeit und Schwere der durch den Klimawandel verursachten Schäden am Energiesystem ist, desto sinnvoller ist es, einen klimaresilienten Systemplanungsansatz zu verfolgen. Eine resiliente Energiesystemplanung verringert die Wahrscheinlichkeit von Stromausfällen aufgrund von Klimawandelfolgen und minimiert somit die mit den Stromausfällen verbundenen wirtschaftlichen Verluste. Vergleicht man die Differenz der Investitionskosten zwischen BAU und klimaresilienter Planung mit den geschätzten Kosten der Stromausfälle auf den Fallstudieninseln, so wird deutlich, dass sich eine resiliente Energiesystemplanung lohnt: Nach 23 bis 66 Tagen andauernder Stromausfälle erreicht die Investitionsdifferenz die Gewinnschwelle.

Diese Forschungsarbeit gibt einen ersten Überblick über den potenziellen Nutzen und die Anwendbarkeit einer klimaresilienten Energiesystemplanung für vom Klimawandel bedrohte Gebiete und bietet einen Ansatz zur Integration der Klimarisikoanalyse in die Energiesystemplanung. Die Ergebnisse verdeutlichen die Bedeutung der Klimarisikobewertung und der darauf aufbauenden Planung eines resilienten Energiesystems für eine vom Klimawandel bedrohte Region wie Südostasien. Der entwickelte Ansatz verbessert die langfristige Energiezuverlässigkeit der südostasiatischen Inselgemeinden und kann so ihre Klimaresilienz steigern.

Abstract

Southeast Asia is one of the regions most affected by the impacts of climate change. This is particularly true for remote communities on the numerous small islands in the region, underscoring the urgency of building climate change resilience for these remote island communities. In addition, these island communities face the problem of limited and unreliable electricity supply. Access to electricity is a prerequisite for many adaptation measures and thus has the potential to help Southeast Asian island communities improve their resilience. Surprisingly, both aspects electricity access and climate resilience are rarely linked in current energy planning for these island communities. Energy planning in a region highly affected by climate change requires integrated and multidimensional approaches that take these risks into account. Thus, my research aims to enable climate-resilient planning of off-grid energy systems to support island communities' adaptation efforts. This thesis develops and applies an initial and holistic approach towards climate resilient energy system planning building on the literature review, data analysis, and empirical research. Therefore, (i) a climate change risk assessment for Southeast Asian islands is developed and conducted. Based on these results, (ii) site-specific adaptation measures are selected and considered for three representative case study islands through energy system modelling.

Based on the literature review, four different climate change-related hazards that impact current and future energy systems are identified: temperature increase, fluctuation in precipitation patterns (leading to floods and droughts), sea-level rise, and extreme weather events (e.g. cyclones). The climate change risk assessment conducted with QGIS, R and Excel reveals significant frequency and severity of these risks to Southeast Asian islands, their communities, and (future) energy systems. Climate change hazards vary across the region, but patterns and characteristics can be identified: There is a strong, geographically attributable risk for cyclones, a high risk for sea-level rise for smaller islands (resulting in a higher proportion of land loss), and a higher risk of flooding for islands outside the tropical climate classification (Köppen-Geiger). Furthermore, site-specific climate change risk profiles and scales are developed for all islands and included in the analysis.

A list of adaptation measures and associated additional investment costs to reduce site-specific climate risks on off-grid energy systems and climate change-adapted demand structures is then compiled based on the results of the expert interviews conducted. Various energy modelling scenarios run in HOMER helped to map different degrees of climate resilient planning and allow for comparison with common planning approaches (business as usual - BAU) for three case study islands. Evaluation of these scenarios, which simulate different frequencies and severities of climate

change induced damage to the energy system, shows that climate-resilient energy system planning is feasible in most cases: for 6 - 8 out of 9 cases per island, the climate-resilient energy system planning approach shows lower COEs than BAU system planning. The higher the frequency and severity of damages caused by climate change, the more feasible it is to adopt a climate-resilient system planning approach. Resilient power system planning reduces the probability of power outages due to environmental disturbances and thus minimises the losses associated with outages. Comparing the difference in investment costs between BAU and climate resilient planning with the estimated costs of power outages on the case study islands, it is clear that resilient power system planning pays off quickly: after 23 to 66 days of power outages, the investment difference reaches break-even.

This research provides an initial overview of the potential benefits and applicability of resilient energy system planning for areas threatened by climate change and offers an approach to integrating climate change risk analysis into energy system planning. The results highlight the importance of climate risk assessment and resilient energy system planning for climate change threatened regions such as Southeast Asia. The developed approach improves the long-term energy reliability of Southeast Asian island communities and increases their resilience in the face of the intertwined climate and energy challenges.

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List of Acronyms

BAU	Business as usual
CAPEX	Capital expenditures
CGIAR-CSI	Consultative Group on International Agricultural Research - Consortium for Spatial Information
CMIP	Coupled Model Intercomparison Project
CNRM	Centre National de Recherches Météorologiques
COE	Cost of electricity
GADM	Database of Global Administrative Areas
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse gas
HDI	Hydrological Drought Index
HOMER	Hybrid Optimization of Multiple Energy Resources
ICT	Information and communication technology
IPCC	Intergovernmental Panel for Climate Change
IEA	International Energy Agency
MY	Myanmar
MV	Mean value
NGO	Non-governmental organisation
NIC	National Intelligence Council
oemof	Open Energy Modelling Framework
OPEX	Operation expenditures
PAM	Partitioning Around Medoids
PV	Photovoltaic
RCP	Representative Concentration Pathways
RE	Renewable energy
SATH	Satellite Hydrology Project
SDG	Sustainable Development Goal
SHS	Solar-home system
TH	Thailand
UK	United Kingdom
UN	United Nations
USA	United States of America
VN	Vietnam

Chapter 1

Introduction

1.1 Motivation

Southeast Asia is heavily 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, and sea-level rise, the alteration of weather patterns like seasonal monsoons pose a substantial threat to the livelihoods of Southeast Asian people [1, 3, 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) [6]. 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 [7]. 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 [7]. 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 from the impact of climate change [7]. Especially, highly urbanized areas along the coastline are under threat [8]. This situation is worsened as ecosystems that helped to protect coastal areas and their inhabitants, such as mangroves and coral reefs, are also highly impacted by climate change [7]. Indonesia and the Philippines as the two island states have a high number of people at risk from sea-level rise [3]. Projections show that the number of people at risk is expected to increase dramatically by 2050 (e.g. in Indonesia from 13.0 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 [9]. Looking at the issue of electricity access in Southeast Asia, two main points become apparent: firstly, 65 million people currently have no access to electricity, and secondly, many millions only have access to unreliable electricity supply, depending on costly and polluting diesel generators for power provision [10]. Both situations hinder the achievement of the Sustainable Development Goal (SDG) 7: Access to sustainable energy supply for all [11]. Regional policy makers have recognised this challenge and made strong efforts to improve the supply situation e.g. on remote islands. Estimations by the International Energy Agency (IEA) also highlight that all countries in Southeast Asia will achieve universal access by the early 2030s (New Policies Scenario) [10]. To reach this goal it is expected that $ 14 billion is required to be invested [12]. 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 of 26 % via small-scale off-grid solutions such as solar home systems [10]. The two island states Indonesia and the Philippines will reach an even higher percentage of about 75 % of their off-grid population via mini-grids [12]. All energy sources play crucial roles in this regard, but renewables are of special importance for electrifying remote areas and provide a viable alternative to expensive and polluting diesel generators [10]. These facts underline the region's upcoming high investments to connect Southeast Asia's last mile.

Given that both - climate change impacts and the electrification challenge - are crucial issues for Southeast Asian islands, it is obvious that integrated adaptation and energy system planning is necessary for the region's sustainable development. The NIC states that the "[electric power] sector is itself vulnerable to projected changes in climate" [7] and the "[...] Electric power in Asia and the Pacific is [...] a vulnerable sector in a vulnerable region" [7]. 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 [13]. Improved climate change resilience of the communities is strongly connected to access to reliable electricity supply which is a prerequisite for many adaptation measures and enables and maintains many vital functions of communities [14]. 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” [15]. This is underlined by the estimation published within the UN Global Climate Change Action Plan: The cost of climate-related disasters increases to a total of USD 2.7 trillion over the next 20 years while the cost of making infrastructure resilient is about 3 % of this [16]. This emphasises the importance of resilient design and planning of critical infrastructure like electricity systems.

It is therefore a significant weakness that both aspects – electricity access and climate resilience - are barely linked to each other, both in current adaptation and electrification strategy planning. The missing connection becomes obvious while screening literature. While there are studies about climate change impacts on centralised energy systems in the Global North (e.g. Norway [17], Germany [18], USA [19] or Australia [20]), there is a notable lack of current investigation on the effects of climate change on decentralised (off-grid) energy systems in the Global South. A review 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” [14]. Ebinger et al. (2011) also emphasize the importance of integrated-risk based planning processes e.g. in the energy sector to address climate change hazards and build resilience [21]. At the same time they state that the knowledge base is still nascent [21]. 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 [...]”. However, this subject has by far not been investigated sufficiently [22]. This leads to the main objective of my research, which is the development of an approach to integrate climate change risk considerations in off-grid energy system planning.

1.2 Research Questions

In order to achieve this, I developed the following research questions:

Research Question 1: Which climate change risks affect Southeast Asian island communities and their energy infrastructure and to what extent?

- Which climate change risks have an impact on island energy systems?
- Which of these climate change risks occur on Southeast Asian islands and in what degree of intensity?
- Can climate change risk profiles and patterns be identified for these islands?

Research Question 2: How can these island communities be supplied by technically resilient energy systems considering the identified climate risks?

- Which technical measures can increase the resilience of island energy systems to climate change and at what cost?
- How can these measures and related costs be implemented in modelling resilient energy system scenarios?
- Under what circumstances is resilient energy system planning beneficial?

1.3 Structure

To address these research questions, it is first necessary to understand which climate change hazards are influencing energy systems and analyse their probability and intensity for the study area of Southeast Asian islands. Therefore, spatial analysis using the open-source Geographic Information System software QGIS is applied complemented by the statistical software R. Combining both allows for an analysis of different climate change risks and extreme weather phenomena relevant for the islands. A cluster analysis of these climate change risks supports the identification of risk patterns on the islands. In a second step, the impacts of identified risks on the island energy systems are studied and measures to mitigate these impacts are explored. A literature review alongside expert interviews serve to identify suitable adaptation measures and related costs to mitigate climate change risks on the island energy supply systems. The acquired data and results are applied in business as usual (BAU) and resilient energy system modelling for case study islands using the "Hybrid Optimization of Multiple Energy Resources" (HOMER) software. Both energy system planning approaches (BAU and resilient) are evaluated in a next step, upon which recommendations and further research needs are formulated. These aim at integrating, strengthening and advancing climate change resilient energy system planning in the off-grid sector.

The thesis is structured into five chapters. Chapter 2 provides the theoretical framework to this thesis and gives background knowledge on climate risk analysis and resilient energy system planning. The Methodological Approach (Chapter 3) introduces the methods applied for both core topics - climate change risk analysis and resilient energy system planning. Each topic is subdivided into two sections - "data acquisition and processing" (Section 3.2) and "application of data" (Section 3.3). Results (Chapter 4) are presented and discussed by research area (Southeast Asian islands, Section 4.1), followed by the climate change risk analysis (Section 4.2) and resilient energy system modelling and evaluation for case study islands (Section 4.3) and a brief discussion on limitations of the presented research (Section 4.4). Chapter 5 concludes the results and gives an outlook into further research needs and implementation recommendations.

Chapter 2

Background

In this section, I introduce and combine the overarching topics of my research - climate change resilience and impacts on energy systems - and narrow them to the geographic scope of Southeast Asian islands. First, I introduce the theoretical framework for this research - the concept of climate resilience - which is then applied to the case study of Southeast Asian island communities and their energy infrastructure (Section 2.1). Their special situation in the face of climate change is discussed in Section 2.2. Section 2.3 describes how electricity access improves the often precarious situation of island communities in Southeast Asia with regard to climate change impacts and enhances their resilience. It also gives an overview of electrification approaches and adaptation measures to improve the technical resilience of energy systems.

2.1 Concept of Climate Change Resilience

The process of climate change leads to large-scale shifts in the world's climate, economic, and societal systems. Thereby this change is rapidly redesigning the realities and livelihoods of humankind, who are simultaneously the main affected and main driver of such changes [23]. The negative impacts of anthropogenic[1] climate change require systems, societies, and individuals to be capable of quickly adapting to those changes, favouring those with the highest resilience [24]. It is therefore crucial to discuss measures and options to improve the resilience of areas and communities most at risk. In order to do so, we first need to understand what defines and influences climate resilience.

[1]Relating to or resulting from the influence of human beings on nature

Resilience is often considered as the flip-side or even the opposite of vulnerability[2]. Resilience defines how individuals, communities or societies continue to thrive and develop under shocks and stresses [26]. The different aspects to be considered while talking about resilience are summarised by Figure 2.1, which is based on the work of the UK Department for International Development [25]. The exact definition and concept of resilience depends on the sector using the term. In this thesis, the concept of resilience is applied to the context of increasing climate change impacts on Southeast Asian island communities and their energy infrastructure. Climate resilience means the strength to prepare for, sustain, and recover from shocks and stresses caused by the impacts of climate change [26].

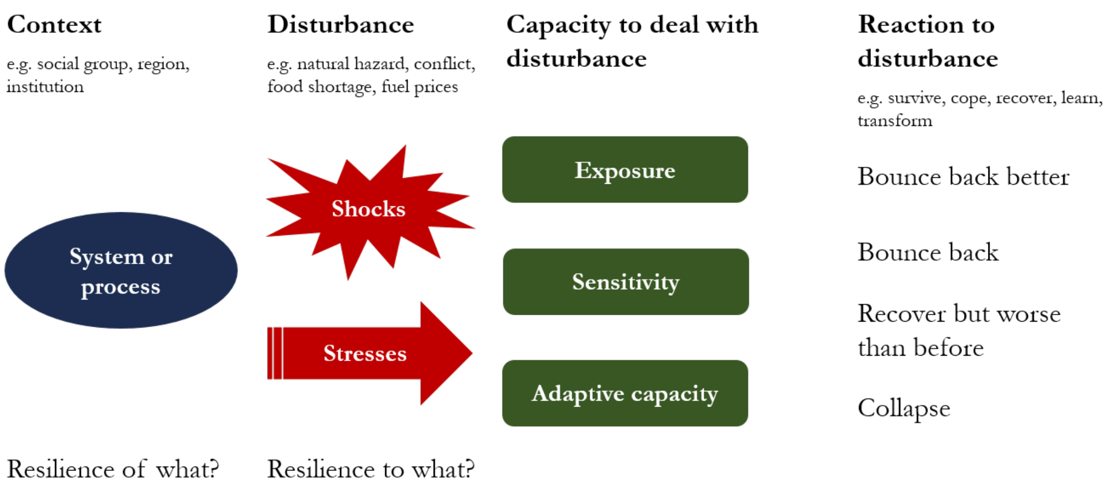

Figure 2.1: *Resilience framework, own visualisation based on [25]*

According to Figure 2.1, it is first of all important to define the context ("Resilience of what?") and the cause of potential disturbances ("Resilience to what?") in order to understand who is preparing for what [27]. For example, one can study the resilience of a specific island community or an island energy system to set the context ("Resilience of what?"). My research is motivated by the necessity to increase the climate resilience of island communities and studies the climate resilience of island energy systems more specifically ("Resilience of what?" -> island energy system). In this thesis, I focus on disturbances (shocks and stresses) caused by the impacts of climate change ("Resilience to what?" -> climate change impacts). Climate change induced shocks are sudden events like storms, landslides, and extreme weather events

[2]The degree to which a person, process, or system is susceptible to, or unable to cope with, the adverse effects of shocks and stresses [25]

that have a relatively short duration, but create an immense impact on communities [25]. Climate change related stresses are long-term trends such as increasing temperatures, natural resource degradation or prolonged droughts [25].
Every individual, community or energy system (in this context) has a certain capacity to deal with this disturbance depending on their (i) exposure, (ii) sensitivity, and (iii) adaptive capacity. Exposure is the degree of which e.g. a community and their infrastructure is exposed to climate change [25]. The exposure to climate change induced shocks and stresses is often difficult to influence as it is mainly determined by geographical position, and in the case of Southeast Asian island communities, relocation to other islands or the mainland poses a last resort. Sensitivity is the likeliness to experience adverse consequences while being exposed to hazards [28]. Adaptive capacity refers to the ability to cope with or recover from shocks and stresses and relates to factors that allow communities to anticipate and plan for stresses and disasters effectively: to learn from experiences of previous hazards and to act based on the lessons learnt of that experience [28]. In summary, exposure and sensitivity indicate the potential impact. The potential impact and adaptive capacity together are indicators for vulnerability. The adaptive capacity and potential impact are two important factors to influence how the individual, group, or infrastructure reacts to and gets out of the disturbance (reaction to disturbance) [29].

In summary, this thesis looks at islands communities and their energy infrastructure as context and it analyses climate change induced shocks and stresses as disturbance. As sensitivity and exposure is usually high for most islands communities, increasing the adaptive capacity will be at the center for further analysis within this research. Measures to improve climate resilience of communities and their infrastructure are manifold and include the development of proper disaster risk management, increasing communities' independence and livelihood options amongst others. Out of the manifold measures to increase adaptive capacity, reliable energy access is a key enabler and will be further discussed in Section 2.3.4.

2.2 Southeast Asian Islands in the Face of Climate Change

In this section, the context of research - South East Asian island communities - is further defined and elaborated. After a general overview of the Southeast Asian island landscape, their special role in a world affected by climate change is highlighted.

2.2.1 Southeast Asian Island Landscape

The Southeast Asian region extends over the southern and northern hemisphere near the equator. It includes eleven countries, namely Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. Many of those encompass long coast lines; four nations are island states (Indonesia, Philippines, Brunei, and Timor Leste). Even though the Andaman and Nicobar islands politically belong to India, their geographical location is within the Western part of Southeast Asia. The island group faces similar climate change challenges and is therefore included in the scope of this research. Figure 2.2 gives an overview of Southeast Asian countries and the region's location on the world map.

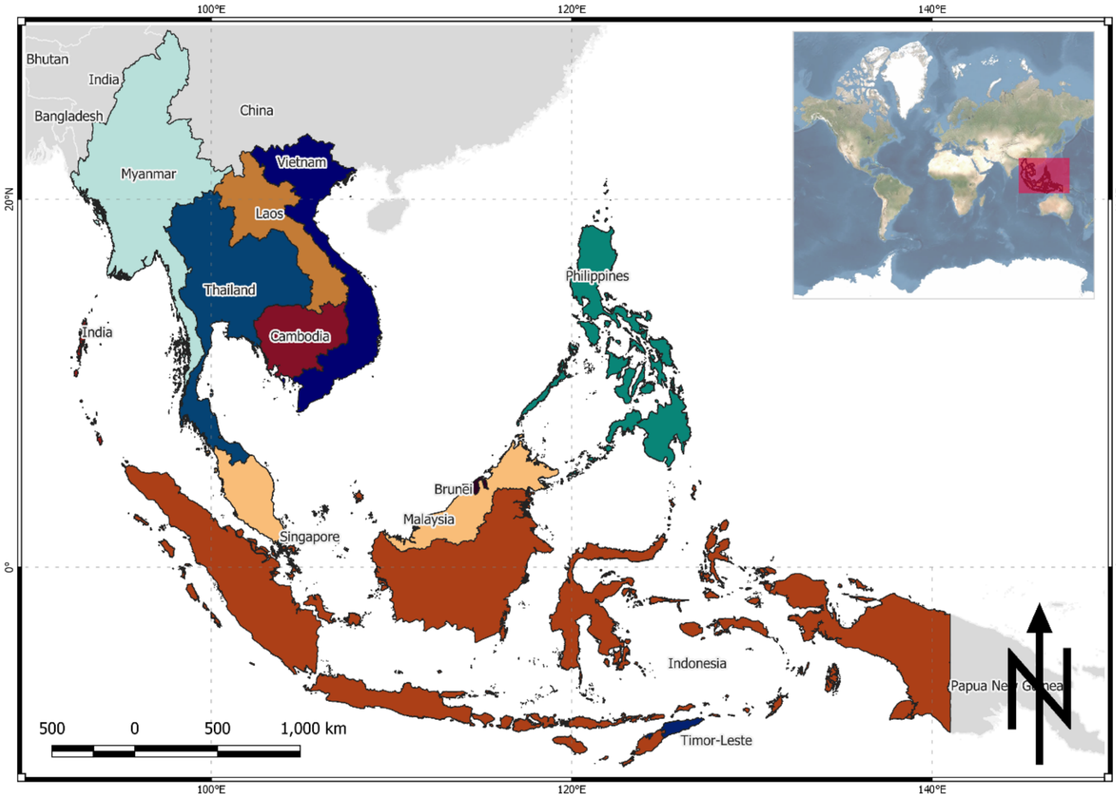

Figure 2.2: Map of Southeast Asian countries plus Andaman and Nicobar Islands (India) and the region's location on the world map

This research focuses on islands situated in the sea or river deltas connecting to the sea. Mainland islands situated in lakes or rivers face different climate change hazards than islands situated in the sea as their climate is influenced by the surrounding land masses rather than of the surrounding ocean [30]. Mainland islands in Southeast Asia are therefore not considered. It is difficult to give an exact number of islands situated in Southeast Asia because figures and statistics vary. Different sources (mainly WorldData and WoldAltas) indicate up to approximately 34,000 islands in Southeast Asia including the Andaman and Nicobar islands. Table 2.1 lists the number of islands per country.

Table 2.1: *Overview of Southeast Asian countries and number of islands situated in the sea*

Country	**No. of islands**	**Source**
Brunei	10	[31]
Cambodia	64	[31]
India *(only Andaman and Nicobar islands)*	836	[32]
Indonesia	18,307, 17,504	[31], [33]
Laos	-	
Malaysia	878	[31], [33]
Myanmar	1,000	[31], [33]
Philippines	7,641	[31], [33]
Singapore	63	[31]
Thailand	1,430	[31], [33]
Timor Leste	3	[31]
Vietnam	4,000	[31], [33]
Total	34,232, 33,429	

2.2.2 Vulnerability of Southeast Asia and its Islands

Southeast Asia is one of the regions most affected by the impacts of climate change globally [1]. This is particularly relevant for remote communities located on the numerous small islands in the region as further elaborated in this section. Figure 2.3 on the following page maps multiple climate hazards for Southeast Asia considering tropical cyclones, floods, landslides, droughts, and sea-level rise. Darker colors indicate a higher climate hazard index. Table 2.2 (following page) gives an overview of climate change hotspots in the region and their dominant hazards as determined by Yusuf et al. (2009) [34].

The following island hotspot areas can be identified: (i) the Philippines challenged by cyclones, landslides, floods, and droughts, (ii) the western and eastern parts of Java Island (Indonesia) threatened by landslides, floods, droughts, and sea-level rise, (iii) islands in the South China Sea, particularly in the Southern part of Vietnam facing sea-level rise, (iv) islands located in the Gulf of Thailand (Thai and Cambodian

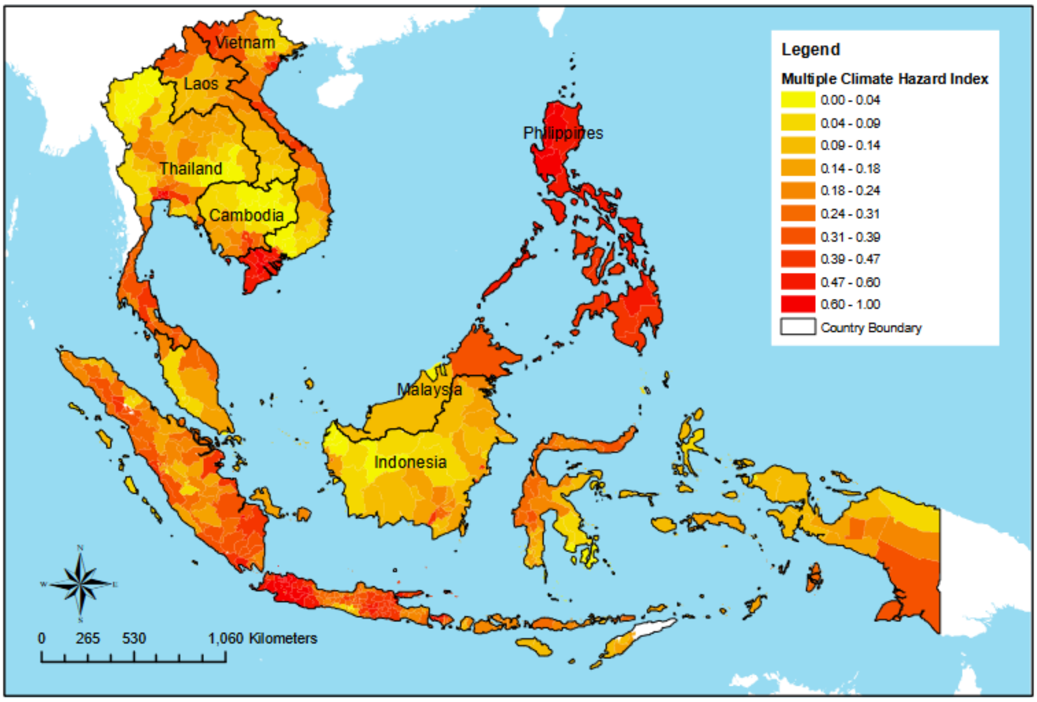

Figure 2.3: *Multiple hazard map of Southeast Asia, Myanmar is not considered [34]*

Table 2.2: *Climate change hazard hotspots in Southeast Asia according to [34]*

Hotspot area	**Dominant threat**
Northwestern Vietnam	Droughts
Eastern coastal areas of Vietnam	Cyclones, droughts
Mekong region of Vietnam	Sea level rise
Bangkok and its surrounding area in Thailand	Sea level rise, floods
Southern regions of Thailand	Droughts, floods
The Philippines	Cyclones, landslides, floods, droughts
Sabah state in Malaysia	Droughts
Western and eastern area of Java Island, Indonesia	Droughts, floods, landslides, sea level rise

islands) challenged by sea-level rise and floods, and (v) most islands in the Andaman Sea (Thailand) affected by droughts and floods.

Thomas et al. (2020) emphasise that climate change impacts associated with the ocean (e.g. sea level rise or tropical cyclones) are of particular concern since many islands have close connections between settlements and coastal environments [30].

On islands, many communities and their infrastructure are located close to shoreline resulting in high levels of exposure to escalating impacts of climate change [30]. This also applies to marine resources and the biodiversity on and around the island which often influence the sectors making the bulk of the island's Gross Domestic Product (GDP) (e.g. tourism, fishery, or agriculture) [30]. In addition to this, Moghim et al. (2019) determine a low environmental resilience for Southeast Asia [35]. Thus, islands in Southeast Asia are heavily impacted by a changing climate, while at the same time having limited mitigation options. Adaptation to climate change impacts is therefore an essential element to sustain livelihoods on the numerous islands in Southeast Asia. As mentioned in Section 2.1, building adaptive capacities is key to counter vulnerabilities and improving resilience. Electricity access is one important pillar to support measures improving adaptive capacities and is discussed in more detail in the following section.

2.3 Electricity Access in the Face of Climate Change

2.3.1 Defining Electricity Access

According to the International Energy Agency (IEA) there is no internationally-adapted definition of energy access. However they identified common grounds within different definitions being [36]:

- Household access to a minimum level of electricity,
- Household access to safer and more sustainable cooking and heating fuels and stoves (i.e. minimum harmful effects on health and the environment as possible),
- Access to modern energy that enables productive economic activity, e.g. for agriculture, shops or industry, and
- Access to modern energy for public services, e.g. electricity for health facilities, schools, and street lighting.

They furthermore define "locales" of energy consumption within a community as households (covering electricity, heating, and cooking demands), productive engagements (e.g. shops, agriculture, and artisans), and community facilities (being health and educational facilities, street lighting, government and public buildings) [36, 37].

In order to measure progress towards SDG 7, the IEA simplifies its energy access definition as “a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average” and projects this to equal an annual minimal electricity consumption of 1,250 kWh per household [36].

In this thesis, I focus on energy access limited to electricity and therefore not considering access to cooking fuels such as charcoal, wood, or gas. I build upon the IEA’s considerations and define electricity access as given if a basic level of household and community needs are met and productive use is enabled.

2.3.2 Electrification Approaches

The three common options to electrify communities 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 2.3.

Table 2.3: *Electrification options and their application, based on [38]*

Electrification option	**Electricity consumption**	**Population density**	**Distance to grid**	**Complexity of terrain**
Grid extension	high	high	close	easy
Mini-grids	medium/high	medium/high	medium/far	medium
Small stand-alone systems	low	low	far	complex

These three options are not equally prone to be affected by the impacts of climate change. In this thesis, I focus 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 climate change induced hazards [39]. 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 (SHS) 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. Depending on the users and their mindfulness, the climate resilience of small stand-alone systems is considered high [13]. Because of their low vulnerability to the impacts of climate change, small standalone systems and submarine grid extension are not further considered in this research. Mini-grids however combine generation, transmission, and distribution on the island and are designed to cover the local demand. All technical components (generation sources, transmission, and distribution as well as storage technology) and the local demand is influenced by climate change [22,40]. Therefore, island electrification via mini-grids is the focus of this research: The system design and setup, its technical components as well as related demands are considered and further analysed.

2.3.3 Renewable Energy Potential for Electricity Access in Southeast Asia

Access to electricity is a top priority for policy-makers in Southeast Asia. They made great progress, with electrification rates rising by 28 % since 2000 being at 90 % in 2017 [10]. The large number of communities situated on remote and difficult to access islands makes the challenge to reach the last mile more difficult. It is estimated that 65 million people still lack access to electricity in Southeast Asia [10]. 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 compare this with electrification via decentralized mini-grids (700 million USD) [41]. The study finds renewable energy (RE) based hybrid systems most feasible for the majority of islands and submarine cable interconnection more promising for a few larger islands [41]. 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 technology combined with battery storage solutions and/or diesel back-up generators, are one of the most feasible solutions [42]. SHS are often applied in very sparsely populated areas with high distances to the next grid connection point and low electricity consumption [43]. Thus, RE-hybrid mini-grids and SHS play a crucial role to reach the last mile on Southeast Asia's remote islands.

Solar and wind power potential. Renewable energy sources have a high potential in Southeast Asia: Figure 2.4 shows solar power (left) and wind power (right) potentials within the region. Focusing on the islands, the majority have a radiance of 4.75 to 6 kWh/m^2/day and therefore a high solar power potential. Wind speeds differ in the region: While some parts in the North-East (mainly the Philippines and East-coast of Vietnam) face wind speeds of 5 m/s to more than 6.5 m/s resulting in high wind power potential, other parts have 3 m/s to 4.5 m/s or even less wind speeds limiting the wind power potential. Because of their promising potential, both, wind, and solar power generation sources, are considered within this research.

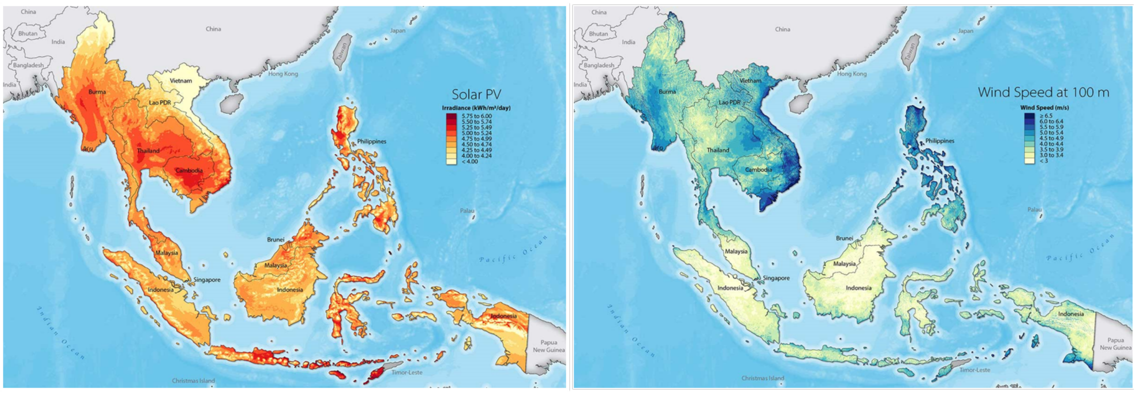

Figure 2.4: *Solar radiance (left) and wind speed (right) maps for Southeast Asia [44]*

Hydro power potential. Hydro power potential is highly site-specific depending on local water sources like rivers and lakes. Many small islands face fresh water scarcity and have no local water sources limiting their hydro power potential. Other, often larger islands in the region show high hydro power potential e.g. Borneo (Indonesia) or Mindanao (Philippines) [45]. Where islands show hydro power potential, this generation source is also considered for further analysis.

Biomass power potential. Biomass production on the numerous small islands of the region is limited due to space constraints. Even though larger islands in Southeast Asia have abundant biomass potential (e.g. through massive plantation industries in Indonesia or Malaysia), power generation based on biomass is not considered within this research [45]. All renewable energy sources are affected by climate change, but biomass shows inter-linkages and inter-dependencies to changing environmental conditions throughout the whole supply chain. To supply power plants with fuel (biomass), the water, energy, and food nexus is touched and the crop production is deeply interrelated with social structures and power dynamics of communities. Inter-dependencies and correlation are complex if looking at climate change impacts and resilience of energy systems based on biomass. The assessment is going beyond the scope of this work and is therefore excluded from this research.

2.3.4 Role of Electricity Access on Livelihood and Building Climate Resilience

Access to sustainable and reliable energy is a central pillar of human development and well-being and is one of the United Nations (UN) SDGs: Affordable, reliable, sustainable, and modern energy for all (SDG7) [46, 47]. Access to energy is essential to achieve other SDGs like alleviating poverty (SDG1), advancing health (SDG3), improving education (SDG4), and water and sanitation (SDG6) [47]. Improved climate change resilience is strongly connected to access to reliable electricity supply which is a prerequisite for many adaptation measures and enables and maintains many vital functions of communities [14]. Examples of (i) improved water management, (ii) application of Information and Communication Technologies (ICTs) and advanced health services enabled by access to reliable electricity supply are given in the following.

Agricultural activities heavily depend on the **availability of water**. However, water sources are threatened by a higher variability of precipitation patterns with an increasing trend to extreme events (floods or droughts) caused by climate change. Farmers are therefore challenged by increasingly unreliable water supply. Through the application of storage, pumps, and efficient irrigation systems, energy access increases productivity and robustness in the agricultural sector and at the same time enables food preservation (e.g. through the application of cooling technology) advancing overall food security [40, 48]. Additionally, electricity supply enhances access to drinking water: Water purification and desalination technologies will play an increasing role in providing access to clean water in many countries, particularly among coastal and island communities [49].

Through the usage of **ICTs**, such as mobile phones, radio, television, and satellite phones, communities gain access to relevant information to protect their livelihoods (e.g. weather forecasts) and are able to communicate with disaster management institutions in case of emergency. This allows for improved preparedness and response in case of incoming disturbances. The application of ICT as well as implementation and reliable operation of early warning systems is enabled, once a community receives access to electricity [14].

Rural health centers are able to extend their services once they receive access to reliable electricity supply. This allows the operation of a wider range of medical equipment and storage of vaccination and medicine through cooling technologies (freezers and fridges) [14]. Both allows more treatment options. With access to electricity, rural communities gain independence from urban infrastructures (e.g. hospitals, health and vaccination centers), attract medical staff and are enabled to provide first aid and accelerate the recovery process in case of an emergency [50].

Within this research, expert interviews are conducted to create an empirical understanding of the inter-linkages of climate change and electricity provision on Southeast Asian islands and identify potential adaptation measure to mitigate climate change risks on energy infrastructure. A detailed overview and approach of these interviews covering three different target groups (experts, technology providers, and island communities) is given in Section 3.2.2. Some findings from the interviews conducted are highlighted in the remainder of this chapter to underline the main messages for the study area. However, the majority of interview results are summarised in Section 4.3.1.

As presented, many dimensions of livelihood, especially in rural areas, heavily depend on reliable electricity access. The development of many sectors shows inter-linkages with energy access and have benefits for the communities and their climate resilience. This is confirmed for the study area of Southeast Asian island communities by the interviewees. Figure 2.5 on the following page shows an overview of the responses to the question "How important is access to reliable electricity supply for increased resilience for the island communities?" with answer categories ranging from "very important", "important", and "moderately important" to "slightly important" and "not important". All 22 interviewees gave a largely unified answer and categorized electricity access either as "very important" (18 answers) or "important" (4 answers). Out of these, the four representatives of island communities all stated that electricity access is "very important" for increased resilience. This underlines that a holistic approach and integrated planning of community and energy development is needed in order to create and sustain the positive effects of electricity access for island communities in Southeast Asia. Increased resilience of both - communities and energy supply systems - is required in the face of increasing climate change impacts.

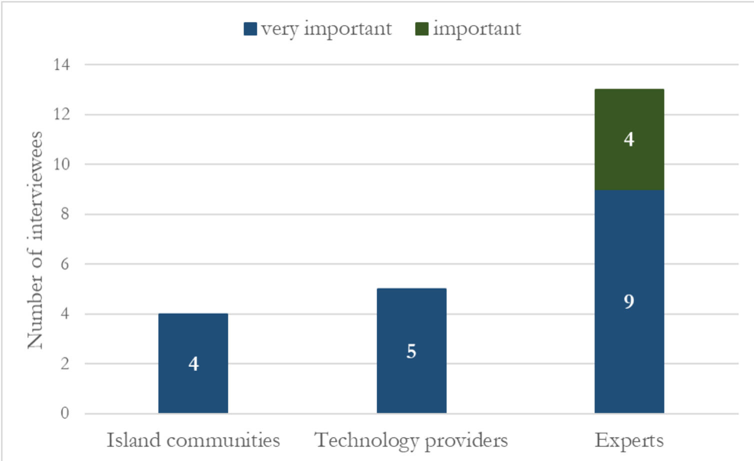

Figure 2.5: *Importance of electricity access for building climate resilience according to 22 interviewees*

2.3.5 Climate Change Resilient Energy Systems

For energy systems to withstand current and future climate change impacts, it is necessary to consider these changes in technical designs and integrate social structures and adaptation needs into the planning procedure. Energy systems lacking climate change impact considerations in their planning phase are prone to partly or fully fail in the face of increasing climate change impacts (see examples from the field in Figure 2.6). As a consequence, the benefits evolving from energy access on the community will cease, increasing their vulnerability.

Figure 2.6: *Solar panels destroyed by hail and storm (left), house destroyed by a storm (middle), electricity lines destroyed by storm (right) on Bulon Don island, Thailand. Taken by Katrin Lammers, 2017*

Defining the Research Scope

Research on this topic is slowly setting off. In the last decade, a growing number of research projects have been initiated to better understand the implications of climate risk for energy systems [51]. However, most of the research is limited to centralized power grids. In addition, there is a strong focus on power grids in the Global North. Significantly less research is being conducted on energy systems in the Global South. The lack of relevant investigations of climate change impacts and adaption strategies for energy systems in the Global South is highlighted by the IPCC in its Fifth Assessment Report [52]. Research is conducted, for example, on the energy systems of Norway [17], Germany [18], USA [19] Australia [20], Ecuador [53], Portugal [54], South Africa [55], and Rwanda [56]. There are studies on centralized, national energy grids focusing on modelling the adjusted demand with heating and cooling having major impacts [17,57,58]. Others assess the production capacities and find that changes in water resources are mainly affecting hydro power and thermal power plants [54,56,59]. Some studies are looking at the impact of climate change on the wind and solar potential [55,60]. All of these research papers, however, study the impact of climate change on energy systems within the context of larger centralized systems. Among the limited number of research papers on energy systems in the Global South, the research by Handayani et al. (2019) stands out, since it is based on empirical evidence [61]. They evaluated the results from stakeholder interviews regarding extreme weather and climate impacts on the centralized power sector in Indonesia. Given that the data is limited to thermal power plants and large scale hydro power generation, its contribution to the presented research is limited.

Decentralised and rural energy systems (mini-grids) are highly relevant for the Southeast Asian island context, however, electricity access and climate resilience are barely linked in current planning. A review on this 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" [14]. Ebinger et al. (2011) also emphasize the importance of integrated risk-based planning processes in the energy sector to address occurring climate change impacts and build resilience [21]. Another review conducted by Schaeffer et al. (2012) reveals the various impacts of climate change on energy systems and underlines that little research has been conducted on this subject, although "[...] 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 [...]" [22].

I validate these findings and research gap for my research focusing on Southeast Asian island communities by conducting a review of electrification case studies for Southeast Asian islands. The aim of this literature review is to identify case studies giving an information on the specific project location (islands or villages) including basic information on current or planned energy supply and analyse whether they include climate change considerations in their planning or implementation phase. The literature review was limited to Science Direct and followed a key word search approach applying "Southeast Asia" and "island(s)" as decisive criteria and "energy access" and/or "power supply" as additional requests. More details on the literature review are given in Appendix A.1. After applying the above mentioned criteria, I identified 17 island electrification case studies and only one mentions the topic climate change. The study assesses the mitigation potential of switching to renewable energy sources. However, the link to adaptation and resilient energy system planning is missing. Figure 2.7 gives an overview of the identified case study island locations.

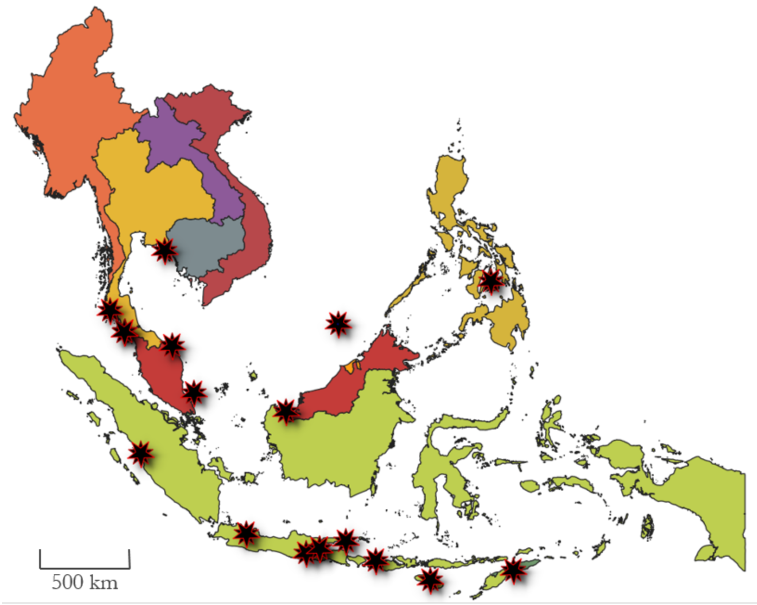

Figure 2.7: *Map of 17 electrification project case study locations*

The message is underlined by another answer statistic of the conducted interviews mentioned above: The question "To which degree are climate change impacts currently integrated in energy system planning?" is answered by the majority of interviewees (11) with "slight degree", with 5 persons even saying "no degree" (answer categories: "no answer", "very high degree", "high degree", "moderate degree", "slight degree", and "no degree"). In contrast, the importance to consider climate change impacts in energy system planning in the future is ranked to "very important" by the majority of interviewees (11) and to "important" by an additional six persons. Three interviewees did not give an answer and only two chose the answer category "slightly important" and "moderately important". None of them said that the integration of climate change impacts in energy system planning is "not important".

In summary, literature and case study review as well as expert interviews conducted within the scope of this research confirm the missing link of energy system planning to climate change risk assessment for the study area of Southeast Asian islands and highlight the importance to integrate these two topics.

Climate Change Impacts on Energy Systems

To sustain positive effects of electrification for the island communities, the energy systems have to withstand current and future climatic impacts. In order to protect and adapt today's and tomorrow's energy systems, it is first necessary to understand, which climate change impacts affect these systems in what way. Stuart et al. (2017) and Schaeffner et al. (2012) identified four main climate change induced shocks and stresses impacting energy systems [40], [22]:

- Temperature increase,
- Precipitation fluctuation (droughts, torrential rains, floods),
- Extreme weather events (storms, cyclones), and
- Sea-level rise.

These hazards are intensified by climate change and can impacts the following elements of energy supply systems:

- **Technical components**: The technical components (grid, generation units etc.) can be impacted by e.g. landslides and flooding caused by heavy rainfall or rising sea-level or due to storm surges causing partly or full system failure [22, 40].
- **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 hydro-power, bio-energy, solar, and thermal power plants [22].

- **Demand and peak loads to be supplied**: Increasing temperatures will lead to higher cooling and storage demands and therefore rising demands (base and peak loads) [22, 40].

Figure 2.8 on the following page shows more details on how the four climate shocks and stresses are affecting generating sources (wind, solar, diesel), batteries, and grid infrastructure as well as the demand.

While looking at the different impacts, it appears that an increased temperature and precipitation fluctuation mostly impact efficiency and output of the systems leading to increased demand and peak loads. In more extreme cases, fluctuations in precipitation can also lead to flash floods and landslides causing outages and supply interruptions. Most impacts on energy systems caused by sea-level rise and extreme weather events are rather affecting the technical components (equipment) leading to damage.

The interview results highlight the severity of climate change impacts on energy systems for the study area of Southeast Asian islands. When asked, which impacts were already observed on the island energy systems, all of the above mentioned impacts are mentioned: heavy storms (cyclones) and lightning strikes were leading to broken solar panels, electricity lines, wind power plants, and houses, rising tides (sea-level rise) and flooding caused by intense rainfalls flushed away or broke down hydro power plants, buildings, and other infrastructure, and extreme temperatures resulted in overheating and failure of equipment such as batteries and charge controllers. When asked to rank the strength of climate change impacts on the islands' energy systems, most interviewees (10) estimate a "strong impact" followed by 6 people estimating a "very strong impact". Nobody said there is "no impact" or just a "slight impact".

Temperature increase

Wind power generation	⇒ Decreased air density may decrease energy output
Solar power generation	⇒ Reduced solar cell efficiency
Diesel generation	⇒ Decreased efficiency ⇒ Disruptions of production transfer and transport
Grid	⇒ Increased electrical resistance decreasing efficiency ⇒ Increased fire risk damaging grid lines
Demand	⇒ Increased energy demand for cooling and irrigation ⇒ Reduced energy demand for heating

Precipitation fluctuation

Wind power generation	*No significant impact*
Solar power generation	⇒ Increased cloud cover and humidity decreases solar generation output
Diesel generation	⇒ Disruptions of production transfer and transport ⇒ Heavy precipitation threatens diesel units not appropriately sheltered
Grid	*No significant impact*
Demand	⇒ Increased power outages and disruptions ⇒ Floods and droughts may require additional emergency energy capacity ⇒ Increased energy demand for cooling ⇒ Reduced energy demand for heating ⇒ Increased energy demand for irrigation

Extreme weather events

Wind power generation	⇒ Alternation in wind speed may increase output variability ⇒ Damage of equipment
Solar power generation	⇒ Damage of equipment
Diesel generation	⇒ Equipment damage may decrease plant lifetime and output ⇒ Disruptions of production transfer and transport ⇒ Disruptions of import operations
Grid	⇒ Damage of grid lines reducing system reliability
Demand	⇒ Damage of infrastructure and power outages

Sea-level rise

Wind power generation	⇒ Damage of off-shore equipment
Solar power generation	⇒ Damage of infrastructure through salt-water corrosion
Diesel generation	⇒ Increased risk of damage to off-shore infrastructure and coastal stations
Grid	⇒ Damage of infrastructure through salt-water corrosion
Demand	⇒ Increased need for desalinisation plants and water efficient irrigation techniques

Figure 2.8: *Impact of increased temperature, precipitation fluctuation (e.g. leading to floods and droughts), extreme weather events (e.g. cyclones), and sea-level rise on energy system components and demand according to [22, 40], icons created by [62–65]*

Adaptation Measures for Resilient Energy Systems

Adaptation measures to mitigate the above mentioned shocks and stresses can be divided into engineering and non-engineering measures [66]. Engineering measures directly aim at increasing the resilience of technical assets to the impacts of climate change, while non-engineering measures aim at increasing the resilience of the whole energy system including the technical assets and sometimes the community itself.

Engineering measures. Table 2.4 on the following page gives a (non-exhaustive) overview of technical adaptation measures as described by Stuart (2017) and Schaeffer et al. (2012) [22, 40]. These individual or combined measures address and improve an energy systems' resilience. They should be selected depending on the hazard(s) occurring in the specific area of installation. In general, a diverse energy mix as well as modular and distributed system setups are of great value as they enhance energy security by eliminating reliance on a single source, line, or system and lead to higher system reliability. In the following, a selection of measures are described.

Increased Temperatures. As temperatures are increasing in many parts of the world, it is essential to place sensitive components like batteries and inverters in a cool environment (e.g. proper concrete building with air circulation or even air-conditioning) and install cables underground to benefit from the cooling effect of the ground. Transformers and substations also benefit from the application of cooling technology to sustain their efficiency.

Flooding and Sea-Level Rise. To reduce risk of flooding in coastal areas, it is recommended to install energy supply systems in areas of high elevation or far from shorelines. In coastal environments, all system components should be resistant to or protected from salt-mist corrosion. It is also beneficial to install sensitive components (e.g. batteries and inverters) in enclosed spaces (houses, containers). Containerized solutions make it easier to relocate the energy infrastructure to other areas if e.g. rising sea-level or flood surges are endangering its operation. Containers also offer the opportunity to artificially pile up the infrastructure in case of scarce land resources in high elevations. Installing containerized solutions on poles reduces the surface affected by floods and landslides, which makes them a promising solution for communities affected by floods and landslides. Up to a certain flood level, it is also recommended to use underground cabling as it reduces the risk of electricity poles been flushed away.

Table 2.4: Overview of technical adaptation measures (engineering measures) to mitigate climate risks on (off-grid) energy systems based on [22, 40]

Measure	Explanation
Diversification of energy mix & high renewable energy shares	Less dependency on fossil fuels (often transported from the mainland)
	Diverse energy mix creates reduced sensitivity to blackouts/shortcuts (no dependency on one single power source)
	Enables local energy generation according to the best resource available
Modular and distributed systems	Reduced sensitivity to total system failure (if one part of the modular system fails, another part might be able to operate independently)
	Transmission and distribution lines are often physically exposed and thus vulnerable to e.g. storm surges, modular and distributed grid lines reduce dependence on single lines
	Interconnecting several mini-grids to larger supply systems to enhance energy security; in island cases: option to interconnect island grids to larger grids via submarine cables to reduce sensitivity to total system failure
Energy container solutions	Increased flexibility of rearranging the system's position
	Allows for reactive actions in case of changing hazard zones
	Allows to easily raise the energy system above the ground in case of frequent flooding or land slides
Concrete-sided buildings	More resistant to wind and salt corrosion than e.g. metal or wood housing (important for an island context)
	Stays cooler than metal housing
Underground cabling	Higher resistance to wind and to a certain extend to flood surges
	Cooling effect on cables
Cooling for substations, transformers, inverters & storage technology	Increased efficiency and lifetime of components

Storms. To decrease the impacts of storms on grid infrastructure, it is beneficial to invest in underground cabling to reduce their exposure to storms (in landslide-proof areas). Deeply grounded mounting structures of solar power stations are important in areas with high wind speeds. Considering vertical wind turbine technologies while designing and planning wind power stations helps to reduce sensitiveness to rapid changes in wind direction and peaks. Concrete buildings to host energy infrastructure in low flood risk areas are able to protect sensitive technology from storm surges.

Non-engineering measures. Apart from purely technical measures, there are also managerial and social adaptation measures to combat climate change impacts on energy systems: more robust operational and maintenance procedures are beneficial as well as integrated and holistic land use planning and management [66]. Specific design codes, risk analyses, and standards are required to support mainstreaming of climate resilient energy system planning [66]. Contingency plans and emergency procedures should be developed to enable continuous emergency supply and security. Improved and continuously updated forecasting and modelling approaches help to detect upcoming bottlenecks enabling proper emergency supply and security [40,66].

To be successful, energy projects have to be applied in a locally anchored and sensitive manner considering cultural aspects and address the need of those using the system [67]. Participatory energy planning instead of top-down approaches empower communities to take action and reflect their specific needs leading to increased community resilience [68]. The aim of participatory planning is that communities can directly get involved in the planning and implementation of the measures that will affect them leading to a higher public acceptance. They thus develop the resilience to manage disaster risks while getting support from organisations with predictive capabilities [68]. Different tools to include the public in political planning and decision making to create participatory processes exist for that matter: Frequent meetings and workshops between community representatives and politicians, public hearings, trainings, surveys as well as joint field trips, and offering community ownership and management are some of them [69]. Community- and nature-based solutions for improving climate resilience, which are developed combining traditional and scientific knowledge, tend to be more sustainable and accepted within the communities [70]. Often the involvement of women in these participatory measures and planning processes also adds to increased likeliness of implementation and acceptance [68, 71, 72]. In her report on the role of women in sustainable energy development, Cecelski (2000) finds that women are the mainstream users and often producers of energy [67].

Without women's involvement in renewable energy projects, these projects carry a certain risk of being inappropriate, and failing [67].

In summary, if electrification projects are expected to cope with current and future environmental shocks and stresses caused by the impact of climate change, it is necessary to consider these changes in technical designs and integrate social structures and adaptation needs into the planning procedure. This thesis focuses on the technical side of adaptation and aims to integrate necessary changes in planning and implementation. To facilitate this process on a technical level, it is important to understand the risks and approaches to increase resilience of energy systems. Thus, I conducted a climate change risk assessment for the study area and developed an approach to integrate the risk profiles of specific islands into off-grid energy system planning which is presented in the next chapter.

Chapter 3

Methodological Approach

This thesis consists of two main topics: climate change risk analysis and resilient energy system planning for the study area of Southeast Asian islands. Figure 3.1 gives an overview of the two thematic blocks and reveals consecutive steps taken to answer the research questions (see Section 1.2) over the course of this chapter. Defining the scope is the first step to be taken. After this, data acquisition and processing of both - climate change risk and resilient energy system planning data - are following. The results of both thematic blocks are then combined to apply the data to common energy planning procedures.

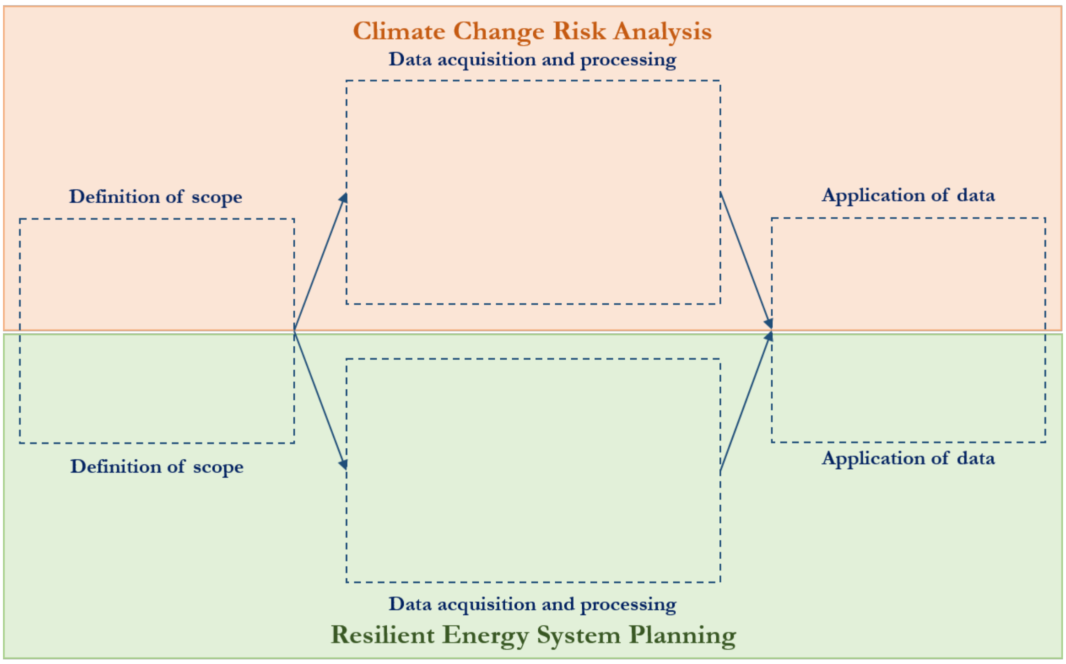

Figure 3.1: *Overview of methodological approach and consecutive steps, own visualisation*

3.1 Definition of Scope

The definition of scope as presented as first step in Figure 3.2 is provided in the previous chapter (Chapter 2). The argumentative framework and essential definitions as basis for this research is presented (Section 2.1). The special case and high vulnerability of Southeast Asia and its islands as geographical area is determined by literature review and highlighted in Section 2.2. Furthermore, the literature analysis showed that energy provision via mini-grids tends to be the most promising solution for the majority of islands, and at the same time represents the most vulnerable energy infrastructure (Section 2.3). Section 2.3 also identifies common climate change hazards impacting energy systems that are considered within this research. The scope of this research is thus defined to analyse and support the integration of climate change risk considerations into mini-grid design and planning on Southeast Asian islands as most vulnerable cases.

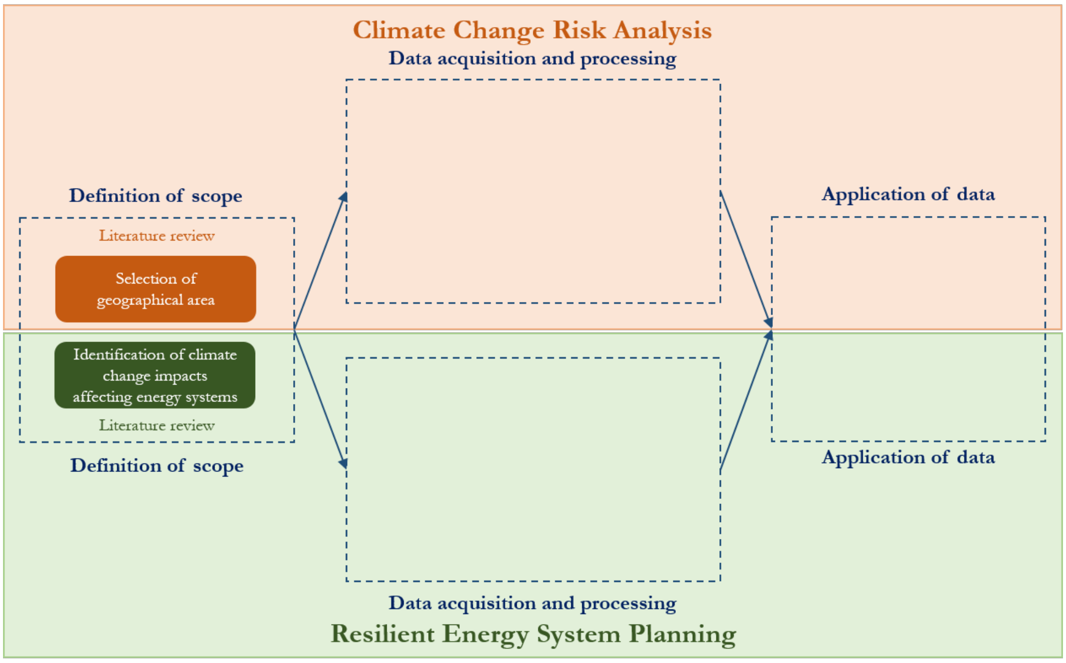

Figure 3.2: *Overview of methodological approach and consecutive steps - definition of scope, own visualisation*

3.2 Data Acquisition and Processing

Data screening and evaluation is essential to this research. The data acquisition and processing to support the climate change risk assessment and resilient energy planning for Southeast Asian islands is elaborated in this section.

3.2.1 Climate Change Risks

In the following, an overview of data acquisition and processing of climate change induced risks on Southeast Asian islands leading to an island-specific climate change induced risk database is given as visualised in Figure 3.3.

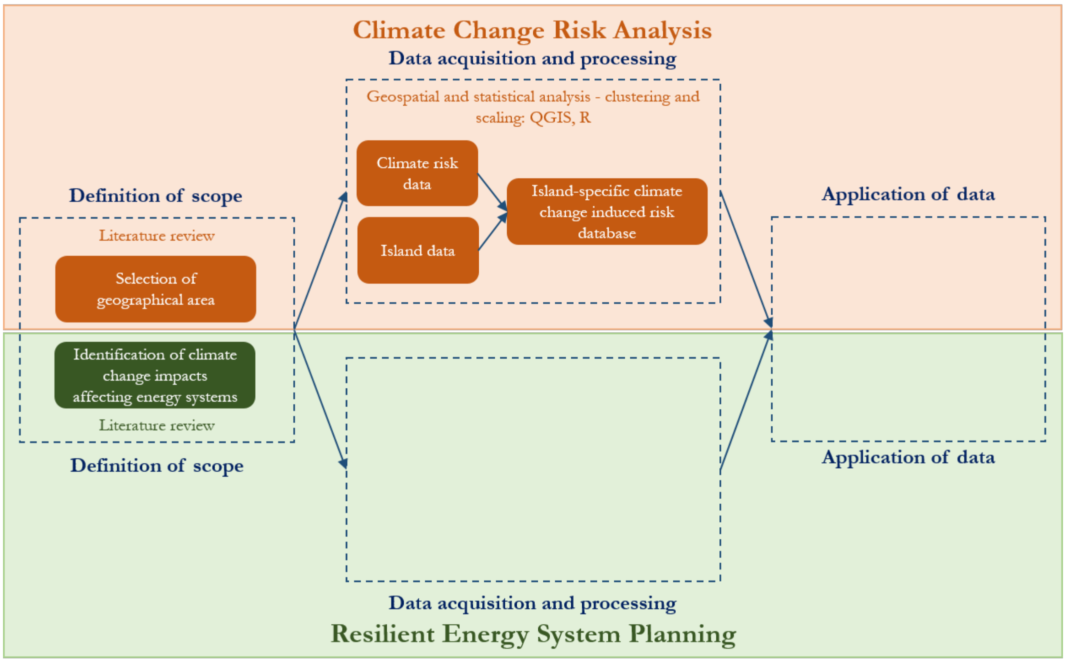

Figure 3.3: *Overview of methodological approach and consecutive steps - data acquisition and processing for climate change risk assessment, own visualisation*

While screening and acquiring spatial data for this research, three main criteria are applied:

- Only open access data is considered to guarantee transparency and enable transferability of the results to other regions,
- Only datasets available for all countries of Southeast Asia are considered to guarantee comparability, and

- The data with the highest spatial resolution fulfilling the aforementioned criteria is preferred.

In order to process the acquired spatial data, the programs R together with R Studio, QGIS, and Excel are utilised. R is an open source programming language for statistical computing, featuring multiple packages that support spatial calculation [73]. QGIS is an open source software for Geographical Information Systems, provides various integrated data processing tools and is used for data analysis and geographical visualisation [74]. QGIS visualises the results immediately, which helps to detect errors and supports general understanding of the applied datasets [74]. Excel is applied for basic processing and calculation and comes with the advantage of quick results and statistical visualisation generation. The QGIS and Excel files as well as the R code compiled within this research are provided digitally and attached to this thesis (see Apprendix A.2). Selecting which programme is applied for which task depends on computing time, complexity, and accuracy of the method. Utilising all programs hand in hand results in the most efficient method for each task.

To understand the island landscape of Southeast Asia as basis for further analysis, spatial data for each country and their subdivisions is required as a first step. A typical spatial data source is the Database of Global Administrative Areas (GADM). GADM is an open source database of the world's administrative areas and boundaries, which is applied in this research [75]. The GADM data lays the foundation for the island boundaries (polygons) and facilitates the allocation of island specific climate change impacts. Figure 3.4 (following page) describes the GADM data processing. The GADM data of each country is merged into a single layer. Then the *Clipping* function is used to erase the mainland parts of Southeast Asia to receive an island data layer. For islands consisting of more than one country (e.g. Borneo island as part of Brunei, Malaysia, and Indonesia or Timor island as part of Timor-Leste and Indonesia), inner island boundaries are dissolved in QGIS to generate single island polygons. This allows to determine single values - instead of multiple ones - per island in the attribute table. In a second step, climate change related data is processed and overlaid with each island.

For this analysis, it is necessary to select data, which is determined based on the most suitable global circulation models and emission scenarios. The Intergovernmental Panel on Climate Change (IPCC), the United Nations' body for assessing the science related to climate change, bases its assessments on so-called Representative Concentration Pathways (RCPs). These scenarios include time series of emissions and concentrations of greenhouse gases (GHGs), aerosols, and chemically active

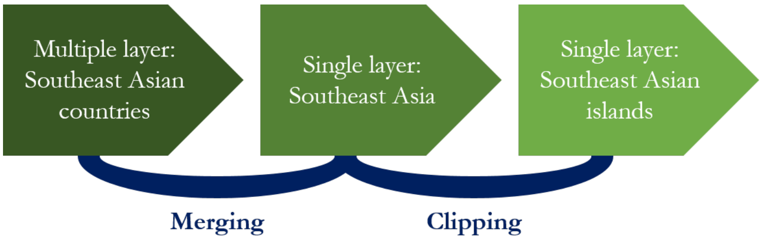

Figure 3.4: *Processing of GADM datasets in QGIS to receive a dataset of Southeast Asian islands, own visualisation*

gases, as well as land use/land cover until the year of 2100 [76]. Integrated Assessment Models are calculating corresponding emission scenarios. The IPCC selected four of these scenarios for further analysis and included them into their Fifth Assessment Report as basis for climate predictions. They include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with high emissions (RCP8.5) [77]. The names of the RCPs refer to the respective radiative forcing levels. RCP2.6 is representative for a scenario that aims to keep global warming likely below 2 °C above pre-industrial temperatures and is thus the scenario in line with the Paris Agreement [77]. However, recent research shows that the RCP2.6 scenario is not likely to represent the currently slow progress in mitigation efforts [78,79]. Global emission peaks for most sectors had to happen in 2020, which the international community failed to achieve [79]. Furthermore, emissions tracked until 2020 are higher than projected within the RCP2.6 scenario [78]. Schwalm et al. (2020) even argue that the highest RCP8.5 seems to be the most realistic when compared to projected and monitored emissions until 2020 [78]. To find a compromise between current developments and planned mitigation actions and international agreements, the RCP4.5 scenario is selected as basis for datasets applied in this research. Table 3.1 (following page) gives an overview of the predictions of temperature and sea-level rise for the different RCPs, comparing two time periods (2026 - 2065 and 2081 - 2100) with temperature recordings from 1986 - 2005 as baseline.

Temperature Rise Risk

Temperature data is derived from WorldClim, which is a database consisting of global weather and climate data of high spatial resolution. The gridded data is available for historic (1960 - 1990) and future conditions (2040 - 2060). Historic condition data is based on measurements taken, processed and provided by Fick

Table 3.1: Overview of Representative Concentration Pathways (RCPs) and their related temperature and sea-level rise predictions

Temperature rise			
RCP	Radiative Forcing	Global mean surface temperature rise	
		2046 -2065	2081 - 2100
RCP2.6	2.6 W/m^2	0.4 - 1.6 °C	0.3 - 1.7 °C
RCP4.5	**4.5 W/m^2**	**0.9 - 2.0 °C**	**1.1 - 2.6 °C**
RCP6.0	6.0 W/m^2	0.8 - 1.8 °C	1.4 - 3.1 °C
RCP8.5	8.5 W/m^2	1.4 - 2.6 °C	2.6 - 4.8 °C
Sea-level rise			
RCP	Radiative Forcing	Global mean sea-level rise	
		2046 - 2065	2081 - 2100
RCP2.6	2.6 W/m^2	0.17 - 0.32 m	0.26 - 0.55 m
RCP4.5	**4.5 W/m^2**	**0.19 - 0.33 m**	**0.32 - 0.63 m**
RCP6.0	6.0 W/m^2	0.18 - 0.32 m	0.33 - 0.63 m
RCP8.5	8.5 W/m^2	0.22 - 0.38 m	0.45 - 0.82 m

et al. (2017) [80]. For future conditions, the data is modelled based on the four different RCPs and available for different Global Climate Models (GCM) that were applied to predict trends in temperature and precipitation developments. Which GCM fits best for a specific region depends on the location and the regional weather and climate phenomena. Kamworapan et al. (2019) evaluated different GCMs for the Southeast Asian region [81]. In their analysis, they found that the most suitable model is the so called CNRM-CM5-2 [81]. As the data obtained through this model is not available on the WorldClim database, data based on the second best GCM according to Kamworapan et al. (2019) was selected for further analysis (CNRM-CM5) [81]. The GCM output is down-scaled and calibrated (bias corrected) using WorldClim 1.4 as baseline [80].

The risk of rising temperatures in this thesis is described as change in annual mean temperature between the historic data (1960 - 1990) and future data (2040 - 2060) - a simplified method described by FAO (1998) and Hargreaves et al. (1994) [82,83]. The data input consists of average monthly minimum and maximum values. First, the annual maximum and minimum temperature are calculated for each island:

$$t_{\text{yearly,min}} = \frac{1}{12} * \sum_{n=1}^{12} t_{\text{min,n}} \tag{3.1}$$

$$t_{\text{yearly,max}} = \frac{1}{12} * \sum_{n=1}^{12} t_{\text{max,n}} \tag{3.2}$$

In a second step, the annual average temperature is derived for each island [82, 83]:

$$t_{\text{yearly,ave}} = \frac{t_{\text{yearly,max}} + t_{\text{yearly,min}}}{2} \tag{3.3}$$

To recognise trends in temperature on the islands from 1960 - 1990 ($t_{\text{yearly,ave,1975}}$) until 2040 - 2060 ($t_{\text{yearly,ave,2050}}$), the difference of the average temperatures is calculated (t_{df}):

$$t_{\text{df}} = t_{\text{yearly,ave,2050}} - t_{\text{yearly,ave,1975}} \tag{3.4}$$

Flood and Drought Risk

Literature and data review reveals no openly available data to directly assess flood and drought risk covering the whole Southeast Asian region. Therefore, an own calculation is conducted.

For assessing the risk of flood and drought, precipitation and temperature data is derived from the WorldClim database as mentioned above. In addition, datasets on the soil-water balance (SW_{frac}) describing the fraction of water in the soil available for evapotranspiration[1] and extraterrestrial radiation[2] (RA) are obtained from the Consultative Group on International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI). CGIAR-CSI is a data provider, which processes data from WorldClim together with inputs from various weather stations, prepares different raster datasets, and describes its methodology. The data is available for research purposes. Trabucco et al. (2019, 2007) provide the geospatial dataset

[1] movement of water from the Earth's surface (e.g. soil) to the atmosphere by evaporation and transpiration

[2] radiation on top of the earth's atmosphere

on extraterrestrial radiation data available as part of CGIAR-CSI's Global-Aridity and Global-PET Database and the soil-water balance data as part of their Global High-Resolution Soil-Water Balance dataset [84], [85].

A simplified method to indicate trends towards floods and droughts based on the Hydrological Drought Index (HDI) by the Satellite Hydrology Project (SATH) is applied [86]. This index gives the ratio of precipitation to evapotranspiration (sum of evaporation from the land surface plus transpiration from plants). As mentioned above, precipitation data is downloaded from the WorldClim database. The actual evapotranspiration ($\mathrm{Et}_{\mathrm{a,yearly}}$) can be calculated based on the soil-water balance (CGIAR-CSI database) and the potential evapotranspiration ($\mathrm{Et}_{\mathrm{p,yearly}}$), which requires several calculation steps:

First, the extraterrestrial radiation (CGIAR-CSI database) with a unit of MJ/m^2*d has to be converted to equivalent evaporation (m_{E}) in *mm/day* [87]. Allan et al. (1998) defined the following formula to relate the extraterrestrial radiation (RA) to equivalent evaporation (m_{E}):

$$m_{\mathrm{E,RA}} = 0.408 * RA \qquad (3.5)$$

The value of the radiation (RA) is given as the average value for the 15^{th} day of the month. To calculate the potential evapotranspiration, the annual radiation is required. Therefore, daily values are converted to monthly values [84, 85]:

$$m_{\mathrm{E,RA,monthly}} = m_{\mathrm{E,RA}} * \frac{No.of days}{month} \qquad (3.6)$$

And finally it is converted to a yearly value [84, 85]:

$$m_{\mathrm{E,RA,yearly}} = \frac{1}{12} * \sum_{n=1}^{12} m_{\mathrm{E,RA,monthly}} \qquad (3.7)$$

Based on findings of Hargreaves et al. (1994), the potential evapotranspiration ($\mathrm{Et}_{\mathrm{p,yearly}}$) can be estimated by the following formula [83]:

$$Et_{\mathrm{p,yearly}} = 0.0023 * m_{\mathrm{E,RA,yearly}} * (t_{\mathrm{yearly,ave}} + 17.8) * \sqrt{t_{\mathrm{yearly,range}}} \qquad (3.8)$$

The yearly average temperature ($t_{\text{yearly,ave}}$) is calculated above. The temperature range is derived by calculating:

$$t_{\text{yearly,range}} = t_{\text{max, yearly}} - t_{\text{min,yearly}} \tag{3.9}$$

The actual evapotranspiration ($Et_{\text{a,yearly}}$) is the product of the potential evapotranspiration ($Et_{\text{p,yearly}}$), the soil coefficient and the vegetation coefficient. According to Trabucco et al. (2019), the influence of the vegetation is insignificant and is set to 1, the soil coefficient is the SW_{frac} divided by one hundred [84].

$$Et_{\text{a,yearly}} = Et_{\text{p,yearly}} * \frac{SW_{\text{frac}}}{100} \tag{3.10}$$

The HDI considers site specific precipitation values and relates it to the water holding capacity of the soil and surrounding temperatures. It gives an indication for the vulnerability of sites with tendencies for floods (value above 1) or droughts (values below or equal to 1) [86].

$$HDI = \frac{precipitation, yearly}{Et_{\text{a,yearly}}} \tag{3.11}$$

Table 3.2 summarizes the flood and drought risk classification for the HDI values.

Table 3.2: *Hydrological Drought Index and its classification, based on [86]*

HDI	**Classification**
<= 0.5	high drought risk
>0.5 - 0.75	moderate drought risk
>0.75 - 1	slight drought risk
>1 - 1.25	slight flood risk
>1.25 - 1.5	moderate flood risk
>1.5	high flood risk

Sea-Level Rise Risk

In order to assess the challenges that arise from rising sea-levels for Southeast Asian island communities, the digital elevation model CoastalDEM, developed by Climate Central, an independent organisation of researchers and journalists reporting climate change impacts to the public, is applied. This model is based on the commonly used Shuttle Radar Topography Mission (SRTM) 3.0 data, but it corrects the systematic overestimation of height, especially in urban agglomerations and dense forests [88]. It claims to be more accurate and realistic than SRTM [88]. Risk assessments based on CoastalDEM result in more land loss through sea-level rise: By 2050, 200 million people more are vulnerable towards rising sea-levels than previously estimated based on SRTM [88,89]. Vietnam, Indonesia, and Thailand are within the top six countries with the highest population living below average annual flood level in 2050 [89]. Apart from the elevation dataset, ClimateCentral provides data on future sea-level rise projections based on CoastalDEM. As this dataset is not available under an open license, it is not applied in this research. Instead, the CoastalDEM model is combined with sea-level rise projections according to Kopp et al. (2014) [90]. Their projection (K14) is a local sea-level rise model which takes numerous variables into consideration, such as ocean dynamics, heat content, and salinity and is also utilised in the aforementioned ClimateCentral's sea-level rise projection dataset [89, 90].

The main risk of sea-level rise for islands is the loss of land. The land area is defined by the tide lines and can be assessed by combining the elevation dataset CoastalDEM with sea-level rise projections (K14). In this thesis, a bathtub model is used for calculating sea-level rise. The bathtub inundation model presumes that an area with an elevation (CoastalDEM) less than a projected flood level (K14 projection) will be flooded like a "bathtub" [91]. The bathtub model is based on elevation data only and does not require detailed hydrological data that is often absent [91]. According to K14 projections with RCP4.5 as emission scenario, sea-level rise is likely to be in the range of 0.21 - 0.31 cm with 0.26 cm being the median (time range 2000 and 2050) [92]. For assessment within this research the median of 0.26 cm is considered.

In order to calculate the land loss of each island as a result of sea-level rise, the values for the raster cells within the CoastalDEM data are reclassified: Cells with an elevation higher than 26 cm above normal zero receive the value 1 ($cDEM_{26}$), cells equal or higher than normal zero receive the value 0 ($cDEM_0$). The difference between these two classified datasets describes the raster cells lost after 26 cm sea-level rise ($cDEM_{df26}$):

$$cDEM_{\text{df26}} = cDEM_0 - cDEM_{26}. \tag{3.12}$$

In order to relate the land loss raster cells ($\text{cDEM}_{\text{df26}}$) to the real sizes of the islands (metric system), the resulting raster dataset has to be converted from the Coordinate Reference System 4326 (curved surface) to 3857 (flat surface). The area of land loss ($\text{area}_{\text{df26}}$) is then calculated by multiplying the area of the raster cell in the metric system (area_{rc}) with the factor of land loss ($\text{cDEM}_{\text{df26}}$):

$$area_{\text{df26}} = area_{\text{rc}} * cDEM_{\text{df26}}. \tag{3.13}$$

The numerous islands in Southeast Asia have very different sizes. A small island will be considerably more affected by a certain area of land loss than a bigger island, which is losing the same area. To address this issue, the land loss is further calculated in percentage of area lost in relation to the island size ($\text{area}_{\text{df26\%}}$):

$$area_{\text{df26\%}} = \frac{area_{\text{df26}}}{area_{\text{island}}} * 100\%. \tag{3.14}$$

Cyclone Risk

Looking at extreme weather events occurring in Southeast Asia, it becomes obvious that tropical cyclones present a well-known threat. To consider this risk, the 50-year return period of tropical cyclones provided by the World Bank is integrated into further analysis [93]. This global dataset is based on 2,594 historical cyclones and takes topography, terrain roughness and bathymetry[3] into account [93]. A combination of hazard, vulnerability, and risk modelling tools enabled the estimation of cyclone occurrence from 2015 until 2065 and the data is applied e.g. in the United Nations Global Assessment Report on Disaster Risk Reduction [94]. The data gives an estimation on the number of expected cyclones over a 50-year period for a specific location.

Table 3.3 on the following page gives an overview of all applied datasets to conduct the climate change risk assessment.

[3] Bathymetry is the information about the underwater topography of the ocean having direct influence on the formation of storm surges

Table 3.3: *Overview of datasets to assess climate change related risks*

Data	Type	Unit	Temporal Resolution	Current Time Frame	Future Time Frame	Spatial Resolution	Source	Risk assessed
Temperature	Average min. and max.	°C	Monthly	1960 - 1990	2040 - 2060	30 arcsec	WorldClim, [95, 96]	Temperature rise, flood and drought
Precipitation	Average	mm	Monthly	1960 - 1990	2040 - 2060	30 arcsec	WorldClim, [95, 96]	Flood and drought
Extraterrestrial Radiation	Average	MJ/(m²*day)	Daily	1950 - 2000		30 arcsec	CGIAR-CSI, [85]	Flood and drought
Soil-Water Content	Average	%	Monthly	1950 - 2000		30 arcsec	CGIAR-CSI, [84]	Flood and drought
Elevation Model CoastalDEM	Spatial elevation	m		2019		3 arcsec	Climate Central, [89]	Sea-level rise
Tropical Cyclones	50-year return period	No.	50 years	2015	2065	100 arcsec	WorldBank, [93]	Cyclone

Climate Change Risk Scaling and Clustering

The four climate change induced hazards are expressed in different units:

- Sea-level rise => % of island area lost over time,
- Temperature => difference in °C over time period,
- Flood and drought => index (no unit), and
- Cyclones => No. of cyclones over time.

In order to make the risks comparable and facilitate the translation of climate change induced risk into energy system planning, a five-point Likert scale is applied (from insignificant to severe risk), with an additional option of no risk. Table 3.4 gives an overview of the scales and their indication. For each hazard, the respective value ranges are distributed equally on the scale from 1-5. If an island has no risk for one or more of the considered climate change impacts, the scale “0” (no risk) is assigned.

Table 3.4: *Five-Point Likert scale to compare the intensity of occurring climate change risks, based on [97]*

Scale	**Indication**
0	no risk
1	insignificant risk
2	minor risk
3	moderate risk
4	major risk
5	severe risk

Due to the high quantity of islands in Southeast Asia, assessment of risk patterns and high risk areas is difficult by only looking at island specific climate risk data. Therefore, I apply a cluster analysis to the datasets described above. Cluster analysis supports unsupervised pattern recognition in large datasets [98]. The dataset is clustered in the most possible homogenous group by minimising intra-cluster variation while maximising the variation to other clusters [99]. In this research, the Partitioning Around Medoids (PAM) cluster method is applied. It is the most robust approach accounting for outliers in the climate risk datasets, given the many islands considered [100]. The PAM method defines clusters and representative medoids (real data points) for each cluster. The medoid is the most central and characteristic data point for the cluster showing the lowest average dissimilarity to all data points within the same cluster. In this research, a representative island (medoid) for each risk cluster is determined by applying the PAM method [99]. The cluster analysis is conducted with the statistical software R and respective packages [73, 101]. Before applying the PAM cluster method, the dataset is scaled (z-transformation) applying the "scale" function within R to compensate for the differences in value ranges. The distance between data points is measured in euclidean distance [99]. The PAM cluster method requires a fixed number of clusters to operate (cluster resolution) [101]. The *fviz_nbclust* function of R is able to determine the optimal cluster resolution with two different methods for a dataset: The average silhouette values and elbow method [102]. Both are applied for a range between 1 and 10 clusters. The results are then visualised in a cluster plot using the R function *fviz_clust*. If more than two observations shall be visualised, it automatically applies a principal component analysis [102].

3.2.2 Adaptation Measures and Cost Structures for Island Energy Supply Systems

After the analysis of island-specific climate change risks, potential measures to reduce the impacts of identified risks and related extra investment costs are studied. In Figure 3.5 on the following page this step is added to the method flow. It results in a risk-specific adaptation measure database including related extra investment cost.

The aim of this thesis is to integrate climate change risk considerations into energy system modelling to improve climate resilience of Southeast Asian island communities and their energy infrastructure. This integration of climate change impacts requires a translation of risk assessment outputs into common energy system modelling inputs. Most energy system modelling tools developed for the off-grid sector are based on least-cost optimisation approaches. Either the simulation tools apply solely economic criteria focusing on the energy supply, or the tools combine economic criteria with additional dimensions such as environmental or social impact [103]. For example, HOMER is a widely applied closed-source energy modelling tool and Offgridders an open-source application developed within the Open Energy Modelling Framework (oemof) [58, 104].

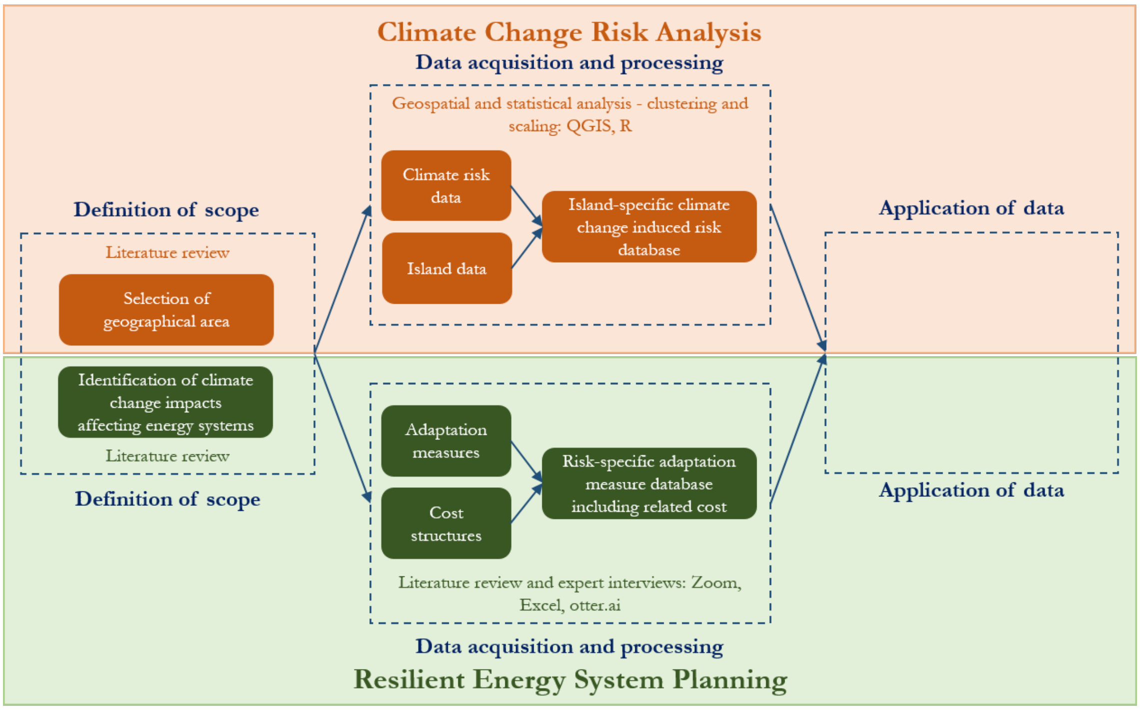

Figure 3.5: *Overview of methodological approach and consecutive steps - data acquisition and processing for resilient energy system planning, own visualisation*

Main input criteria are [104, 105]:

- Load profile / demand,
- Renewable energy potentials / resource availability,
- Selection of energy system components,
- Initial investment costs for energy system components (capital expenditures - CAPEX), and
- Operation costs for the system (operation expenditures - OPEX) and fuel costs.

Based on these main input criteria, the climate change risks (stresses and shocks) are first differentiated by the type of changes they are provoking (gradual or sudden changes, see Section 2.3.5) and then by required adjustments (protective measures and/or adjusted operational data and efficiency, see Section 2.3.5) to manage these changes. This results in adjusted CAPEX for system components, adjusted demand and load to be supplied as new input criteria for resilient energy system planning. Figure 3.6 (following page) visualises the translation of climate change risks into energy system modelling language as described above.

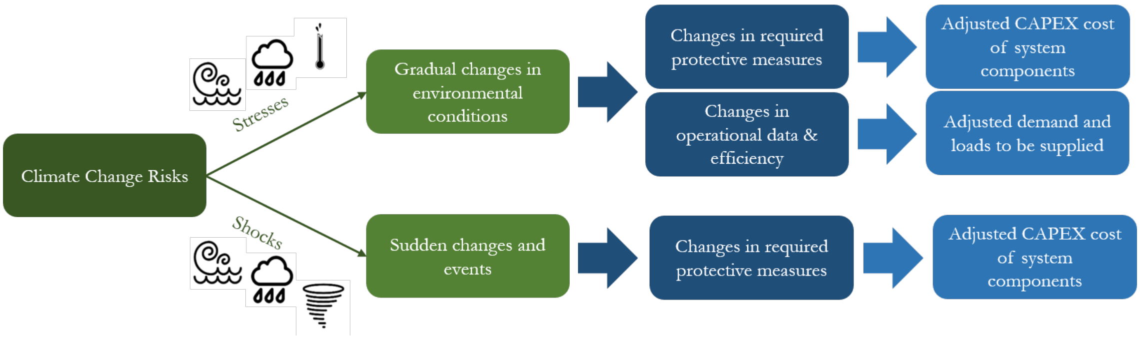

Figure 3.6: *Translating climate change risks into energy system modelling language, own visualisation*

Section 2.3.5 addresses the lack of relevant literature in the field of climate impacts on off-grid energy systems and climate resilience. In order to feed the presented theoretical approach of translating climate change risk into energy system modelling language, quantitative data (adjusted CAPEX and demand) is required. Since there is no open-access data available that can be applied in this context so far, pioneering work is required: To establish a solid data basis, expert interviews are conducted. In the following, the development, conduction, and evaluation of these expert interviews is presented (Figure 3.7).

Figure 3.7: *Expert interview development, own visualisation*

Interview Preparation

Content and Type of Interview

The main objective of conducting the expert interviews is to gather information of adaptation measures to increase the energy system's resilience. Once in contact with many relevant stakeholders in the field, I also assess the necessity of integrating climate change risks considerations into off-grid energy system modelling (see Section

2.3.5) and justify the developed approach. The following topics and questions are addressed and answered in the expert interviews:

- **Necessity**: Is the integration of climate change risk considerations into off-grid energy system modelling needed?
- **Framework**: How can this integration look like? What are important pillars?
- **Data**: What are suitable adaptation measures to increase the energy system's resilience and at what cost? How do climate change impacts affect demand?

The nature of the information targeted by the research objectives as listed above is inherently different. After assessing different types of interviews fulfilling different purposes, semi-structured interviews are identified to suit the developed research objectives best. The content of the interviews combines research that requires an exploratory approach and at the same time seeks quantitative data. To address this, the mixed-method approach is applied combining quantitative and qualitative research including both, open-ended and closed-ended questions.

Relevant Stakeholder Groups

A prerequisite to obtain a comprehensive perspective on a research subject through interviews is the consideration of all relevant stakeholders. Therefore, three different stakeholder groups are identified to gain a holistic assessment:

- **Experts** (e.g. policy makers, governmental agencies, insurance, and finance sector, NGOs, universities): people who have a certain expertise in the topic of off-grid electrification and/or climate resilience or are regional experts; they often have interdisciplinary expertise rather than extensive technical expertise (compared to the second group)
  The interviews with members from this group offer a holistic perspective on off-grid (climate resilient) energy provision and enable the development of a comprehensive and adequate framework.
- **Technology providers** (e.g. utilities, project developers, technology provider): people who have a strong focus on energy system technology and in-depth technical knowledge and expertise in the field of off-grid systems; they are either directly involved in the implementation or operation of island energy projects at the ground or provide the components for the implementation of energy project on the islands

The interviews with members from this group offer an in-depth technological perspective, experience, and insights from the field and current challenges arising from climate change in planning, implementation, and operation of off-grid energy systems.

- **Island communities**: people that are affected by the impacts of climate change and have local expertise; they are directly involved in the usage and the maintenance of the island energy systems
  The interviews with members from this group enable insights into the 'lived experience' of people on the ground.

Relevant stakeholders are identified for the three groups aiming at high diversity (background, gender, and level of involvement) and coverage of expertise regarding different energy system components (e.g. solar system, grid etc.). A mixture of cold and warm calling is applied: Based on the network I developed during my professional stays in Southeast Asia, I added all relevant direct contacts to the potential interviewee list. In addition, relevant institutions, networks, and persons identified in internet searches, and recommended by former partners complement the list.

Interview Guideline

According to the three different stakeholder groups as presented above, three separate interview guidelines are developed, to reflect the inherently different knowledge base and background among the groups. While the overall content of all three interview guidelines is the same, a different focus is placed on each of them. All three interview guides follow the same structure divided into three parts:

- *part A*: open-ended questions
- *part B*: quantitative closed-ended questions
- *part C*: qualitative open-ended questions

Following the problem-centered approach by Witzel (1985), the first part (A) consists of open-ended questions to gain in-depth results of exploratory nature [106]. This allows an understanding of the personal background and uncovers a multiplicity of perspectives. In the second part (B), closed-ended questions are used to both portray a detailed picture of measures to increase climate resilience of energy systems and to obtain quantitative data for a respective quantitative characterisation. For both, part A and part B, the portion of questions are tailored to each interview group individually. While part A and part B are designed to obtain comprehensive and detailed insights, part C is designed to enable a direct comparison of individual views and stakeholder groups regarding the main objective of this research. For that reason, part C is identical for all three interview groups. Part C is composed of closed-ended questions with predefined qualitative answer-categories.

Figure 3.8 gives an overview of the variation between the three different interview groups and respective types of questions (Part A, B, C). The interview guideline for the interview group *experts* focuses on a discursive approach, which is reflected by the greater share of open-ended questions and thus a greater weighting of part A. The interview guides for *technology providers* and *island communities* focus on obtaining qualitative and quantitative categorical data, which is reflected in greater weighting of part B. The implemented interview guidelines can be found in the appendix (Appendix A.3.1, Appendix A.3.2, Appendix A.3.3).

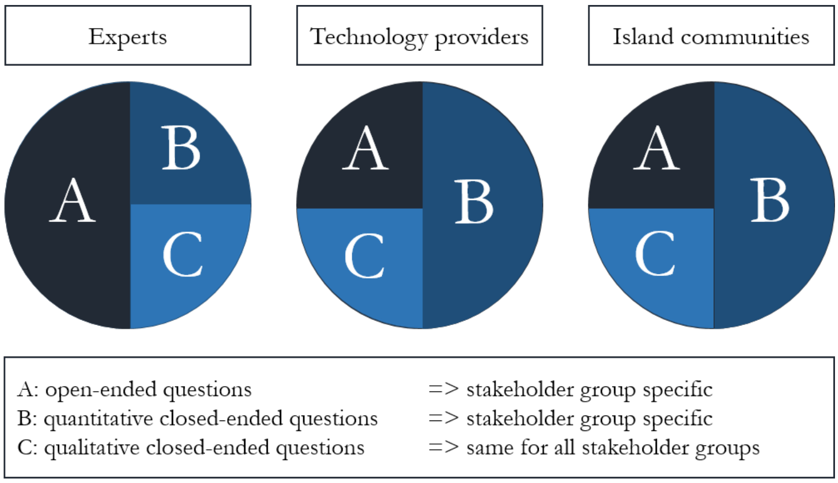

Figure 3.8: *Structure of expert interview guidelines according to respective stakeholder group, own visualisation*

Interview Conduction

Potential interviewees are contacted via email. The invitation to participate in an expert interview for research purposes informed about the content and the methodical approach. Organisational matters of the interviews such as the intended duration of one hour and use of Zoom as communication platform are also communicated beforehand to guarantee transparency. Once the potential interviewees agreed to participate, all questions are shared beforehand to receive considered answers during the interviews. Before starting the interview, interviewees are offered confidentiality and anonymity and are asked for their permission to record the interview for research purposes only. At the beginning of each interview, the purpose, content and methodical approach are explained in a short presentation. When conducting the interview, it is important for the interviewer to remain neutral, in order to not bias the answers given [107]. At the end of the interview, the interviewees are given the opportunity to give additional information relevant to the research topic, which was not covered by the presented questions. More details are given in the interview guidelines for each group (Appendix A.3.1, Appendix A.3.2, Appendix A.3.3).

Interview Evaluation

The evaluation approach is based on the different types of questions and output. In the following, the types of outputs are described as well as the approach to evaluate and analyse the acquired data.

Outputs

The different types of questions lead to various data outputs (statements, qualitative, and quantitative data) as specified in Table 3.5. From closed-ended questions, either a quantitative or a qualitative dataset is obtained, depending on the answer categories of the questions. These outputs are systematically structured based on the answer categories and compared. Evaluation of answers given to open-ended questions is more complex. Following Kergel (2017), a step-wise approach is applied [108]: First, the recorded interviews are transcribed into a written summary and essential statements are derived. Second, the statements are categorised and thematically structured. The transcription of the interviews is facilitated by the otter.ai software.

Table 3.5: *Interview outputs created by different types of questions*

Type of question	**Output**
open-ended	essential statements
closed-ended (qualitative answer categories)	qualitative dataset
closed-ended (quantitative answer categories)	quantitative dataset

Evaluation and Analysis

Figure 3.9 shows the relevant interview output for the various research objectives, in accordance with the respective interview methods used. Furthermore, the figure shows the primary evaluation and analysis approach for the three research objectives.

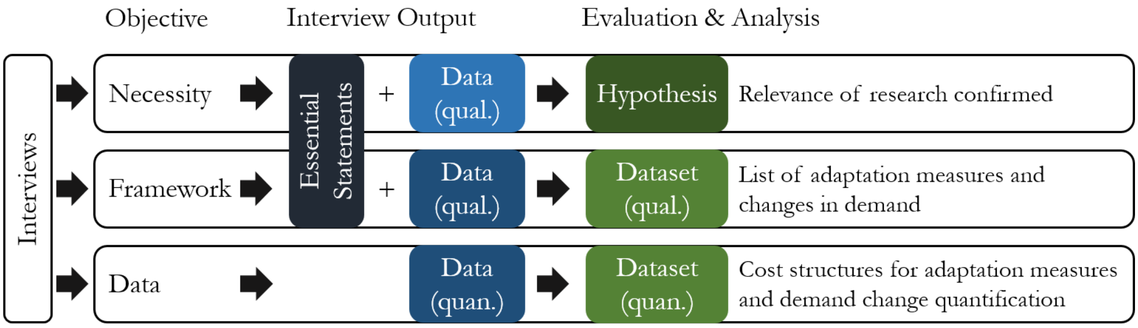

Figure 3.9: *Overview of interview objectives, related outputs, and the evaluation process, own visualisation*

Interview part A with its open-ended questions enables the extraction of essential statements related to the conducted research. The relevance of the research and thus the necessity to integrate climate change considerations into off-grid energy system planning gets approved or disproved. At the same time the extracted statements may give first insights into climate change induced effects on energy systems and potential adaptation measures. Interview part B with its closed-ended questions facilitates the quantification of climate change impacts on energy systems and related cost. In addition, this part may reveal additional understanding of damages and potential measures to reduce these. Interview part C, consisting of closed ended-questions with qualitative answer categories, facilitates the confirmation or declining of the research relevance and enables comparison between the three interview groups. Interview outputs highlighting the relevance of this research or giving an overview of climate change impacts on the ground are already mentioned in the Background chapter (see Section 2.3.5). The evaluation of the qualitative part leads to a list of adaptation measures and changes in demand of energy systems as a result of climate change. The evaluation of the quantitative part comes in form of common statistical data analysis listing mean majority, mean, and mean top third values as presented in the results chapter (Section 4.3.1).

3.3 Application of Data - Island Energy System Modelling

After acquiring and processing climate change risk and adaptation measure data, both databases are combined and applied to case study islands, visualised in Figure 3.10. Case study islands are identified based on the findings of the cluster analysis described in Section 3.2.1 (medoid islands).

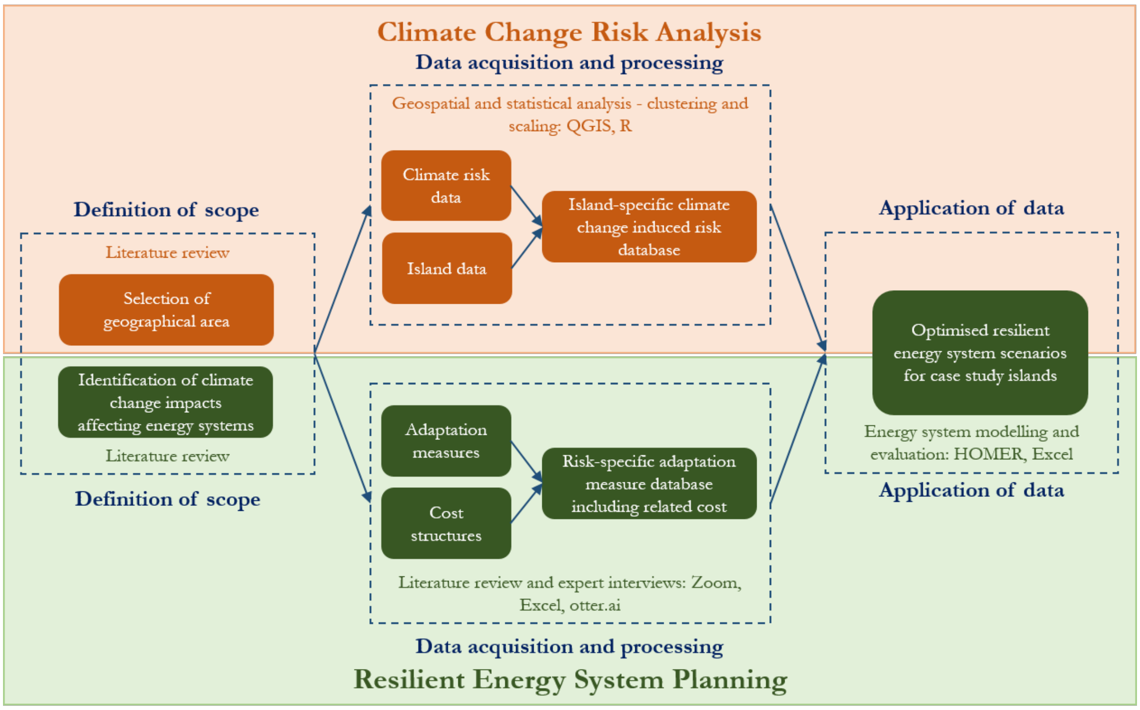

Figure 3.10: *Overview of methodological approach and consecutive steps - application of data, own visualisation*

In the following, the modelling tool and assessed scenarios to compare different island energy systems are described in more detail.

3.3.1 Modelling Tool

The "Hybrid Optimization of Multiple Energy Resources" (HOMER) software is an internationally applied and well-known tool to optimise and simulate off- and on-grid mini-grids and simultaneously run sensitivity analyses to simplify evaluation of feasible energy system configurations [109–111]. The tool enables energy system modelling including several components, e.g. photovoltaic (PV), storage, diesel generator, wind turbine, hydrokinetic, controller, and inverter, and offers the automatic retrieval of solar and wind potential data as well as temperature profiles for specific project locations [109]. When calculating different scenarios, HOMER is balancing generation and consumption, calculating the costs for each scenario [111]. Results are generated in the form of graphs and tables, sorted by the best system setup according to selected criteria (e.g. minimising cost or fuel consumption) [111]. HOMER is an easy-to-handle tool which does not require high computing power or coding skills [111].

Within this research, the island energy systems are optimised and simulated with the modelling tool HOMER Pro version 3.14.4 (2020). Optimisation in this case refers to least-cost planning preferring the system setup with the lowest cost of electricity (COE).

3.3.2 Scenarios

For each island case, different scenarios are modelled in order to compare "business as usual" (BAU) and climate resilient energy system planning. Table 3.6 gives an overview of calculated scenarios.

Table 3.6: *Overview of energy system modelling scenarios, including modelling approach, base and climate cases for components and demand*

Scenario	**Type of modelling**	**Component cost**	**Demand**
BAU	Optimisation	Base	Base
BAU_clim	Simulation	Base	Climate
Climate_high	Optimisation	Climate_high	Climate
Climate_all	Optimisation	Climate_all	Climate

The scenarios differ in the modelling approach (optimisation and simulation) as well as in two main input parameters:

Component cost. Cost structures of system components (e.g. PV, battery etc.) are differentiated between *base*, *climate_high*, and *climate_all*. Cost related to *base* are the current initial investment costs for system components without measures for increased resilience. The *climate_high* cost structure represents adjusted CAPEX (see Section 3.2.2) for system components if the island is affected by moderate to severe climate change risks (scale 3 to 5, see Section 3.2.1) for flooding, sea-level rise, and/or cyclones. The initial investment for the *climate_all* cost structure relates to adjusted CAPEX for system components affected by any of the aforementioned climate change risk, no matter which scale. For most components, the investment and replacement costs can be entered when adding the respective power source or storage technology in HOMER. However, the investments for grid and power house infrastructure on the islands are not reflected in usual input parameters within HOMER. Thus, they are combined and entered as "system fixed capital cost".

Demand. The analysis differentiates by *base* and *climate* demand. The business as usual demand is the *base* demand. The *climate* demand is considering climate change induced changes in demand structures caused by temperature increase determined in the interviews as described in Section 3.2.2.

BAU scenario

BAU refers to a scenario where the demand and component costs are in line with commonly applied data not considering any climate change impacts (*base* cost structure and demand). This scenario is used to optimise the energy system and determine, which system components are suitable to be installed on the specific islands taking solar and wind power potential into account. Hydro power is considered, if any local hydro power sources (rivers or lakes) can be detected.

BAU_clim scenario

The *BAU_clim* scenario includes the increased demand caused by rising temperatures "*climate* demand" (base and peak loads to be supplied) while other input variables remain the same as in the *BAU* scenario (*base* cost structure). The system is simulated with the system setup (components) as well as size (installed capacities) determined in the *BAU* scenario. No optimisation is applied. This scenario helps to understand the consequences of current energy system planning without taking climate change impacts on the demand into consideration. It helps to evaluate the ability of the system to operate and supply the island community with electricity over project lifetime despite climate change induced demand growth.

Climate_high scenario

The *Climate_high* scenario includes the *climate* demand and the adjusted CAPEX as described for *climate_high*. This scenario takes climate change induced changes in the demand into consideration and reflects necessary adjustments to the system design looking at moderate to severe risks. The energy system is optimised based on these criteria.

Climate_all scenario

The *Climate_all* scenario is similar to the *Climate_high* scenario, but takes all occurring site-specific risks into consideration (scale 1 to 5, see Section 3.2.1). Therefore, all measures to reduce occurring climate change risks on energy system components are taken into account and reflected by adjusted CAPEX.

3.3.3 Evaluation

After optimising and simulating energy systems for the identified case study islands, the above mentioned scenarios are evaluated. Two different approaches are applied to compare and evaluate business as usual planning with climate change sensitive energy system planning. The first one is reflecting potential climate change hazards and related damages to the energy system for the business as usual planning. The second one calculates potential cost of outages caused by climate change induced disruptions and relates these with the additional investment costs in climate change sensitive energy system planning.

Occurrence and Severity of Climate Change Induced Damage

The aim is to estimate the potential climate change impacts and related repair and replacement costs comparing the *climate* and *BAU* scenarios. In order to estimate the impacts realistically, the frequency of occurrence as well as the degree of damage caused by climate change impacts need to be considered. Partly as well as fully destroyed energy system components (degree of damage) for various frequencies of climate change induced incidents (occurrence of damage) are simulated. Therefore, the component lifetime is reduced to 5, 10, and 15 years (simulating a climate hazard occurs every 5, 10, or 15 years of system operation destroying the respective components partly or fully) and the replacement costs is set to 25 %, 50 %, 75 %, and 100 % of the original investment costs (meaning that the given percentage of the respective component must be replaced after 5, 10, or 15 years of operation). Table 3.7 (following page) gives an overview of the twelve resulting evaluation scenarios and their abbreviations that are applied to the *BAU* and *BAU_clim* system setups.

Each evaluation scenario and its respective cost of electricity is compared to the two climate resilient energy system scenarios. This comparison enables the assessment at what point and under which conditions the implementation of a climate-resilient energy infrastructure instead of business-as-usual system planning is economically more viable.

Table 3.7: *Overview of evaluation scenarios for energy system modelling and their abbreviations as applied the BAU and BAU_clim system setups*

Damage frequency every...	**25 % damage**	**50 % damage**	**75 % damage**	**100 % damage**
5 years	$E_{5,25}$	$E_{5,50}$	$E_{5,75}$	$E_{5,100}$
10 years	$E_{10,25}$	$E_{10,50}$	$E_{10,75}$	$E_{10,100}$
15 years	$E_{15,25}$	$E_{15,50}$	$E_{15,75}$	$E_{15,100}$

A hybrid approach - based on HOMER outputs and calculation done via an Excel cash flow sheet - is applied to calculate evaluation scenarios COEs and described in the following. Using purely HOMER, an evaluation including frequent damages and repair costs is not possible. If component lifetimes are adjusted to reflect damages and repair costs, the regular replacement circles of components as well as salvage values at the end of project lifetime are distorted. HOMER offers no option to reflect partly destroyed equipment (e.g. 25 %) with reduced lifetime and at the same time consider e.g. the remaining 75 % of the system persisting (having their own salvage and replacement schedule). That is why a manual approach calculating COEs via dynamic Excel files is applied. In order to do so, a cash flow model exported from HOMER as Excel file for the *BAU* and *BAU_clim* scenario serves as basis for further calculations. Nominal and discounted economic values for each system component are included in the exported HOMER table. This cash flow table is transformed to a dynamic cash flow model to calculate COEs for the evaluation scenarios (occurrence and degree of damage) by inclusion of all necessary economic parameters:

- **Net Present Value, NPV**: present value of all the costs of installing and operating the system over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime (sum of all discounted values)
- **Nominal discount, i'**: is the rate at which people could borrow money, set to 8 % for this thesis
- **Inflation rate, f**: expected inflation rate is set to 2 % for this thesis

- **Interest rate (real discount rate), i**: is used to convert between one-time costs and annualized costs and is based on the nominal discount rate (i') and the expected inflation rate (f)

$$i = \frac{i' - f}{1 + f} \tag{3.15}$$

- **Annuity factor (capital recovery factor), $\mathbf{CRF_{25}}$**: is used to calculate the present value of an annuity

$$CRF_{25} = \frac{i * (1 + i)^{25}}{(1 + i)^{25} - 1} \tag{3.16}$$

- **Total annualized cost, $\mathbf{C_{ann,tot}}$**

$$C_{\text{ann,tot}} = CRF_{25} * NPV \tag{3.17}$$

The COE is then calculated as the dividend of total annualized cost of the system in EUR/yr ($C_{\text{ann,tot}}$) and total electrical load served in kWh/yr (E_{served}):

$$COE = \frac{C_{\text{ann,tot}}}{E_{\text{served}}}. \tag{3.18}$$

The annual load (E_{served}) as well as capital, operating, replacement, and salvage costs are extracted from HOMER simulations of the *BAU* and *BAU_clim* scenarios.

According to the specific evaluation scenario (see Table 3.7), damage frequencies of 5, 10, or 15 years and additional investment costs to replace or repair affected components (25 %, 50 %, 75 %, and 100 % of damage) are added to the cash flow model.

To understand the impact of diesel prices on the feasibility of climate resilient energy system planning compared to BAU planning, the evaluation approach is applied for two different diesel prices.

Cost of Power Outages

As Meles et al. (2020) highlight, being connected to electricity is only one obstacle to take, the other one is the reliability of supply [112]. This reliability has an economic value and is evaluated in addition to the cost of electricity comparison [112, 113]. Within this research the cost of power outages is assessed to evaluate the economic value of reliable supply. Therefore, common cost of outages for the research region are studied. Literature review shows a lack of transferable figures to analyse the outage costs for the islands assessed within this research. Looking at Southeast Asia, the costs of power outages are mostly analysed for industrial and commercial sectors, e.g. for Thailand, the Greater Mekong Subregion Academic and Research Network state that "average planned [industry] outage costs are [...] 74.94 Baht/kWh, and 16.23 Baht/kWp, whereas the average unplanned outage costs are [...] 308.41 Baht/kWh, 68.47 Baht/kWp, respectively" [114] and Panya et al. (2010) analysed industrial outage costs for different regions in Thailand [115]. These figures are barely applicable to the case study islands as their industrial and commercial sector is limited and community supply is at the center. However, important to remember is the fact that unplanned outage costs as those provoked by climate change induced shocks and stresses have a higher economic impact - in case of Thailand approximately four times higher [114].

An evaluation of outage costs in relation to GDP of several Philippine regions (Visayas, Mindanao, Luzon and National Capital Region) is a helpful proxy to assess the costs of outages for the case study islands [116]. Mindanao as an agricultural and fishery dominated and mostly non-touristic island group shows a GDP loss of approximately 646.37 Mio. Pesos for a one-hour power outage [116]. According to Census data (2020), Mindanao has a population of 26.25 Mio. people [117]. This results in a GDP loss of 24.6 Pesos (0,017 Euro) in a one-hour power outage per capita.

This value is related to typical power outage times as determined in the expert interviews (Outage_time $_{\text{interviews}}$) and the population of each case study island (*Pop_Cisland*):

$$Cost_{\text{Power Outage}} = \frac{0.017\ EUR}{h} * Pop\_Cisland * Outage\_time_{\text{interviews}} \qquad (3.19)$$

The cost of power outage is calculated for each island and compared to the difference of total investment costs of the *BAU _clim* and *Climate _high* scenario. For this approach, it is assumed that the outage occurs at least once over project duration on the case study islands. If the calculated cost of outage is higher than the difference in total investment costs, climate change resilient energy planning is likely to be more feasible than the BAU system planning.

This concludes the methodological approach of my research and all steps visualised in the overview graph (Figure 3.1) are presented. In the following chapter, the results of the described methodological approaches are presented.

Chapter 4

Results and Discussion

In the following, a comprehensive overview of research findings is presented and discussed: First, the study area of Southeast Asian islands is presented, followed by an overview of main climate change hazards on the islands and their characteristics. The third part summarises the energy system modelling and planning results and evaluation for three case study islands. At the end of this chapter, limitations of the presented results and developed approach are identified and discussed.

4.1 Overview and Scope: Southeast Asian Islands

The final number of islands included in this research is 11,083. An overview of the islands covered in the analysis and sorted by country is given in Table 4.1 (following page).

The significantly lower number of islands covered in this analysis compared to the islands listed in Table 2.1 is explained by limited data availability of the GADM and climate change risk assessment datasets. Further analysis of the islands requires the availability of data for every island. Islands that are lacking at least one information (such as temperature, precipitation, elevation or cyclone data) are therefore excluded from further analysis.
According to GADM data, there are 13,606 islands within the research region. 6,068 islands are lacking data for temperature and precipitation development (WorldClim data). Comparison of several island groups shows that temperature and precipitation are similar on neighbouring islands. To increase the number of islands included in this research, spatial extrapolation is applied. Which means that data gaps are partially closed by employing a 50 km threshold around the islands with missing

Table 4.1: *Number of islands per country as included in analysis*

Country	Number of islands
Brunei	7
Cambodia	120
India (Andaman and Nicobar Islands)	116
Indonesia	4,285
Laos	0
Malaysia	498
Myanmar	2,757
Philippines	1,698
Singapore	20
Thailand	642
Timor Leste	4
Vietnam	936
Total	11,083

data and assigning the data of their closest neighbour. After applying this method, 25 islands remain without data for precipitation and temperature projections and are thus completely excluded from further analysis. Further, the elevation model (CoastalDEM) is not available for another 37 islands, causing missing data for a total of 62 islands.

Another challenge is the country assignment of the island data. For 2,461 islands, the country assignment is missing and further analysis of their data entries reveals that many either belong to Pakistan or are situated in inner parts of bigger islands (e.g. wetlands or river islands) and are therefore also excluded from further analysis. Cambodia and Myanmar show higher numbers of islands included in this research than listed in Table 2.1. This is due to rugged river deltas and coastlines including sand banks, rocks, and small river islands that are detected as islands (surrounded by water), but are not listed as islands officially.

4.2 Climate Change Risk Analysis

To integrate climate change risks into energy system planning, the understanding of site-specific risks is important. In the following, the results of the climate change risk assessment as described in Chapter 3.2.1 are presented. First, the four previously identified climate change risks and their potential impacts on energy systems are analysed. Then the developed climate change risk clusters are described and risk scaling is applied.

4.2.1 Increased Temperature

All analysed islands show a temperature increase. The minimum projected temperature increase is 0.98 °C and the maximum 1.48 °C. The risk of temperature increase is reflected differently in energy system planning than the other three hazards and is covered by an adjusted electricity demand. The correlation of increased temperature and the demand are determined by the expert interviews (see Section 4.3.1). The scaling of temperature increase is not relevant for energy system modelling (see Section 4.3) and done for comparative reasons only. Figure 4.1 shows the respective temperature rise ranges for each Likert scale category. Figure 4.2 (following page) indicates that most islands (4,987) are facing a temperature increase within a range of 1.14 °C to 1.26 °C (risk scale 3) and 4,466 islands a temperature increase of 1.02 °C to 1.14 °C (risk scale 2). Eight islands are within the highest risk category of a temperature increase of up to 1.5 °C until 2040 - 2050.

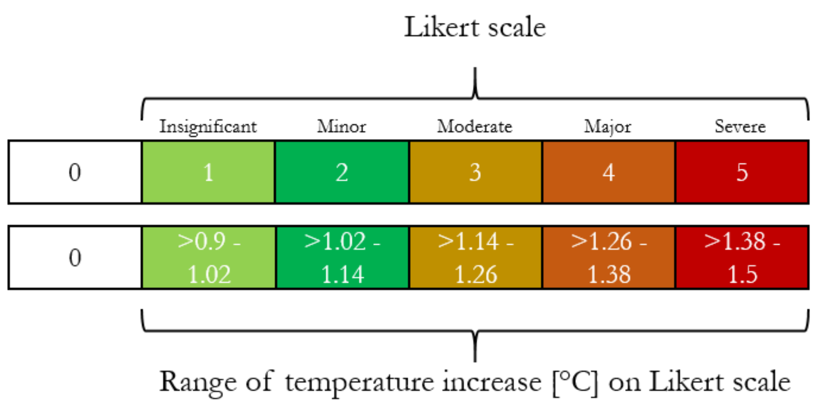

Figure 4.1: *Risk scale (top) and respective ranges of temperature increase [°C] (bottom)*

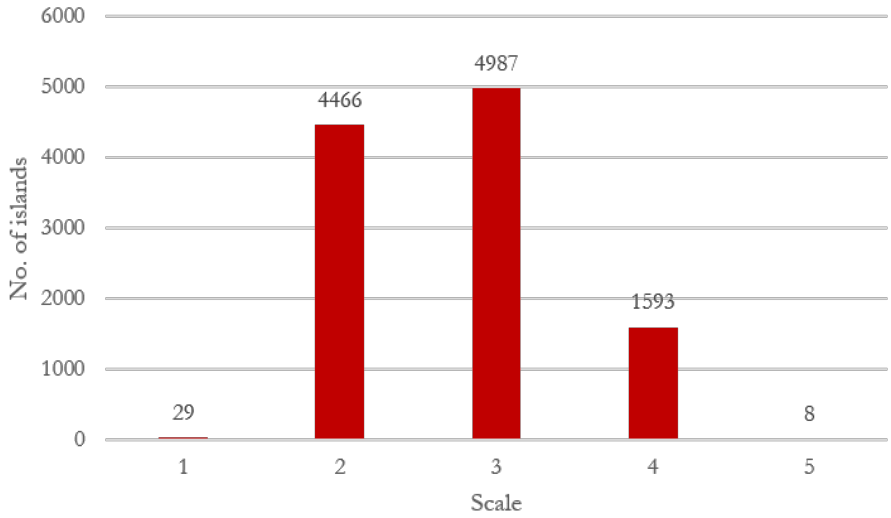

Figure 4.2: *Frequency distribution of temperature increase*

4.2.2 Flood Risk

According to the advanced HDI scale as described in Section 3.2.1, no drought risk for any analysed island exist. Therefore, only flood risk and the respective index range is further considered. The minimum value of HDI is 1 and the maximum value is 4.67 for all islands. All analysed islands show at least an insignificant flood risk (scale 1). Figure 4.3 visualises the application of the Likert scale (1 to 5). The values range from 1 "insignificant risk" (as minimum) to above 1.5 "severe risk" (as maximum).

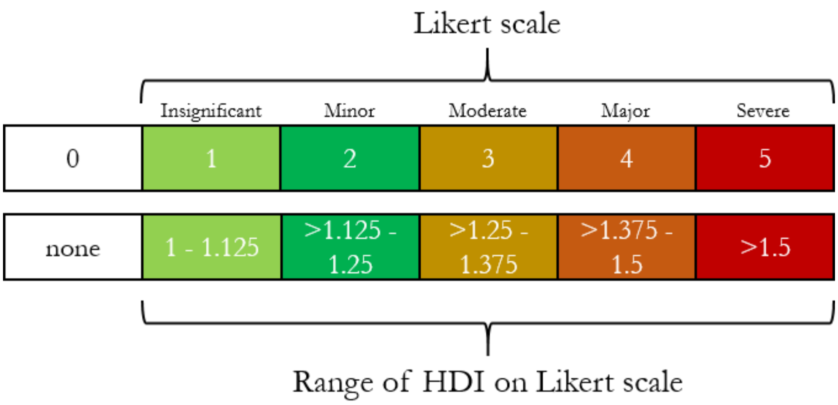

Figure 4.3: *Risk scale (top) for flood and respective HDI ranges (bottom)*

Figure 4.4 (following page) shows the right-skewed distribution of flood risk for Southeast Asian islands. Noticeably, the vast majority of islands (7,671) show a severe flood risk (scale 5). The lower the risk scale the fewer islands are part of the respective risk scale.

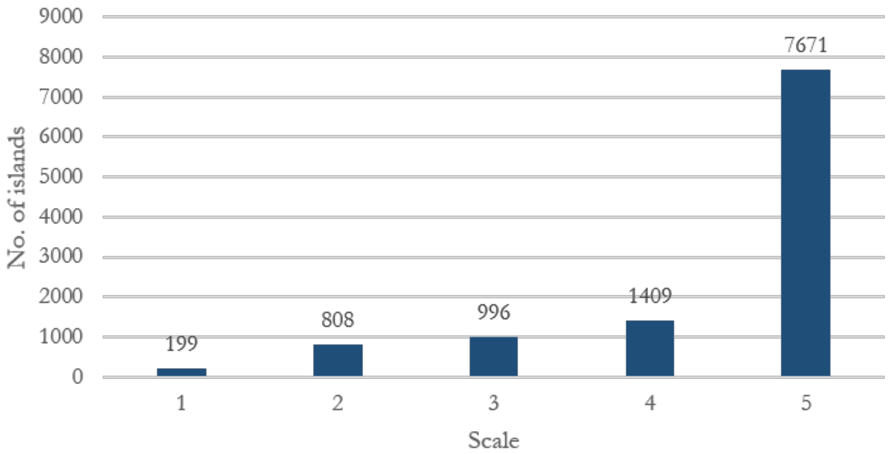

Figure 4.4: *Frequency distribution of flood risk*

4.2.3 Sea-Level Rise Risk

To implement risk scaling for sea-level rise, 0 % of island land loss is taken as minimum and 100 % as maximum value representing a globally applicable scale. The island data also includes the range of 0 % as minimum and 100 % as maximum of projected land loss. The respective risk scale ranges are summarised in Figure 4.5 (following page). In contrary to the flood risk distribution, the sea-level rise risk shows a left-skewed distribution with another spike for risk scale 5 (see Figure 4.6, following page). This U-shape distribution has 2,708 islands in risk scale 1 and 880 islands within risk scale 5. Severe risk (scale 5) means that these 880 islands are loosing a minimum of 80 % and up to 100 % of their land area, resulting in an alarming threat to communities living on these islands. Numerous islands (6,717) are assigned to have no sea-level rise risk. However, the resolution of the CoastalDEM dataset is 3 arcsec (approximately 90 m x 90 m pixel-size) averaging the elevation of the islands over an area of approximately 8,100 m^2. This often leads to overestimation of the height along shorelines. In addition, most coastal exposure analyses refer to the first few vertical meters above high tide lines, leading to estimates highly sensitive to small errors and differences in land elevation [118]. Thus, the actual number of islands without risk of rising sea-level is most likely lower than presented in Figure 4.6.

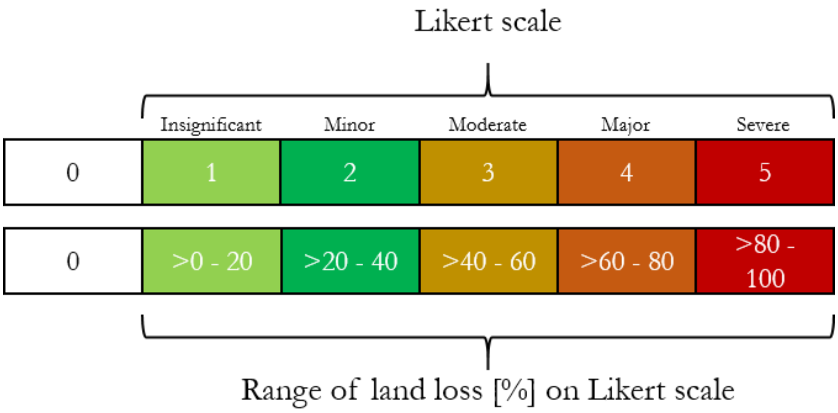

Figure 4.5: *Risk scale (top) and respective ranges of land loss [%] due to sea-level rise (bottom)*

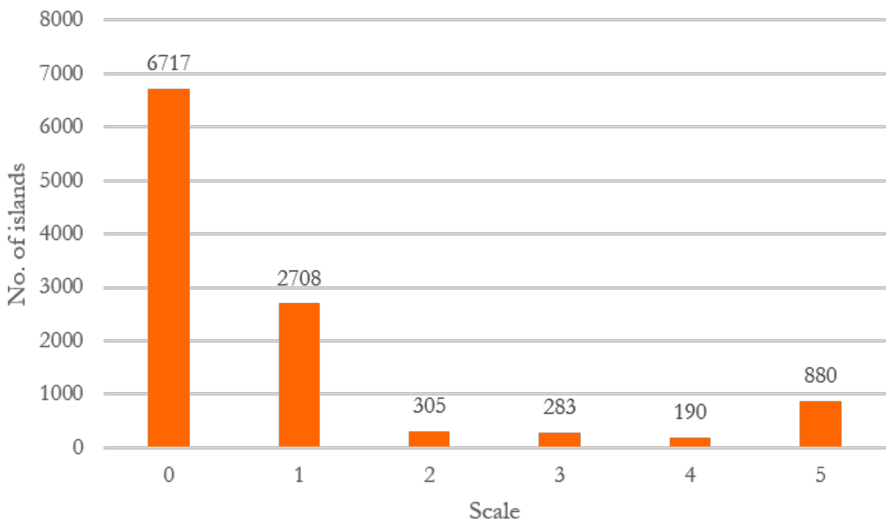

Figure 4.6: *Frequency distribution of land loss due to sea-level rise*

4.2.4 Cyclone Risk

The global cyclone projection dataset shows a maximum of 350 cyclones withing 50 years. To determine the scaling, this maximum value together with values above 0 are equally distributed to the five risk scales (>0 to 350 cyclones on a scale from 1 to 5). The range (number of cyclones) for each of the five scales is listed in Figure 4.7 (following page). The island data shows a maximum of 267.04 cyclones and a minimum of 0.02 cyclones. Thus, there are no islands within the highest risk category (ranging from more than 280 to 350 cyclones) and no islands without cyclones at all.

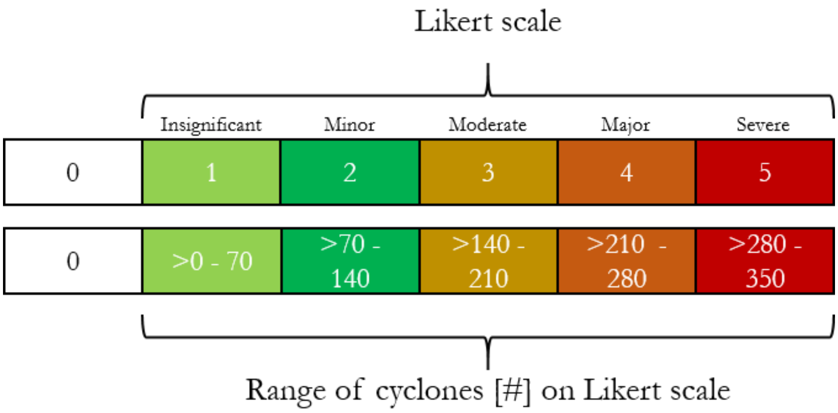

Figure 4.7: *Risk scale (top) and respective ranges of occurring cyclones (bottom)*

Figure 4.8 shows a left-skewed distribution. A total number of 6,512 islands are likely to face up to 70 cyclones within the next 50 years (risk scale 1), which still represents threatening conditions to critical infrastructure on the islands in the near future. Major cyclone risk applies to 464 islands (risk scale 4) with a projected number of up to 267 cyclones (maximum value for dataset) within 50 years, which could mean an average number of up to 5.3 cyclones per year for the respective island. The lowest risk category (scale 1) with a minimum of 0.02 cyclones within 50-years for one island translates to one cyclone happening every 2,500 years representing an insignificant risk for the respective island.

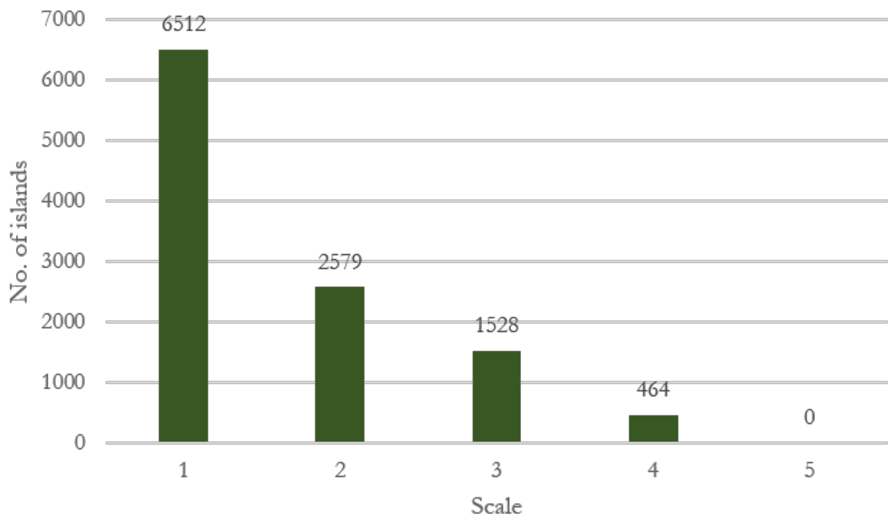

Figure 4.8: *Frequency distribution of cyclone risk*

4.2.5 Climate Change Risk Cluster

In order to detect risk patterns of the Southeast Asian landscape, a cluster analysis is conducted. As described in Section 3.2.1, the first step to run a cluster analysis applying the PAM method is to determine the optimal number of clusters. The elbow method suggests for the climate change risk dataset a number of 3 or 8 clusters (as being the "bend of the elbow") as shown in Figure 4.9. The graph is a direct output of the *plot* function within R. The total within Sum of Square (y-axis) is a measure of total intra-cluster variation or quality of the clustering. The optimal number of cluster is the "bend in the elbow" in the graph. For the applied dataset, 3 and 8 clusters appear appropriate. Running the cluster analysis, a cluster resolution of 3 produced a more promising cluster plot showing larger parts of non overlapping data for the different clusters (maximising inter-cluster dissimilarities and intra-cluster similarities) as further explained below.

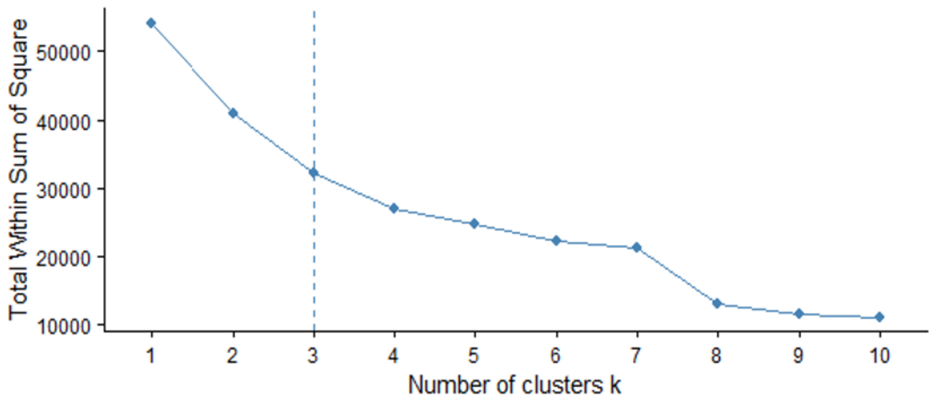

Figure 4.9: *Optimal number of cluster (k = 3) determined by elbow method, statistical, and graphical analysis conducted with R*

In a second step, the cluster analysis (PAM) is run. The cluster plot (Figure 4.10, following page) shows the inter-cluster dissimilarities and intra-cluster similarities. Cluster 1 (red) and 2 (green) are overlapping partly as well as Cluster 2 and 3 (blue). The overlap between Cluster 1 and 3 however is relatively small. Even though each cluster has its specific profile, there are also similarities for some characteristics, which is important to keep in mind for further analysis.

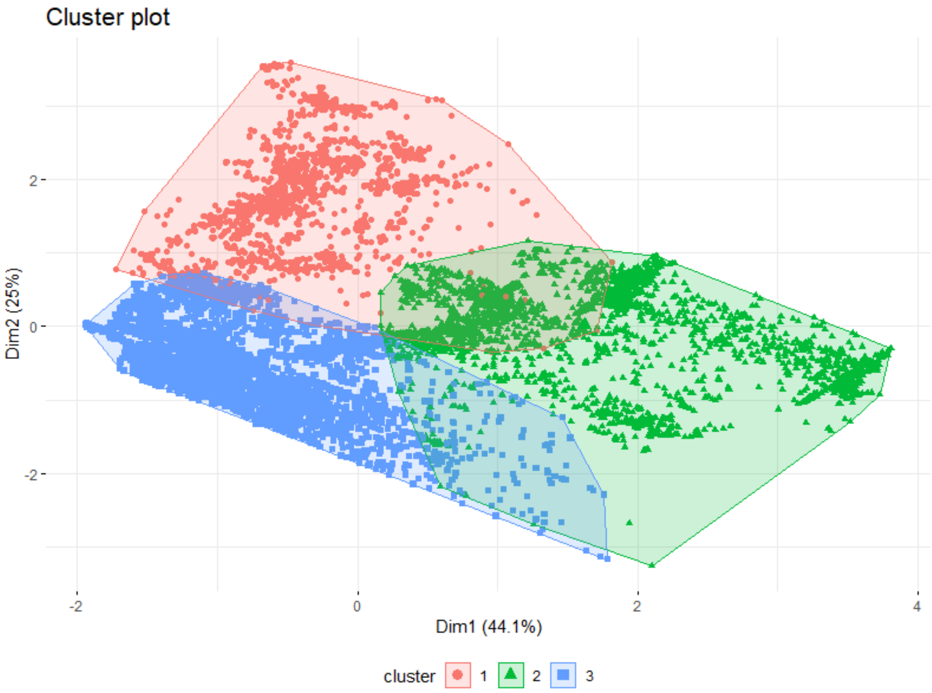

Figure 4.10: Cluster plot of PAM cluster analysis with 3 cluster, statistical and graphical analysis conducted with R

To detect similarities and differences between the three clusters and develop specific risk profiles for each cluster, the cluster boxplots (purple, turquoise, and yellow) for each of the climate change risks are shown in Figure 4.11 (following page). Islands within Cluster 1 (purple) are strongly affected by cyclones (boxplot top left, Figure 4.11) while sea-level rise, temperature increase, and flood risk are comparably low for this cluster. Cluster 2 (turquoise) contains many islands heavily affected by sea-level rise (top right, Figure 4.11), temperature increase (bottom left, Figure 4.11), and flood risk (bottom right, Figure 4.11) compared to the other two clusters. Islands within Cluster 2 show the second highest risk for cyclones of the three clusters. The projected cyclones count, sea-level rise, and flood risk is the lowest for islands within Cluster 3. Islands grouped in Cluster 3 are more affected by temperature increase than those within Cluster 1, but less affected than those within Cluster 2.

The boxplots for cyclone count, temperature rise, and flood risk show relatively few outliers compared to the boxplot for sea-level rise. This might have several reasons. One could be the inaccuracy of the sea-level rise dataset caused by its comparably low resolution (90 m x 90 m) which is particularly relevant for smaller islands. Another reason might be that risk patterns of land loss caused by sea-level rise are barely detectable for the islands, which could also explain the overlap of all clusters

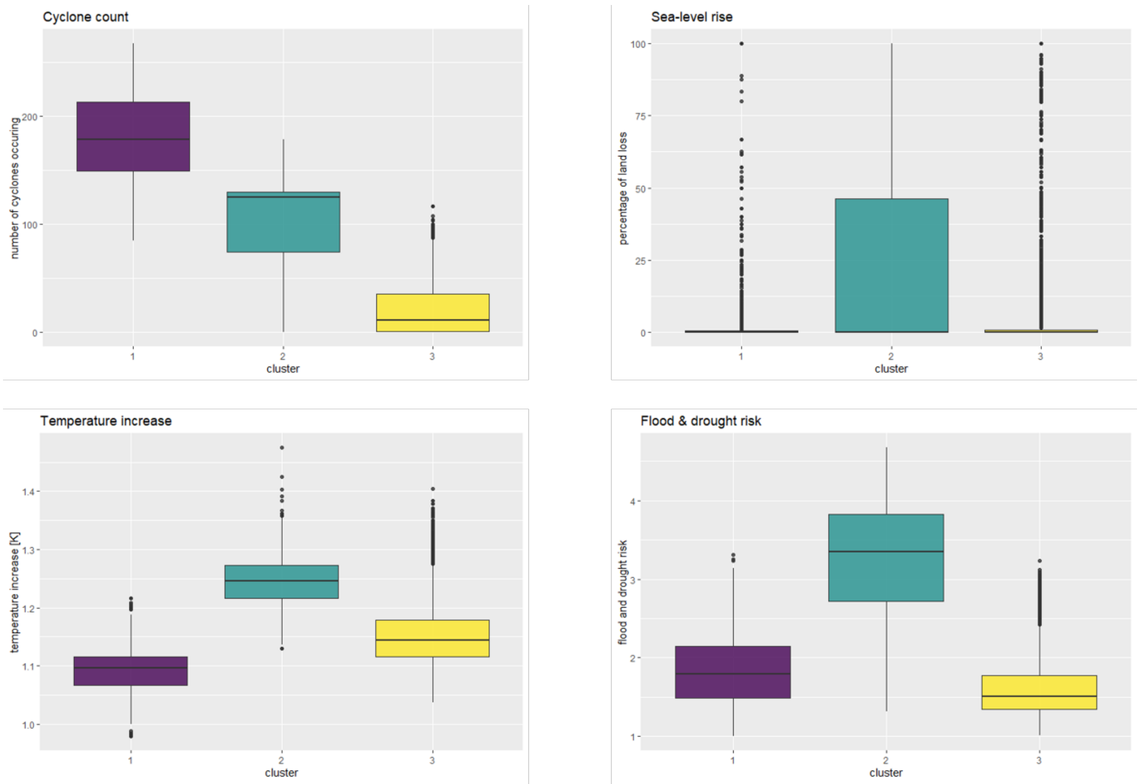

Figure 4.11: *Cluster boxplots of the four different climate change risk, statistical and graphical analysis conducted with R*

for some characteristics in the cluster plot (Figure 4.10). The characteristics of the sea-level rise boxplot also support this hypothesis. The boxplot (top right, Figure 4.11) reveals numerous outliers for Cluster 1 and 3 and the interquartile range of Cluster 2 is comparably high. Due to the large proportion of identical low values in the dataset, the median line for all sea-level rise boxplots is almost identical to the first quartile and therefore not visible. Similar to the other three analysed climate change hazards, Cluster 3 has the highest number of outliers for sea-level rise. The reason might be the relatively diverse risk profile of this cluster (see below).

Table 4.2 (following page) summarises the main characteristics for each cluster. Cluster 3 groups the largest number of islands (6,109) followed by Cluster 2 with 3,243 islands and Cluster 1 grouping 1,731 islands. The risk characteristics match well with the boxplots: Cluster 1 being most affected by cyclones, Cluster 2 by sea-level rise, increasing temperature, and flooding, and Cluster 3 showing low - yet existing - risks for all analysed climate change impacts with some islands being more threatened (highest number of outliers for all analysed risks). A sophisticated assessment on the characteristics of sea-level rise based on the boxplots is only possible to a limited extend as described above. Thus, the mean values for each cluster complement the analysis: Islands within Cluster 2 loose a mean value of 24 % of its land to the rising sea, resulting in a mean risk scale of 3.21. Mean sea-level rise induced land loss of Cluster 3 accounts for 6 % and 3 % for Cluster 1. The mean values of risk scaling reveal a high risk for flooding for each cluster, while scaling for the other risks differ more between the three clusters. As expected, the mean scale for cyclone risk is the highest for Cluster 1 and comparably low for Cluster 2 and 3. Mean temperature rise scaling is highest for Cluster 2, followed by Cluster 3. Cluster 2 shows a significantly higher mean risk scale for Cluster 2 than for the other two clusters.

Table 4.2: *Climate change risk cluster characteristics as determined by PAM cluster method*

	Cluster 1	**Cluster 2**	**Cluster 3**
No. of islands	1,731	3,243	6,109
Mean values per cluster			
Temperature rise [°C]	1.09	1.25	1.15
Flood index [-]	1.83	3.21	1.60
Sea-level rise [%]	3.07	27.69	6.08
Cyclone count [#]	178	109	21.77
Mean risk scale per cluster			
Temperature rise	Minor	Moderate	Moderate
	2.05	3.40	2.58
Flooding	Severe	Severe	Major
	4.47	4.98	4.07
Sea-level rise	Insignificant	Moderate	Minor
	1.24	3.24	1.59
Cyclone	Moderate	Minor	Insignificant
	3.07	1.92	1.07

The geographical distribution of the clustered islands is shown in Figure 4.12 (following page). The majority of islands within Cluster 1 (purple) belongs to the Philippines. Others are located on the central East coast of Vietnam, the Andaman and Nicobar islands, East Timor and islands situated in South-Eastern Indonesia. These locations align with global cyclone zones, which explains why cyclones represent the main hazard of Cluster 1 islands [119]. This is also in line with risk hotspots identified in Section 2.2.2. Most islands of Cluster 1 can be classified as “tropical savannah" according to Köppen-Geiger [120]. Tropical savannahs usually experience less rainfall than other tropical climates explaining the comparably low flood risk for Cluster 1. The turquoise marked islands of Cluster 2 are relatively small islands compared to those grouped in Cluster 1 and 3. This explains their high proportion for land loss risk. These islands are mostly situated along the coastlines of Myanmar and Thailand and are to a large extent also part of the typical cyclone zones in Southeast Asia explaining their second highest cyclone risk. The majority of the islands within Cluster 2 is part of the "tropical monsoon" area defined by Köppen-Geiger explaining their high flood risk [120]. Cluster 3 islands (yellow) are situated in the central part of Southeast Asia and contain many large islands of Indonesia and Malaysia. These larger islands show a relatively low proportional land loss risk. However, Cluster 3 also groups many small islands, whose land loss proportion is higher explaining the many outliers of Cluster 3 (top right, Figure 4.11). Most islands of Cluster 3 are part of Köppen-Geiger's climate classification "tropical rainforest climate" experiencing high mean annual temperatures, small temperature ranges, and rain throughout the year [120]. These areas are characterised by high quantities of rainfall, which are often absorbed by vegetation (rainforest). This fact is reflected by the relatively low flood risk of islands within Cluster 3.

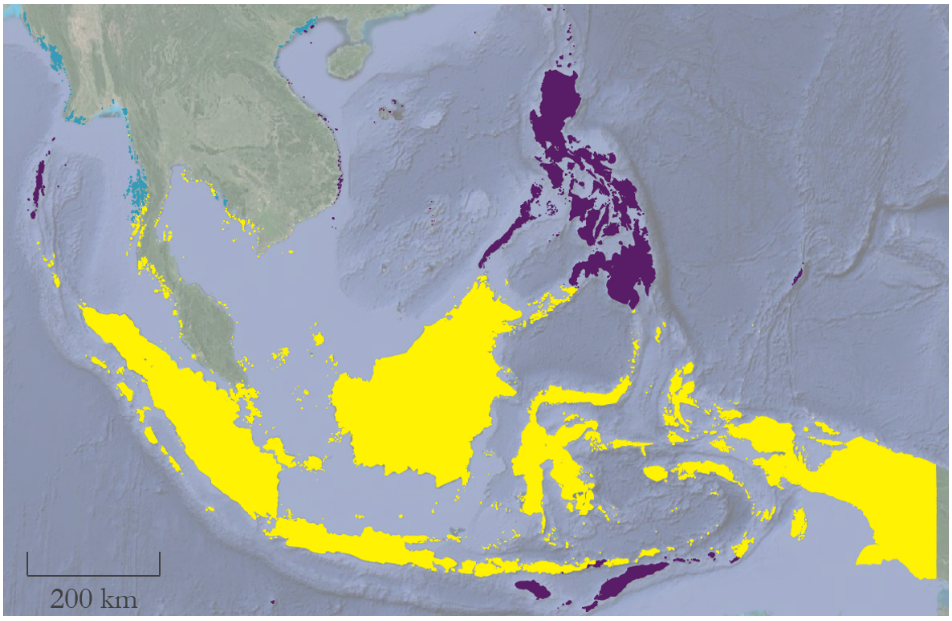

Figure 4.12: *Map of islands grouped into three climate change risk cluster: Cluster 1 (purple), Cluster 2 (turquoise), and Cluster 3 (yellow), statistical and graphical analysis conducted with R*

In summary, some risk characteristics (cluster) are attributed to the geographical location of the islands (e.g. islands situated in one of the global cyclone basins) and some are linked to the general characteristics of the islands (e.g. land loss proportion dependant on size and topography of the island).

4.3 Resilient Energy System Planning

Insights of impacts on energy systems and protective measures to cope with these impacts are necessary to relate the findings of the climate change risk assessment to energy system planning. Interview results as well as three case study islands are presented in order to apply the data and planning approach to real-life cases and evaluate its advantages, disadvantages and applicability.

4.3.1 Adaptation Measures and Climate Change Constraints

A total of 22 interviews were conducted over a two-month period in April and May 2021 to collect information on adaptation measures and related extra investment costs to implement these. Table 4.3 gives an overview on the number of conducted interviews per interviewee group. It shows that interviewees with different functions, backgrounds and expertise representing social society, policy, and economy were interviewed. In the following, the main results needed for further analysis are presented.

Table 4.3: *Breakdown of conducted interviews per interviewee group*

Interview group	Type	No. of interviews
Expert Interviews	Governmental organisation	6
	Research institution	3
	Finance & insurance	2
	Energy policy maker	1
Technology provider	Technology provider	2
	Utility	1
	Project developer	3
Islands community	Thai island community	2
	Philippine island community	1
	Indonesian island community	1

Measures to Enhance Energy System Resilience

Statements and answers given by the interviewees to identify suitable measures to enhance the energy system's resilience are grouped into different levels of involvement. As visualised in Figure 4.13, climate change resilient energy system planning requires adjustments on political and institutional level, has to be reflected in social structures and power dynamics and needs concise technical adaptation measures.

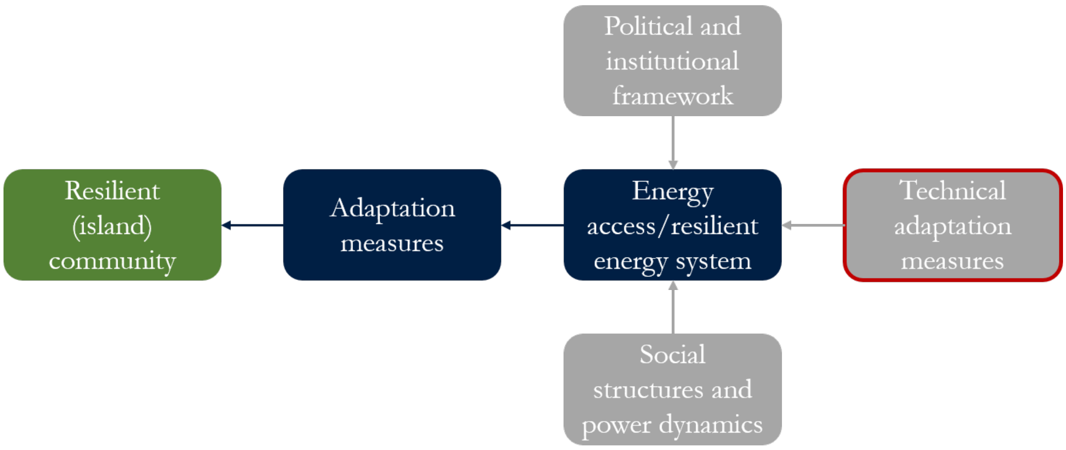

Figure 4.13: *Requirements to enable climate change resilient energy system planning, based on conducted interviews*

The following gives first a broader overview of measures on political and institutional level and provides insights to risk mitigation potentials in social structures and power dynamics. Afterwards, the findings on technical adaptation measures are presented in more detail, as these form the basis for the energy system modelling.

Most interviewees emphasize that climate resilience considerations have to be integrated in political processes by e.g. continuous adjustments of design standards and the development of regulations. Measures that need to be anchored in **political and institutional frameworks** can be summarised to:

- Mandatory risk assessments,
- Development of emergency protocols,
- Development and continuous adjustments of standards, guidelines and regulations,
- Sustainable and integrative land use and watershed management,

- Training and capacity development of local operators on operation and maintenance as well as proper spare part management, and
- Development of financing mechanisms.

Risk assessments at the beginning of project development and the existence of emergency protocols before starting the operation of energy supply systems are perceived to minimise future impacts on systems and enable risk-sensitive actions in case of emergency respectively. These are ideally part of adjusted standards, guidelines, and regulations. This set of mandatory rules shall also include guidance of measures and steps to be taken to mitigate a variety of potential risks to the energy infrastructure in project development, implementation, and operation. Integrated land use and watershed management act as one important part of risk assessment and is also highlighted as measure to protect critical infrastructure by detecting most suitable areas and ways to install energy infrastructure. The importance of proper operation and maintenance, e.g. through well-trained local operators, well-developed spare part management, and continuous accessibility of all system components for effective repair and monitoring, is also mentioned by the interviewees to be an integrative part of suitable adaptation plans. Even though the interviewees confirm the importance of resilient energy system planning on the islands, they also show doubts in the applicability of the concept if no proper financing mechanism and support is in place. Resilient energy systems have higher upfront costs that need to be considered in financing and subsidy schemes.

Social structures and power dynamics are also important to consider in the above mentioned sustainable and integrative land use and watershed management and in conducting training and capacity building of local operators. In addition, ownership and operation management structures and correlations with community empowerment and gender equality are important pillars that have the potential to contribute to increased resilience on a social level.

A detailed list of potential **technical adaptation measures** as recommended by the interviewed experts is summarised in Appendix A.4. The answers can be categorised into measures for specific system components (part I and II) or are related to multiple components and the overall system and its performance (part III). Measures listed in part IV are not applicable to the technical system setup, but to management and operation structures or relate to improved forecasting methods, overall infrastructure planning, regulations, and financing options and thus relate to the political and social level as well.

Measures are manifold and include increased structural strengthening (e.g. of turbines, walls, dams, poles), selection of suitable materials (e.g. salt corrosion resistant and suitability for high temperatures), integration of emergency equipment (backup-diesel generators, emergency points, satellite phones, pumps, drainage, and water reservoirs), automated adjustment mechanisms for components (e.g. tracking of panels and blades), application of cooling technologies (e.g. ventilation, air-conditioning) as well as more robust system setups and interconnection (e.g. self-directed string inverters, modular and decentral setups, focus on simplicity).

Impacts on Investment Costs and Electricity Demand

During the interviews, a special focus was laid to gain insights on projected increased investment costs to implement the identified measures and understand projected changes in demand (base and peak load). These serve as input parameters for energy system modelling in the following sections.

Answer categories for the interviews were given in ranges (see interview guidelines in the Appendix A.3.1, A.3.3 and A.3.2). Mean values are calculated based on these ranges. The interview results are shown as “majority mean value”, “mean value”, and “top third mean value”. The majority mean value refers to the mean of the most selected answer range (e.g. most selected category is up to 5 %, the mean value will be 2.5 %). It helps to understand majority opinions. For the mean value, all answers are taken into consideration. This value is considered for the energy system modelling. The top third mean value takes one third of the answers into consideration, those with the most drastic estimation for increased costs and demand. This answer category gives an impression of extreme opinions. The closer these three values are, the more homogeneous answers were given. In addition, the standard deviation is calculated to measure the variation of all answers.

First, Table 4.4 (following page) shows the results for **adjusted component investment costs** based on different climate change induced shocks and stresses. The increased investment cost reflects the cost to adapt each system component to current and future climate change induced shocks ans stresses. Increased investment cost is described as “extra cost as percentage of original investment costs” for eight system components (wind, hydro, and solar generation as well as inverter, diesel generator, battery storage, power house, and grid). Values are shown for three climate change risks (cyclones, sea-level rise, and flood).

Table 4.4: *Interview results: Mean values (MV) of cost increases (extra cost in [%] of original) and standard deviation for different energy system components and climate change risks*

System component	Risk	Majority MV	**MV**	Top third MV	Standard deviation
		Extra cost in [%] of original			
Wind generation	Cyclones	15.00	**14.00**	18.33	7.00
	Sea-level rise	0.00	**4.38**	5.83	6.34
	Flood	2.50	**7.78**	11.67	8.20
Hydro generation	Cyclones	5.00	**12.72**	20.83	12.13
	Sea-level rise	0.00	**4.58**	9.17	10.89
	Flood	25.00	**17.72**	27.50	11.94
Solar generation	Cyclones	5.00	**9.67**	18.33	7.85
	Sea-level rise	0.00	**9.23**	18.33	10.71
	Flood	5.00	**11.00**	20.00	8.21
Inverter	Cyclones	5.00	**7.69**	14.17	9.33
	Sea-level rise	0.00	**6.00**	10.00	6.63
	Flood	0.00	**3.08**	6.67	4.62
Diesel generator	Cyclones	0.00	**8.85**	19.17	13.32
	Sea-level rise	0.00	**4.00**	6.67	7.35
	Flood	0.00	**4.09**	7.50	7.93
Battery storage	Cyclones	0.00	**5.36**	12.50	9.35
	Sea-level rise	0.00	**2.27**	4.17	3.28
	Flood	0.00	**5.71**	12.50	8.42
Power house	Cyclones	5.00	**12.00**	22.50	10.77
	Sea-level rise	5.00	**7.50**	13.33	9.68
	Flood	5.00	**8.67**	17.50	9.39
Grid	Cyclones	15.00	**21.67**	32.50	13.44
	Sea-level rise	0.00	**6.00**	10.00	8.60
	Flood	0.00	**11.25**	21.67	14.16

According to the interviewees, sea-level rise provokes the lowest estimated additional investment costs to increase the resilience for each system component. The majority of interviewees see no additional investment costs for most energy system components except for the power house (5 % extra investment cost needed to protect the power house against rising sea-level). Top third answers show a range from 4 % (battery storage) to 18 % (solar power plant) of necessary extra investment costs to protect the energy infrastructure. Mean values of all answers given range from 2 % (battery storage) to 9 % (solar power plant) of additional investment costs. Solar power generation and power houses are expected to be most affected by rising sea-level. Standard deviation for sea-level rise values is the lowest for all risks for 50 % of the listed components (wind, hydro, and diesel generation as well as battery storage and grid infrastructure), which shows high consensus amongst interviewees in this regard. Compared to the other risks, the economic impact of increasing the resilience of solar components to protect against sea-level rise has the greatest dispersion of responses, illustrating the uncertainty in assessing the impact of sea-level rise on solar components. This is explained by different assessments of how rising sea-level is affecting energy system infrastructure. Some interviewees purely looked at the difference in shorelines and assumed energy infrastructure not to be placed close to the sea. Thus, they rated the extra investment cost to protect the energy system against sea-level rise as low. Some had space constraints of Southeast Asian island communities in mind and assumed that it is not always possible to install energy equipment far from shorelines. In addition, some even considered the impacts of coastal environments on energy infrastructure like salt-corrosion and thus rated the economic impact for resilient energy infrastructure higher.

Wind generation needs the highest additional investment costs to strengthen the wind power plant against hazards caused by cyclones (14 % mean value, 15 % majority value, and 18 % top third value). These include the increase of structural strength and careful selection of material of mast, blades, and turbines as well as the integration of automated mechanisms and diesel backup generators to put blades in vane positions in case of high wind speeds causing damage to the wind power plant (see Appendix A.4). Standard deviations for wind generation is similar for all risks ranging from 7 to 8. Compared to other energy system components, interviewees show the highest consent in their evaluation of economic impacts to protect wind generation assets against the three climate change risks.

Hydro power stations are estimated to have the highest investments needs to increase resilience against floods (18 % mean value, 25 % majority value, and 28 % top third value). Standard deviation for assessing the extra cost needed to protect hydro power equipment against the impact of climate change ranges from 11 to 12. Measures to achieve higher resilience include the enforcement of civil work (dam, walls, tubes), adjusted design standards (100-year floods slowly become 20-year floods) and integrated watershed and land use management. Implementation of protective measures like additional upstream basins, dams, and walls to effectively manage the water flow are also mentioned.

For solar generation, similar additional investment costs to protect the infrastructure from cyclone (5 % majority value, 10 % mean value, and 18 % top third value) and flood risk (5 % majority value, 11 % mean value, and 20 % top third value) are required with slightly higher investment in flood-prone areas. The variation of answers is slightly lower than for hydro power as standard deviation ranges from 8 to 10. In order to protect solar power plants against cyclones, interviewees suggest to increase structural strength of mounting structures, implement structural protections like wind breakers, integrate automated tracking systems to adjust angles and directions of solar panels (out of wind force) and select most suitable solar panel fixing system (e.g. stronger clamps or easily removable clamps to facilitate quick deinstallation in case of emergency). To protect against the impact of flooding, it is recommended to raise panels above the ground and find smart ways to safely install the panels while water flows are able to pass the area.

Inverters, diesel generators, and power houses are estimated to require more financial means to be resilient against the impact of cyclones than of flooding. Reducing the impact of cyclones (0 % majority value, 5 % mean value, and 13 % top third value) and floods (0 % majority value, 6 % mean value, and 13 % top third value) on battery storage needs almost the same additional investment costs. According to interviewees, the best way to protect sensitive components like battery storage and inverters against cyclones and floods is to install them in proper power houses (with strong foundation, doors, walls, and roofs). Most interviewees assumed this as common practice and rated the additional extra investment cost needed to increase the resilience of batteries and inverters to be low. Consequently, they highlighted the need to strengthen and enforce power houses. In case of flood prone areas, the power house is recommended to be lifted above the ground e.g. by building the house on poles. The standard deviation of answers related to inverter components is comparably low ranging from 5 to 9. For diesel generators, the variation of answers for sea-level rise and flood is very similar (standard deviation of 7 to 8), while those for cyclones is amongst the highest for all answer categories (13). The uncertainty is explained by different perspectives of the interviewees on the placement of diesel generators. While some assumed the generator to be protected by a power house and thus rating the need for additional investment to increase the generators' resilience low, other assumed the generator to be exposed to outside weather conditions and thus rating the investment need higher. For battery storage, the variation of answers is with 3, 8, and 9 similar to that for inverters.

The highest additional investment costs to make energy system infrastructure resilient lays with the grid. According to the interviewees, protecting the grid against cyclones requires 22 % (mean value) additional investment costs, followed by 11 % (mean value) in flood prone areas and 6 % (mean value) in areas affected by sea-level rise. Interestingly, the additional grid investment costs for the most ticked answer category (majority mean value) are noticeably lower with 15 % to protect against cyclones and no required extra investment for sea-level rise and flood. Considering the top third answer, the additional investment reaches high values of 33 % for cyclone risk and 22 % for flooding. Thus, the answers given to protect grid infrastructure against climate change risks are widely distributed. This is confirmed by the calculated standard deviation. For cyclone and flood risk, the standard deviation is with 13 and 14 respectively the highest of all answer categories. While the variation for cyclones is between higher (15 %) or very high (30 %) additional investment cost, the variation to protect against flood risk lays between 20 % and no cost increase at all. Thus, cyclones pose a major risk to grid infrastructure for all interviewees and requires high additional investment cost to be protected. The variation of answers to the question about the risk of flooding can be explained by the respondents' different assessments of whether floods can topple power poles or not. Measures to increase the resilience of grid infrastructure include the structural strengthening of poles and careful selection of components like cables, connectors, and insulators as well as adjusted sizing of cables (considering wind forces and temperature increase).

In summary, grid infrastructure is rated to be the most expensive part of the energy system to protect against the impacts of climate change. Cyclones and floods have a strong impact on all parts of the energy system and require costly adaptation measures. In most cases, the mean value for the the majority of interviewees is slightly lower that the mean value of all interviewees.

Table 4.5 (following page) provides figures for **increased demand** caused by rising temperatures. Again, the "majority mean value" refers to the most selected answer category. The mean value is calculated based on all answers given and the "top third mean value" is calculated taking the top third answers into consideration (1/3 of answers with the highest rating). The "majority" and "top third" mean values are relatively close to each other while the "mean value" is noticeable lower for base and peak load. The required days of autonomy have a narrower distribution than the load values and are similar for “majority mean value” and “mean value” while the “top third” values are around 2 % higher. In comparison to standard deviations calculated for the assessment of additional investment cost for each system component and climate change risk (see Table 4.4), the variation of base and peak load as well as required days of autonomy is low (ranging from 5 to 6). The energy system modelling for case study islands is based on the mean values as presented in the third column of Table 4.5.

Table 4.5: *Interview results: Mean values (MV) and standard deviation of demand increases (base and peak load) and change in required days of autonomy considering climate change impacts*

Parameter	Majority MV [%]	**MV [%]**	Top third MV [%]	Standard deviation
Base load	20.00	**12.83**	20.00	6.34
Peak load	16.25	**13.00**	18.75	5.64
Days of autonomy	17.50	**17.00**	19.17	4.97

4.3.2 Case Study Islands

As result of the cluster analysis as described in Section 4.2.5, three medoid islands are determined. These medoid islands serve as case study islands for the analysis and are presented in the following.

Case Study Island 1: Hon Son Cha, Vietnam

Medoid island for Cluster 1 is an island situated close to the East coast of central Vietnam (see Figure 4.14, following page). Looking at satellite images of that island, it becomes obvious that the island is a small rock formation close to the shoreline and thus not inhabited. The closest neighbour island is Hon Son Cha, also grouped into the same cluster and thus showing similar risk patterns (see Table 4.6, following page). Hon Son Cha is 12.6 km away from the medoid island and in contrast to the rock formation inhabited. Therefore, Hon Son Cha serves as case study island for Cluster 1.

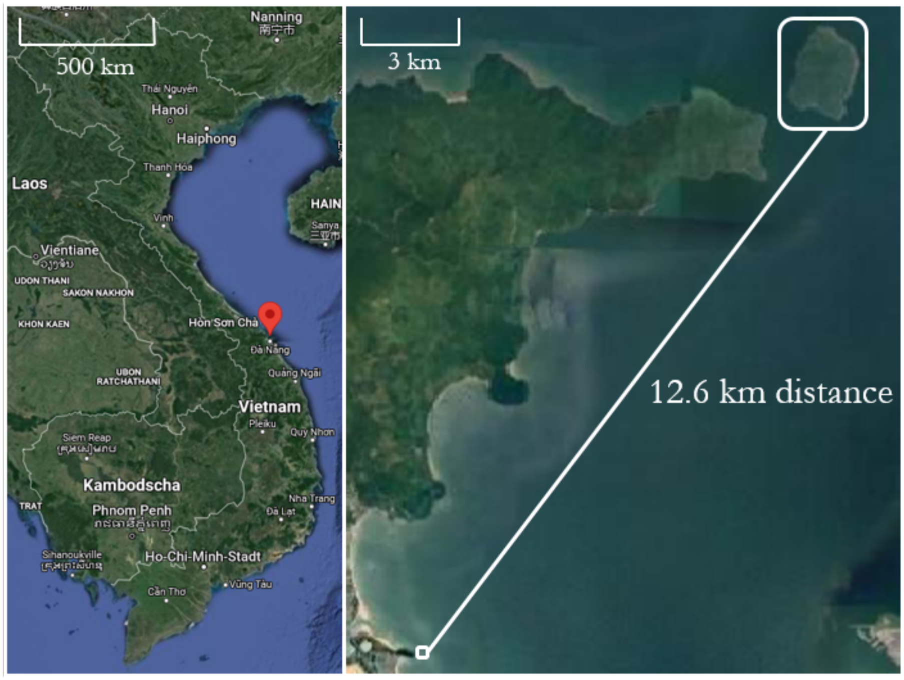

Figure 4.14: *Left side: Location of first case study island Hon Son Cha, Vietnam; Right side: Medoid island of Cluster 1 (white square at the bottom) and its closest neighbour island Hon San Cha (white square on top), Vietnam*

Table 4.6: *Comparison of risk characteristics for case study island 1 (Hon Son Cha) and medoid island 1 (rock island)*

Case study island 1: Hon Son Cha, Vietnam, island ID 9480

Type of risk	**Risk scale**	**Value**
Flood	5	1.59
Cyclone	3	173
Sea-level rise	1	1.47 %
Temperature increase	2	1.05°C

Medoid island 1: Rock island, Vietnam, island ID 3274

Type of risk	**Risk scale**	**Value**
Flood	5	1.83
Cyclone	3	173
Sea-level rise	0	0 %
Temperature	1	1.08°C

Hon Son Cha has a size of 1.46 km^2 and is 0.6 km away from the closest shoreline and 12.6 km to the closest settlement on Vietnam mainland. Satellite images reveal two buildings on the island: a temple and a camping ground with one building. Literature review gives limited information about the island. The island - also called Hon Chao (pan island) - in central Vietnam is only recently explored as tourism destination. The island has no pier, the boats are currently landing on the beach. The island is hilly with a maximum altitude of around 230 m above sea-level (according to Open Topo Map). The island's growing popularity among tourists might indicate growing development and increasing demand for reliable electricity supply. As tourism location, the accommodation options including air conditioning may raise the demand drastically compared to its current, rarely developed state. The satellite images imply no significant hydro power sources on the island (no rivers, lakes etc.) and no agricultural activity (no biomass potential). According to Table 4.6, the island will face very high flood risk (risk scale 5), 173 cyclones are likely to run over the island within the next 50 years (risk scale 3), the average temperature might increase by 1.05 °C (risk scale 2) and the island will loose approximately 1.47 % of its land to the sea (risk scale 1). Flooding and cyclones are the dominating risks. Due to the relatively high elevation of the island (pan shape), it is not heavily affected by sea-level rise.

Case Study Island 2: Magyi Kyun, Myanmar

Medoid island of Cluster 2 is Magyi Kyun located in South-West Myanmar. Figure 4.15 (following page) shows the location and size of Magyi Kyun island. The island has a size of 3.91 km^2, is 15.2 km away from the closest shore-line and 18.4 km away from the closest settlement on Myanmar mainland. The satellite images show a settlement on the North-East part of the island. According to Open Topo Map, the island's highest elevation is around 70 m above sea-level. Magyi Kyun island has a pier (situated on the North-East part of the island), approximately 200 buildings on both sides of the main road (approximately 1.5 km long), several public buildings and a temple. Respective literature reveals no additional information, no touristic infrastructure seems to be in place. A look at the satellite images make agricultural activity on large parts of the islands likely (potentially rice or salt production due to the basin formation). The island has a water basin, but no river or lake, limiting the hydro power potential of the island.

Table 4.7 (following page) lists the types of risk and their scale for Magyi Kyun island: The island has a quite significant flood risk (risk scale 5) and will experience a high increase of average temperatures (1.24 °C, risk scale 4). An estimated number of 124 cyclones will touch the island within the next 50 years (risk scale 2) and the

Figure 4.15: *Location of second case study island Kagyi Kyun, Myanmar*

Table 4.7: *Overview of risk characteristics for case study and medoid island 2 (Magyi Kyun)*

Medoid and case study island 2: Magyi Kyun, Myanmar, island ID 9319

Type of risk	**Risk scale**	**Value**
Flood	5	3.26
Cyclone	2	124
Sea-level rise	1	5.37%
Temperature	4	1.24°C

island will most likely loose 5.37 % of its land to the sea (risk scale 1). Changes in precipitation patterns and rising temperatures are of concern for this island.

Case Study Island 3: Bulon Don, Thailand

The medoid island of Cluster 3 is called Bulon Pai situated in the Andaman Sea in Southern Thailand. The island is not inhabited as satellite images reveal. The closest neighbouring island is Bulon Don at 2 km distance (see Figure 4.16, following page). Bulon Don is inhabited and part of the same risk cluster showing similar risk patterns with slight differences in flood risk (see Table 4.8, following page). Bulon Don serves as case study island for Cluster 3.

Figure 4.16: *Left side: Location of third case study island Bulon Bon, Thailand; Right side: Medoid island of Cluster 3 (Bulon Pai, white square at the bottom) and its closest neighbour island Bulon Don (white square on top), Thailand*

Table 4.8: *Comparison of risk characteristics for case study island 3 (Bulon Don) and medoid island 3 (Bulon Pai)*

Case study island 3: Bulon Don, Thailand, island ID 1203

Type of risk	Risk scale	Value
Flood	3	1.49
Cyclone	1	17
Sea-level rise	0	0%
Temperature increase	3	1.16°C

Medoid island 3: Bulon Pai, Thailand, island ID 6945

Type of risk	Risk scale	Value
Flood	5	1.56
Cyclone	1	17
Sea-level rise	1	2.63%
Temperature	3	1.15°C

Bulon Don is an island of 0.26 km^2 and 14 km away from the closest on-shore settlement including the main pier of the area (Pak Bara pier) and 11 km away from the closest shore to mainland. Bulon Don is a purely local island without any touristic activity [121]. The island is part of Mu Koh Phetra National Park. There is no pier so that boats are currently landing on the beach (East part of the island) [121]. The island consist of a single hill (approximately 90 m maximum elevation, according to Open Topo Map). There are approximately 80 residential houses and three public buildings (mosque, health centre, and school) situated on the rare flat area of the island (close to the beach on the East part) [121]. The island has no agricultural activity and no water sources like rivers or lakes on the island. Hydro power and biomass potential is therefore limited. Some island community members own and share diesel generators (1 - 10 households) for basic electricity supply, the island once owned a central generator to supply the whole island which broke down in 2016 and has not been repaired since [121]. Grid infrastructure is in place, but partly destroyed by storms (see Figure 2.6). In 2020/21 SHS arrived for most households. Table 4.8 gives an overview of climate risks and scales for the medoid island of Cluster 3 (Bulon Pai) and Bulon Don island. Even though the islands are part of the same cluster, the two islands differ in their specific risk profile. However, the basic characteristic of Cluster 3 including low cyclone and sea-level rise risk in combination with medium temperature rise and flood risk compared to the other two clusters remain for both islands. Only the flood risk for Bulon Pai is significantly higher than for Bulon Don because of the steeper topography of Bulon Don. Both flood risk scales - 3 for Bulon Don and 5 for Bulon Pai - are considered the same way in the developed scenarios for resilient energy system planning (see Section 3.3.2). That is why their differences in this specific risk is not significant for further analysis.

4.3.3 Energy System Modelling Results

As the focus of this thesis is to understand climate change impacts on energy systems and integrate these findings to develop an approach for climate change resilient energy system planning, it is on the one hand important to create a representative overview of different island cases. On the other hand these cases need to be easily comparable to draw universal conclusions. The first aspect is covered by selecting island case studies based on the climate change risk assessment. The second aspect is important to consider while making assumptions for the different islands cases. In the following, general assumptions and approaches to model the energy system on the islands are presented. Island-specific assumptions are then mentioned in the respective sub-section for each island.

Most parameters enquired in the expert interviews (see Table 4.4 and Table 4.5) are reflected in editable input parameters provided in HOMER (e.g. investment costs for batteries, diesel, PV, or load profiles). However, the investments for grid and power house infrastructure on the islands are not defined as common input categories in HOMER and are therefore combined and covered as "system fixed capital cost". In line with findings of a study on Thai islands, the power house investment costs are set to 8,800 EUR considering material, transport, and construction expenses for all island cases as baseline (BAU scenarios) [121]. The investment costs of inverters for storage and PV components are combined with inputs for PV and battery investment and replacement costs. The system inverter (converter) is set to "Generic large, free converter" without additional CAPEX costs. Initial investment and replacement costs of system components (per installed capacity) are assumed to be identical. The grid price per meter is set to 12.92 EUR/m according to a mini-grid study conducted on Thai islands [121]. Even though all islands are part of different countries, the assumed price of diesel fuel is considered to be the same for all islands to reduce the impact of fuel price differences on the results. The raw price of 0.763 EUR/l is determined by the mean value of diesel fuel cost in Thailand, Vietnam, and Myanmar (derived on 19th of January 2022). On top of that, an escalation rate of 3.1 % is assumed [121] and the diesel handling and transportation costs are also considered (following findings of interviews conducted on Thai islands [121]). The resulting total diesel fuel price is calculated as 0.942 EUR/l.

Modelling Results: Case Study Island 1 (Hon Son Cha, VN)

The first case study island has no permanent residents, only a temple and and a camping ground that create the electricity demand of the island. Most likely, there are no or only few high demand appliances like air conditioning, refrigeration or freezer, resulting in a generally low demand and daily load profile. Thus, the lowest default load profile within HOMER is selected to model the energy system for Hon Son Cha: the "residential" load. The projected load profile of the island is shown in Figure 4.17 (following page).

A measurement taken with QGIS reveals a potential grid length of 580 m connecting both buildings and the landing beach. The island has no hydro power potential. Therefore, hydro power is not considered in the energy system modelling. Table

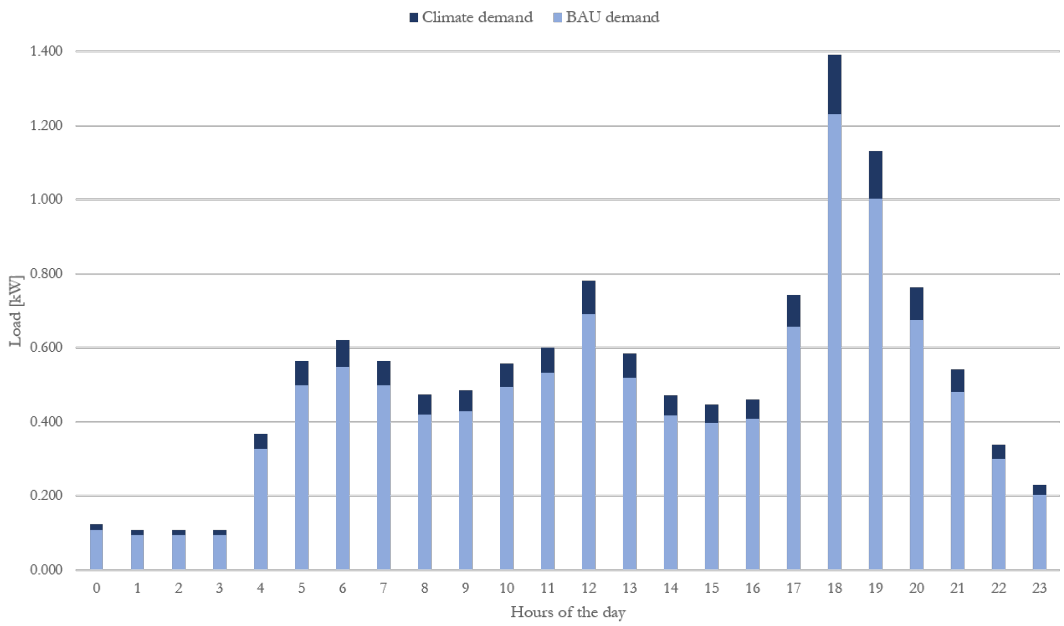

Figure 4.17: *Daily load profile for Hon Son Cha island; "BAU" demand on the left, "Climate" demand on the right*

4.9 (following page) summarises the cost increases for each system component to protect these against the impacts of the three risks occurring on Hon Son Cha island: flooding, cyclones, and sea-level rise. As listed in the Table, protection against flood and cyclone risk needs to be considered for both scenarios, while sea-level rise is only considered in the *Climate_all* scenario. Applying these cost increases to the different system component prices leads to the financial input parameters as shown in Table 4.10 (following page).

The optimisation of potential energy systems on Hon Son Cha island reveals an optimal system setup consisting of PV panels, battery storage, and diesel generators (no wind generation). Thus, wind power generation and its components are not further considered. The energy system modelling results for Hon Son Cha are listed in Table 4.11 (next but one page). The cost of electricity is high and lays between 0.73 EUR/kWh (*BAU_clim* scenario) and 0.86 EUR/kWh (*Climate_all* scenario). To serve the increased demand with constant capacities for solar and batteries, a higher diesel share is necessary for the *BAU _clim* scenario when compared to the *BAU* scenario. This explains the higher fuel consumption and lower RE share of the *BAU _clim* scenario. Interestingly, the COEs are lower for the *BAU_clim* scenario on Hon Son Cha island. Looking at both climate scenarios, they differ only in slightly higher COE for the *Climate_all* scenario (0.03 EUR/kWh difference). Installed capacities

Table 4.9: Cost increases for system components according to developed scenarios - Hon Son Cha

Component	Cost increase flood risk [%]	Cost increase cyclone risk [%]	Cost increase sea-level rise [%]
PV	11.00	9.67	9.23
Battery	5.71	5.36	2.27
Diesel	4.09	8.85	4.00
Power house	8.67	12.00	7.50
Inverter	3.08	7.69	6.00
Grid	11.25	21.67	6.00
	To be considered for the following scenarios:		
	Climate_high	*Climate_high*	*Climate_all*
	Climate_all	*Climate_all*	

Table 4.10: Financial input summary for energy system modelling - Hon Son Cha

Component	Unit	BAU	Climate_high	Climate_all
CAPEX PV	EUR/kW	1,144.0	1,380.5	1,486.1
CAPEX inverters	EUR/kW	253.4	280.7	295.9
CAPEX PV & inv.	EUR/kW	1,397.4	1,661.2	1,782.0
OPEX PV	EUR/kW/a	17.6	17.6	17.6
CAPEX battery	EUR/kWh	380.2	422.3	430.9
CAPEX inverters	EUR/kWh	253.4	280.7	295.9
CAPEX battery & inv.	EUR/kWh	633.6	703.0	726.8
OPEX battery	EUR/kWh/a	10.8	10.8	10.8
CAPEX diesel	EUR/kW	220.0	248.5	257.3
OPEX diesel	EUR/kW	0.097	0.097	0.097
CAPEX grid	EUR	7,493.6	9,960.5	10,410.1
OPEX grid	EUR/a	88.0	88.0	88.0
CAPEX power house	EUR	8,800.0	10,619.0	11,279.0
CAPEX grid & power house	EUR	16,293.6	20,579.5	21,689.1

for all system components remain the same. The slightly higher COE is thus a result of higher CAPEX costs for all system components for the two climate scenarios.

Table 4.11: *Energy system modelling results (HOMER) for case study island 1: Hon Son Cha, Vietnam*

Parameter	**Unit**	**BAU**	**BAU_clim**	**Climate_high**	**Climate_all**
PV size	kW	3.8	3.8	2.3	2.3
Battery size	kWh	11	11	3	3
Generator size	kW	2.3	2.3	2.6	2.6
COE	EUR/kWh	0.749	0.729	0.833	0.861
RE share	%	77.6	68.3	35.0	35.0
Fuel consumption	l/a	269	424	878	878

Hon Son Cha island has a low demand and around 11 kWh ("BAU" demand) are projected to be sold per day over a project duration of 25 years. This in combination with high investment costs - especially for general infrastructure (grid and power house) - explains high COEs for all calculated scenarios on the island. In this case, higher demand of the *BAU_clim* scenario leads to a more beneficial proportion of investment costs to electricity sales (approximately 13 kWh per day) than the BAU scenario resulting in lower COE. High proportions of investment costs to the above listed low electricity sales become obvious when looking at the cost distributions of different system components for the island. Figure 4.18 (following page) visualises the total cost per system component over a standard project lifetime of 25 years including capital investment, replacement, operation, fuel, and salvage costs for the *BAU* scenario. General infrastructure (grid and power house) account for 44 % of the overall system cost. Cost distribution for the *BAU_clim* scenario shows similar values with slightly higher proportions for diesel (18 %) and lower ones for grid and power house (40 %). Both climate scenarios show similar cost distributions as well, but differ from those of the BAU scenarios. Figure 4.19 (following page) represents the cost distribution of the *Climate_high* scenario.

While the proportion of general infrastructure costs remains with 44 % the same as for the BAU scenario, the proportion of diesel costs increases by 19 % and those for battery and PV equipment decreases by 13 % and 7 % respectively. This aligns well with decreased installed capacities for PV and battery storage and slightly lower installed capacities for diesel generation. Large parts of the demand are met by

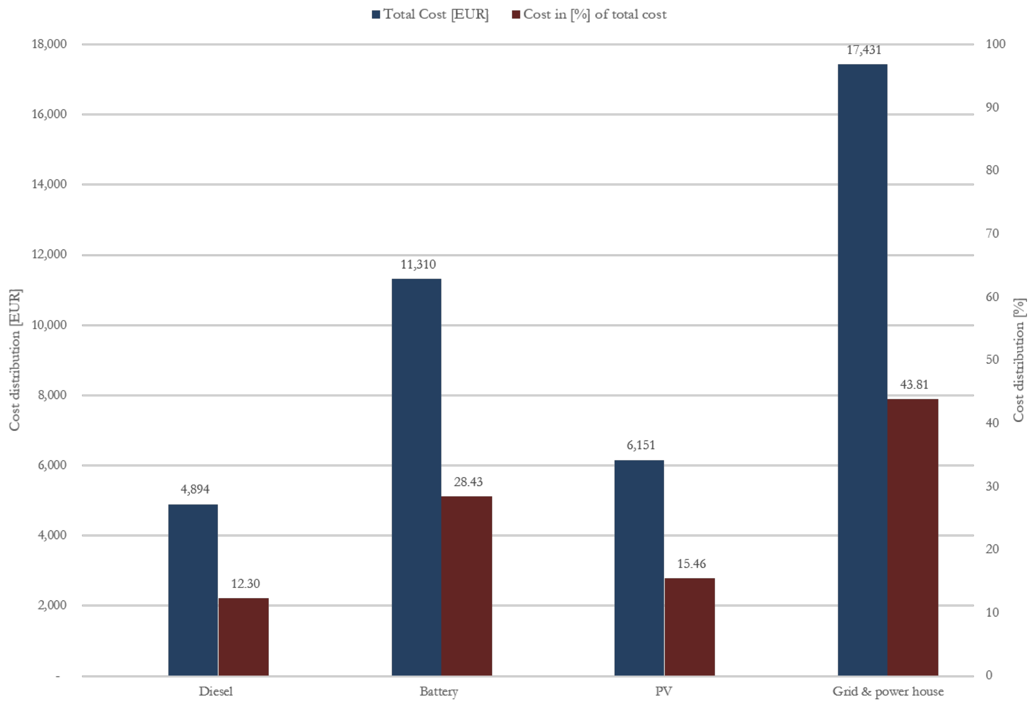

Figure 4.18: *Cost summary and distribution for Hon Son Cha's island energy system, BAU scenario*

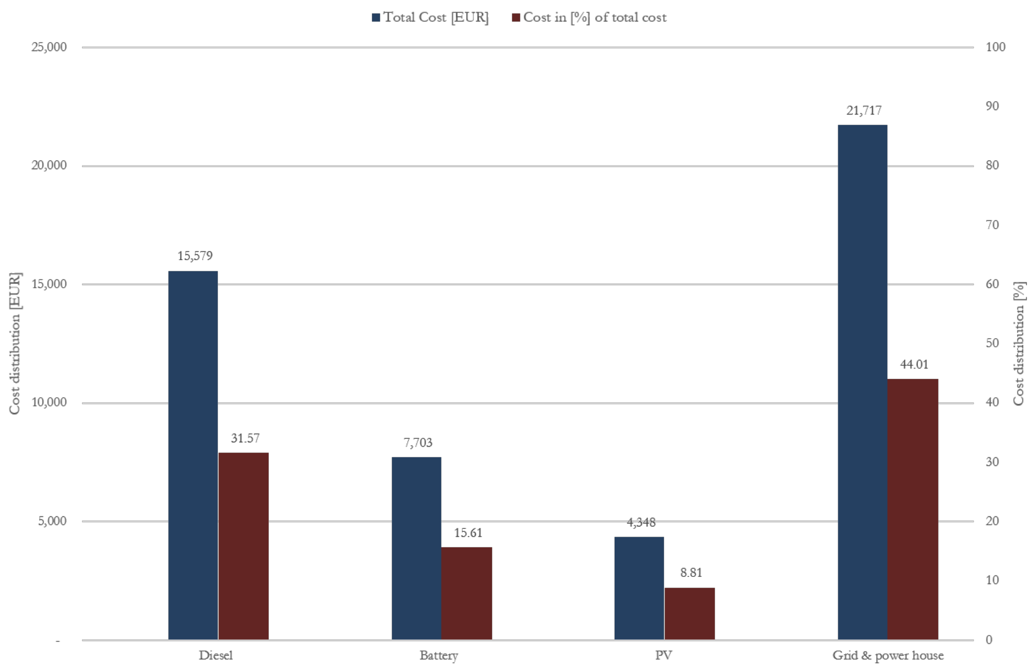

Figure 4.19: *Cost summary and distribution for Hon Son Cha's island energy system, Climate_high scenario*

diesel generation, leading to lower RE shares of the climate scenarios as well as to higher cost proportions of diesel to the overall investment costs.

For this island showing a low daily energy demand of 11 kWh, it is also interesting to further investigate the best mini-grid setup considering the different user types. The island hosts a temple and a camping ground. These users could have the flexibility to allow for capacity shortages making PV/battery systems more viable. PV/battery systems are generally not suitable for configurations where no shortages are allowed, as the system must supply electricity at all times, resulting in very high storage capacities with high initial investment cost. For example, the case of Hon Son Cha, the COE of the BAU system (not allowing electricity shortages) is 1.09 EUR/kWh (compared to 0.749 EUR/kWh for the PV/battery/diesel system) and has a storage capacity of 25 kWh of Lithium batteries (compared to 11 kWh for the PV/battery/diesel system). However, if shortages are allowed, PV/battery systems become more profitable, especially when demand is low. Table 4.12 summarises the modelling results for different allowable annual capacity shortages (1 %, 5 %, and 10 %). In HOMER, this maximum annual capacity shortage [%] is the total capacity shortage divided by the total electric load. Compared to the configuration without allowing for shortages (0 % column), the PV/battery system setup shows the same COE as the PV/battery/diesel system at 10 % of annual shortage allowance.

Table 4.12: *Energy system modelling results for different allowed annual capacity shortages - Hon Son Cha, BAU scenario*

PV/battery system	**Allowed capacity shortage per total electric load**			
	0 [%/a]	1 [%/a]	5 [%/a]	10 [%/a]
PV capacity [kW]	9.7	9.2	7.7	5.2
Battery capacity [kWh]	25	17	11	11
COE [EUR]	**1.09**	**0.935**	**0.798**	**0.748**

Considering Hon Son Cha's low electricity demand and very low population density, as displayed in Table 2.3, the island might be best electrified via the installation of one small stand-alone system (PV panel and battery storage) per building instead of the modelled mini-grid. The high electricity price on the island is also an indicator that the optimised mini-grid might not be the best option to electrify the island. Taking the comparably high infrastructure cost of implementing a mini-grid and the low demand on the island into account, the electricity price can be reduced by installing two small stand-alone systems. From a resilience perspective, small stand-alone systems require fewer additional measures to withstand shocks and stresses, as discussed in Section 2.3.2, and therefore lend themselves to a resilient energy system planning approach.

Modelling Results: Case Study Island 2 (Magyi Kyun, MY)

The second case study island has with approximately 200 the highest number of buildings. The estimation of electricity demand on Magyi Kyun is based on a published load profile of an island in the study region. The load profile of Bulon Don (third case study island) is known due to a study conducted on the island and helps to determine the load profile of Magyi Kyun [121]. To relate the demand of both islands to the number of people living on the island, the hourly load profile of Bulon Don is doubled (twice as many houses on Magyi Kyun island) and shown in Figure 4.20. Magyi Kyun has a significant projected amount of daily electricity sales (358 kWh per day for BAU and 404 kWh per day for climate demand) compared to Hon Son Cha island.

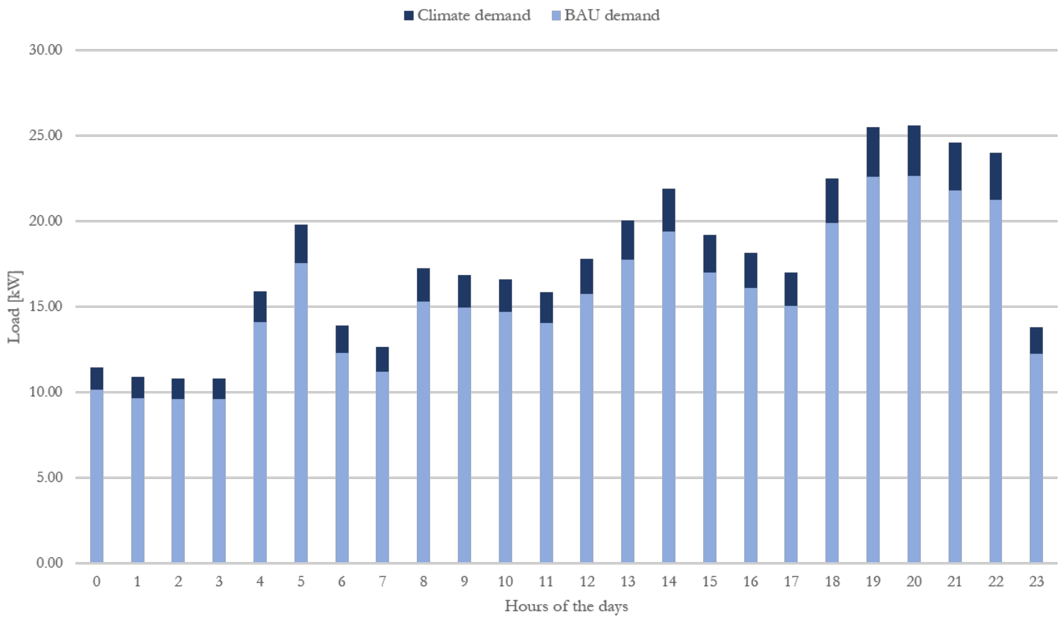

Figure 4.20: *Daily load profile for Magyi Kyun; "BAU" demand on the left, "Climate" demand on the right*

A measurement taken with QGIS reveals a potential grid length of 2.31 km to connect all buildings of the island along the roads. There is no detectable hydro power potential on the island. Thus, hydro power is not considered for energy system modelling on the island. The optimal system layout for Magyi Kyun includes PV, battery storage, and diesel generation. Wind generation reveals low potential and is not considered in the following for economic reasons.

The additional investment costs to protect energy infrastructure against climate change impacts on Magyi Kyun island are summarized in Table 4.13. Higher investments to protect infrastructure against all three risks (flood, cyclones, and sea-level rise) apply to the *Climate_all* scenario, while the *Climate_high* scenario only considers higher investment prices to protect against flood hazards. Table 4.14 (following page) relates these cost increases to total financial input parameters for modelling the energy system on Magyi Kyun island.

Table 4.13: *Cost increases for system components according to developed scenarios - Magyi Kyun*

Component	**Cost increase flood risk** [%]	**Cost increase cyclone risk** [%]	**Cost increase sea-level rise** [%]
PV	11.00	9.67	9.23
Battery	5.71	5.36	2.27
Diesel	4.09	8.85	4.00
Power house	8.67	12.00	7.5
Inverter	3.08	7.69	6.00
Grid	11.25	21.67	6.00
	To be considered for the following scenarios:		
	Climate_high *Climate_all*	*Climate_all*	*Climate_all*

Results of the energy system optimisation and simulation are listed in Table 4.15 (following page). Due to the higher demand caused by the impacts of climate change and constant system setup (simulation instead of optimisation), there is a significant increase in diesel fuel consumption (4,412 l/a) and decrease in RE share (5.6 %) comparing the *BAU* and *BAU_clim* scenario. To meet the increased demand, an upgrade of 6 kW diesel capacity is needed. Looking at both climate scenarios, they differ in PV (7 kW less for *Climate_all*) and battery (9 kWh less for *Climate_all* scenario) capacity. This results in an increased fuel consumption and a decreased RE share. The *Climate_all* scenario obtains increased battery investment costs for three risks (flood, cyclone, and sea-level rise) resulting in a cost increase of around 13 % compared to around 6 % for the *Climate_high* scenario. Therefore, the battery size for the *Climate_all* scenario decreased significantly. Diesel and PV contribute to the

Table 4.14: *Financial input summary for energy system modelling - Magyi Kyun*

Component	Unit	BAU	Climate_high	Climate_all
CAPEX PV	EUR/kW	1,144.0	1,269.8	1,486.1
CAPEX inverters	EUR/kW	253.4	261.2	259.9
CAPEX PV & inv.	EUR/kW	1,397.4	1,531.0	1,782.0
OPEX PV	EUR/kW/a	17.6	17.6	17.6
CAPEX battery	EUR/kWh	380.2	401.9	430.9
CAPEX inverters	EUR/kWh	253.4	261.2	295.9
CAPEX battery & inv.	EUR/kWh	633.6	663.1	726.8
OPEX battery	EUR/kWh/a	10.8	10.8	10.8
CAPEX diesel	EUR/kW	220.0	229.0	257.3
OPEX diesel	EUR/kW	0.097	0.097	0.097
CAPEX grid	EUR	29,799.0	33,151.4	41,396.8
OPEX grid	EUR/a	88.0	88.0	88.0
CAPEX power house	EUR	8,800.0	9,563.0	11,279.0
CAPEX grid & power house	EUR	38,599.0	42714.3	52,675.7

Table 4.15: *Energy system modelling results (HOMER) for case study island 2: Magyi Kyun, Myanmar*

Parameter	Unit	BAU	BAU_clim	Climate_high	Climate_all
PV size	kW	116	116	129	122
Battery size	kWh	303	303	352	343
Generator size	kW	43	49	49	49
COE	EUR/kWh	0.427	0.435	0.444	0.483
RE share	%	84.9	79.3	85.0	83.6
Fuel consumption	l/a	7,963	12,375	8,936	9,818

overall investment similarly (see Figure 4.21, following page), but PV shows a cost increase of 19 % and diesel of 13 % comparing both climate scenarios. Therefore, the PV capacity of the *Climate_all* scenario is also reduced compared to the *Climate_high* scenario.

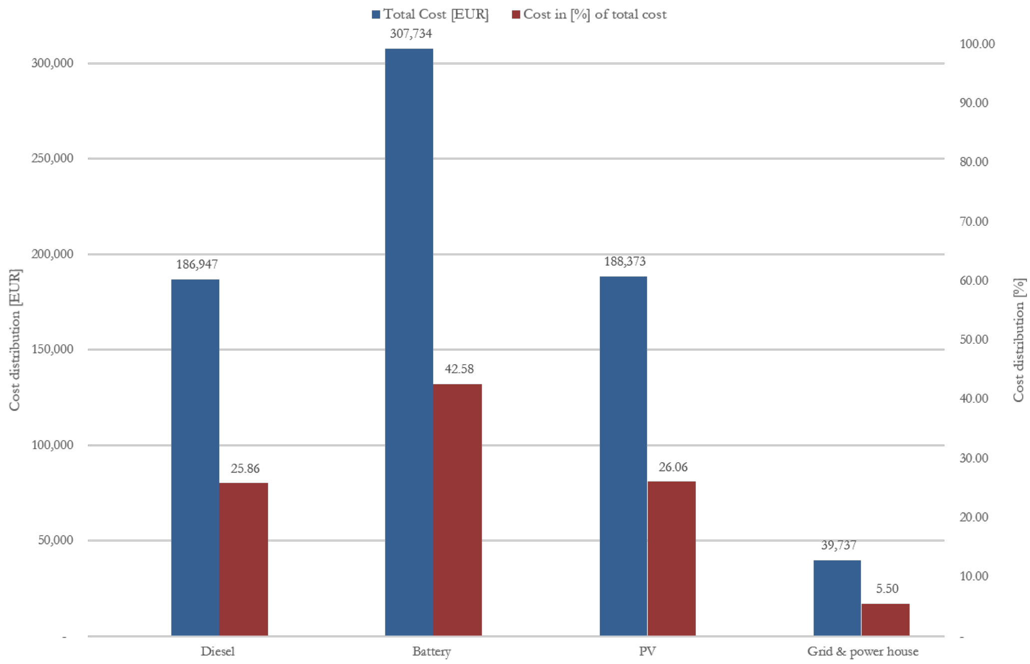

Figure 4.21: *Cost summary and distribution for Magyi Kyun's island energy system, BAU scenario*

Figure 4.21 gives an overview of the cost proportions of different system components for the *BAU* scenario on Magyi Kyun island. The summary includes capital, replacement, operation, fuel, and salvage costs. Cost distributions for other scenarios (*BAU_clim*, *Climate_high*, and *Climate_all*) are similar for this island and are therefore not shown separately. In contrast to Hon Son Cha island, the cost proportion of general infrastructure (grid and power house) in relation to the overall investment is the smallest. Batteries account for the highest (43 %) investment costs followed by PV and diesel generation with respectively 26 %.

The cost per kilowatt-hour on the second case study island is almost half the price as for the first case study island ranging from 0.4 EUR/kWh to 0.5 EUR/kWh. Economies of scale (proportion of investment costs to projected electricity sales) result in lower electricity prices on Magyi Kyun than on Hon Son Cha. Infrastructure expenses distribute to a higher quantity of kilowatt-hours sold on the island. Significantly higher diesel fuel consumption (increase of 4,412 l/a) to meet the increased climate demand on Magyi Kyun island lead to a higher COE for the *BAU_clim* scenario when compared to the *BAU* scenario. The relatively small difference of COEs of the BAU and climate scenarios (when compared to those of Hon Son Cha island) can also be explained by the beneficial proportion of investment and high electricity sales.

The high demand, dense population along the road and low electricity prices make a PV-battery-diesel mini-grid a suitable option to electrify Magyi Kyun island (see Table 2.3). The comparatively small difference in COEs for BAU and climate resilient energy system planning suggests that resilient energy system planning is feasible on Magyi Kyun island if climate change related hazards are likely to occur, as indicated by the island's risk profile.

Modelling Results: Case Study Island 3 (Bulon Don, TH)

The estimated load profile to supply the 80 households and three public buildings on the island with electricity is obtained by an energy system analysis conducted in 2017 and shown in Figure 4.22 [121]. To model the energy system for Bulon Don island, solar and wind power generation alongside battery storage and diesel generators are considered. The island revealed no hydro power potential. Optimisation of the energy system for Bulon Don suggests a PV/battery/diesel setup to be the most promising option. Thus, wind power generation is not further considered. The aforementioned analysis estimated the necessary grid length to 600 m [121].

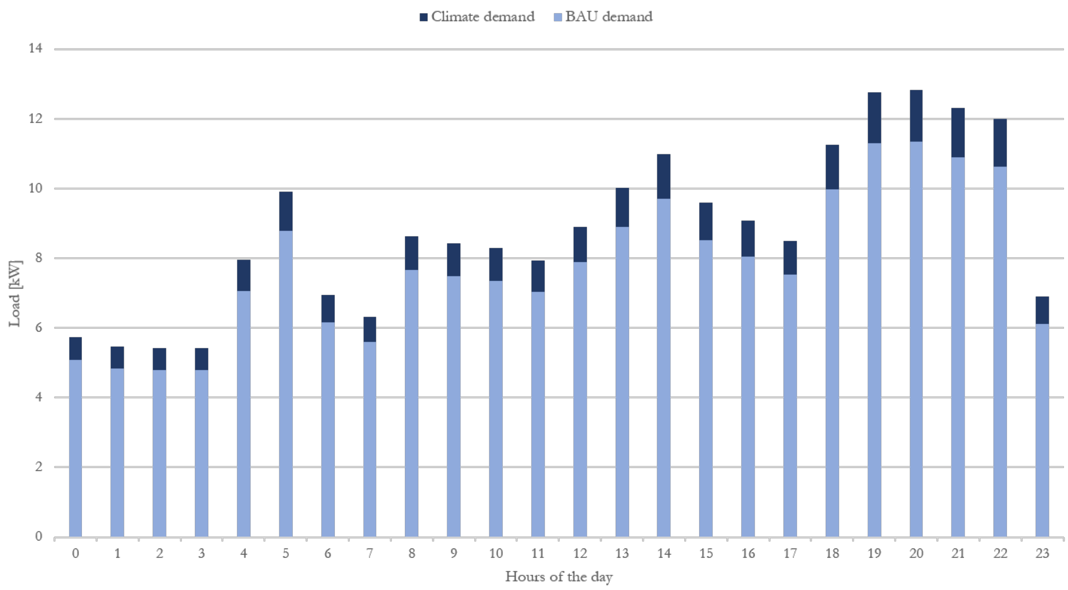

Figure 4.22: *Daily load profile for Bulon Don island; "BAU" demand on the left, "Climate" demand on the right*

Adjusted component prices for flood risk are entered to consider the *Climate_high* scenario. For the *Climate_all* scenario increased investment costs for flood and cyclone risk is applied to all components.

The exact values are listed in Table 4.16 and the resulting financial input parameters can be found in Table 4.17 (following page).

Table 4.16: *Cost increases for system components according to developed scenarios - Bulon Don*

Component	**Cost increase flood risk** [%]	**Cost increase cyclone risk** [%]
PV	11.00	9.67
Battery	5.71	5.36
Diesel	4.09	8.85
Power house	8.67	12.00
Inverter	3.08	7.69
Grid	11.25	21.67
	To be considered for the following scenarios:	
	Climate_high	*Climate_all*
	Climate_all	

Table 4.18 (following page) gives an overview of the modelling results for each scenario. Similar to Magyi Kyun island, the cost of electricity is the lowest for the *BAU* scenario (0.40 EUR/kWh) and highest for the *Climate_all* scenario (0.44 EUR/kWh). Bulon Don island has the lowest COE of all islands (0.3-0.4 EUR/kWh lower than Hon Son Cha and 0.02-0.04 EUR/kWh lower than Magyi Kyun island). The lower COE compared to Hon Son Cha lays in the higher projected sales of 179.2 kWh per day for the *BAU* scenario and 202.2 kWh per day for the *BAU_clim* scenario distributed to Bulon Don's system investment costs (beneficial NPV to annual demand). A look at the detailed cost summary of HOMER for Magyi Kyun and Bulon Don islands reveals that proportional operation and maintenance as well as fuel costs are higher for Magyi Kyun island resulting in higher COEs for the island. While capital, replacement, and salvage costs are double for Magyi Kyun compared to Bulon Don (reflecting the twofold demand of Bulon Don compared to Magyi Kyun), operation and maintenance costs are 2.3 times as high and fuel cost 3 times as high as on Bulon Don island (values derived from *BAU* scenario).

There is a significant increase in diesel fuel consumption and decrease in RE share when looking at the *BAU* scenario compared to the *BAU_clim* scenario caused by higher demand with no changes in the overall system setup (simulation). To meet the increased demand, it needs an upgrade of 3 kW diesel capacity. Looking at

Table 4.17: Financial input summary for energy system modelling - Bulon Don

Component	Unit	BAU	Climate_high	Climate_all
CAPEX PV	EUR/kW	1,144.0	1,269.8	1,380.5
CAPEX inverters	EUR/kW	253.4	261.2	280.7
CAPEX PV & inv.	EUR/kW	1,397.4	1,531.0	1,661.2
OPEX PV	EUR/kW/a	17.6	17.6	17.6
CAPEX battery	EUR/kWh	380.2	401.9	422.3
CAPEX inverters	EUR/kWh	253.4	261.2	280.7
CAPEX battery & inv.	EUR/kWh	633.6	663.1	703.0
OPEX battery	EUR/kWh/a	10.8	10.8	10.8
CAPEX diesel	EUR/kW	220.0	229.0	248.5
OPEX diesel	EUR/kW	0.097	0.097	0.097
CAPEX grid	EUR	7,752.0	8,624.1	10,619.0
OPEX grid	EUR/a	88.0	88.0	88.0
CAPEX power house	EUR	8,800.0	9,560.3	10,619.0
CAPEX grid & power house	EUR	16,552.0	18,187.1	20,922.9

Table 4.18: Energy system modelling results (HOMER) for case study island 3: Bulon Don, Thailand

Parameter	Unit	BAU	BAU_clim	Climate_high	Climate_all
PV size	kW	58.1	58.1	65.6	63.6
Battery size	kWh	156	156	179	170
Generator size	kW	22	25	25	25
COE	EUR/kWh	0.403	0.412	0.420	0.443
RE share	%	89.3	83.7	89.6	88.1
Fuel consumption	l/a	2,852	4,940	3,154	3,618

both climate scenarios, they differ in PV (2 kW less for the *Climate_all* scenario) and battery (9 kWh less for the *Climate_all* scenario) capacity. This is explained by the overall cost structure of the system in combination with cost increases between the two climate scenarios: batteries account for the highest investment (47 %) of total system costs and PV for the second highest proportion of investment (28 %) as shown in Figure 4.23 (cost distribution of all scenarios are similar and are therefore not shown for all scenarios). The *Climate_all* scenario obtains increased battery investment costs for two risks (flood and cyclone) resulting in a cost increase of around 11 % compared to around 6 % for the *Climate_high* scenario. The same applies to PV generation, here the cost increase of the *Climate_all* scenario is 21 % compared to the *Climate_high* scenario with 11 % cost increase.

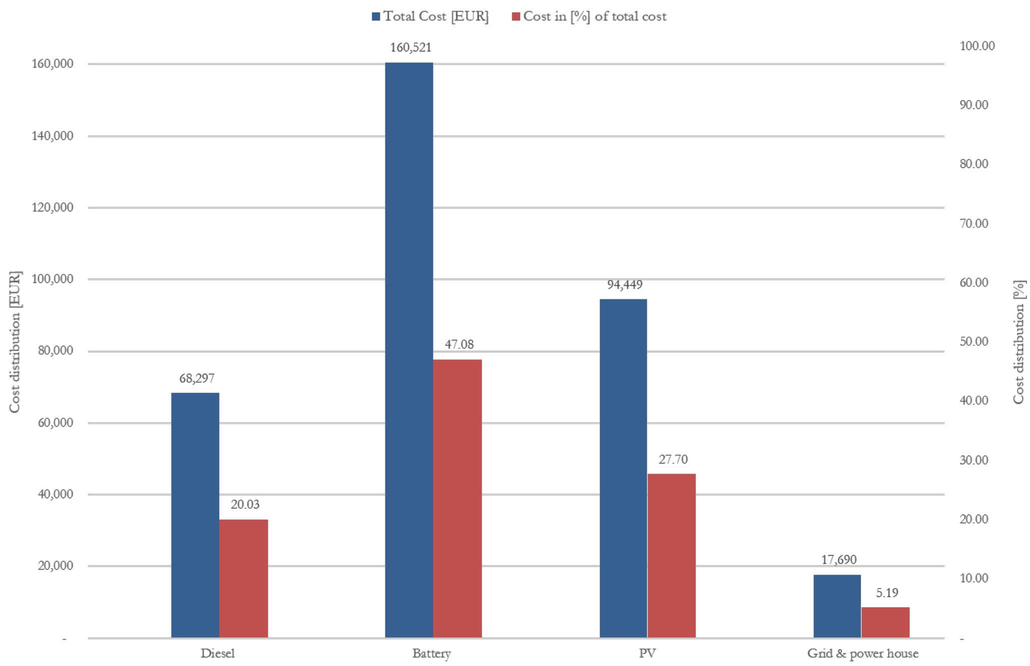

Figure 4.23: *Cost summary and distribution for Bulon Don's island energy system, BAU scenario*

The settlement on Bulon Don is located on the rare plane parts of the island close to the beach. High population density, high energy demand, and a large distance to the mainland and hence the nearest grid connection point make electricity supply via mini-grid the most suitable option (see Table 2.3). Low calculated COE on the island for mini-grid electrification underline these findings. Moreover, the approach of climate resilient energy system planning on the island is recommended when climate change related hazards are likely as the COEs of BAU and resilient energy system planning have comparatively small differences.

4.3.4 Evaluation of Results

The following evaluation aims to determine under which conditions it is viable to include resilience consideration into energy system planning from the very beginning. Assuming that climate change induced damages occur, resilient energy system planning is viable on the long run as soon as the evaluation scenarios show higher COEs than the climate scenarios. A cash flow model serves as basis to calculate COEs of different evaluation scenarios as outlined in Section 3.3.3. In each calculation, damage frequencies (every 5, 10, or 15 years) and severity (25 %, 50 %, 75 %, or 100 % repair cost of the original investment cost needed due to damage) are adjusted according to the above mentioned 12 evaluation scenarios (see Table 3.7). To conclude the evaluation, 72 calculations are realised - 24 for each case study island (12 simulations for the *BAU* scenario and 12 for the *BAU_clim* scenario).

Comparison: Case Study Island 1 (Hon Son Cha, VN)

Figure 4.24 on the following page visualises COEs of all evaluation scenarios for the BAU system setup for the first case study island. Figure 4.25 (following page) shows the same overview for the BAU system setup considering climate demand. The frequency of damage (every 5, 10, or 15 years) is shown on the horizontal axis, the COEs on the vertical axis. Values for different severity of damages (25 %, 50 %, 75 %, or 100 %) can be found as light (25 %) to dark (100 %) brown (BAU demand) and ocher (climate demand) dots. The COEs of the climate scenarios are shown for comparison reasons (*Climate_all* scenario as green line and *Climate_high* scenario as red line). The energy systems of both climate scenarios are assumed to withstand occurring climate change shocks and stresses and remain without damage explaining their steady line.

The figures reveal two interesting facts: (i) the higher the damage frequency (e.g. every 5 years) and severity of damages, the more viable is climate change resilient energy system planning due to lower COEs and (ii) the lower the frequency (e.g. every 15 years) the less important is the severity of damage, as COEs show smaller differences. For Hon Son Cha island, resilient energy system planning is viable for most cases. Only in one case considering the BAU demand ($E_{15,25}$) and three cases considering the climate demand ($E_{15,25}$, $E_{15,50}$, and $E_{10,25}$), the evaluation scenarios show lower COEs than the resilient energy system planning cases (*Climate_high, Climate_all*). In these cases, climate resilient energy system planning has economically no benefits compared to the BAU system planning. All other cases are more feasible if climate change considerations are integrated from the very beginning. For example in most extreme cases of damages happening every 5 years in the *BAU* scenario, COE is 0.17 EUR/kWh ($E_{5,25}$), 0.45 EUR/kWh ($E_{5,50}$), 0.73 EUR/kWh ($E_{5,75}$), and 1.02 EUR/kWh ($E_{5,100}$) higher than for the *Climate_all* scenario.

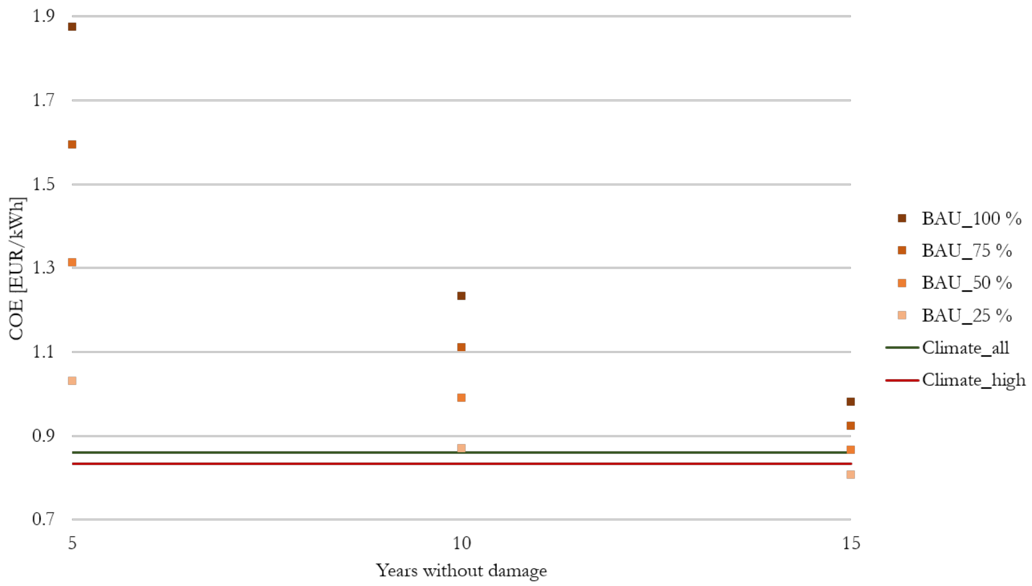

Figure 4.24: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup, Hon Son Cha island*

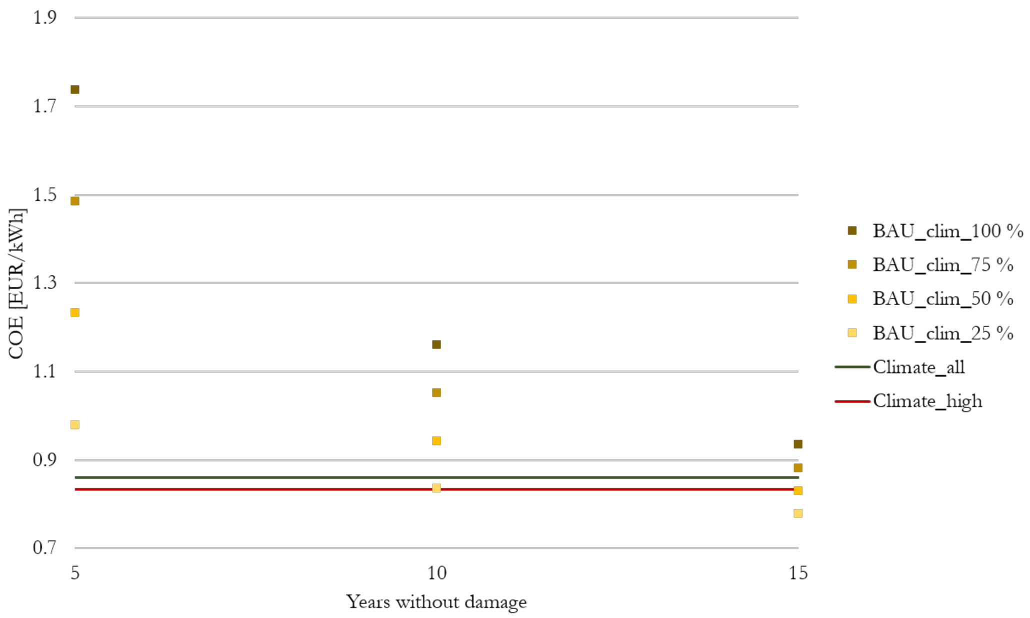

Figure 4.25: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup and climate demand, Hon Son Cha island*

Over project lifetime, $E_{5,x}$ scenarios require four repair actions, $E_{10,x}$ scenarios two, and $E_{15,x}$ scenarios one. The distances between COE dots for different severity of damages for the same damage frequency is approximately 0.06 EUR/kWh ($E_{15,x}$), 0.12 EUR/kWh ($E_{10,x}$) and 0.28 EUR/kWh $E_{5,x}$ revealing a slightly exponential correlation to the number of repair actions over project lifetime.

Table 4.19 summarises the COEs for all evaluation scenarios and shows the COEs for all four baseline scenarios (*BAU, BAU_clim, Climate_high, Climate_all*) for comparison reasons.

Table 4.19: *Overview of 12 evaluation scenario results for BAU and Climate demand and comparison to 4 baseline scenarios - Hon Son Cha island*

Evaluation scenario COEs		
	BAU demand [EUR/kWh]	Clim. demand [EUR/kWh]
$E_{5,25}$	1.030	0.979
$E_{5,50}$	1.312	1.232
$E_{5,75}$	1.593	1.485
$E_{5,100}$	1.875	1.738
$E_{10,25}$	0.869	0.835
$E_{10,50}$	0.990	0.943
$E_{10,75}$	1.111	1.052
$E_{10,100}$	1.232	1.160
$E_{15,25}$	0.807	0.778
$E_{15,50}$	0.865	0.830
$E_{15,75}$	0.923	0.882
$E_{15,100}$	0.981	0.935
Baseline scenario COEs		
BAU	0.749	EUR/kWh
BAU_clim	0.729	EUR/kWh
Climate_high	0.833	EUR/kWh
Climate _all	0.861	EUR/kWh

The evaluation leads to the conclusion that most disruptions of the energy system based on the BAU approach will have a very strong economic impact on Hon Son Cha island leading to high electricity costs on the long run. Resilient energy system planning is in the majority of cases beneficial. Looking back to the risk profile of the island (see Table 4.6), the occurrence of cyclones as well as frequent flood incidents over projected duration are likely, making resilient energy supply even more important. However, the electricity price level on the island - if electrified via a mini-grid - is disproportionate and stand-alone systems are recommended to decrease the electricity price as mentioned earlier. These systems have a high resilience if carefully installed and maintained.

Comparison: Case Study Island 2 (Magyi Kyun, MY)

Figure 4.26 visualises the evaluation results for the BAU system setup and Figure 4.27 (following page) for the BAU system setup considering climate demand for Magyi Kyun. The general observations that (i) higher damage frequencies and higher damage severity favor resilient energy system planning and (ii) damage severity is less important at lower damage frequencies are confirmed.

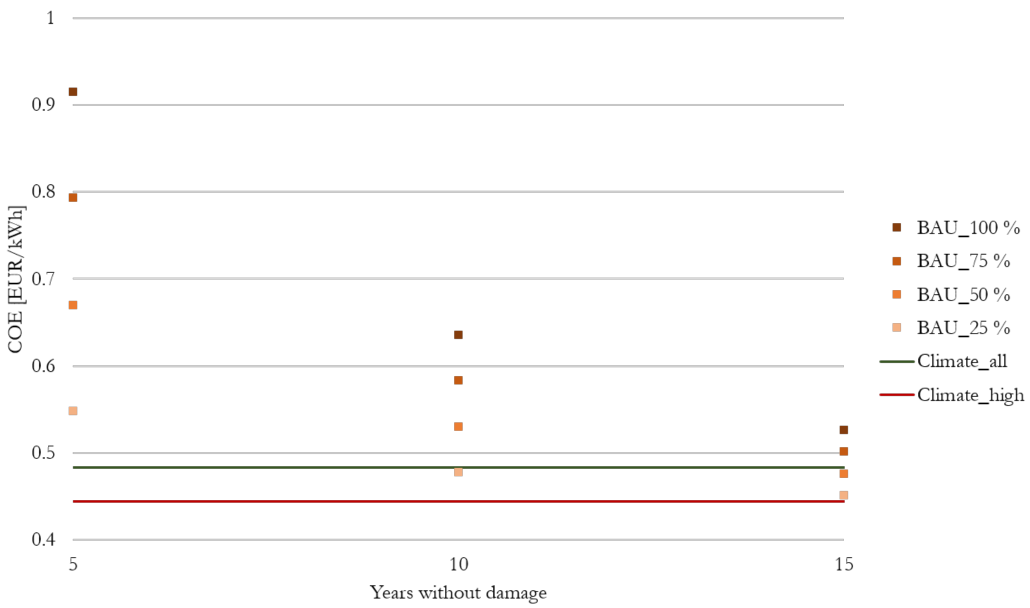

Figure 4.26: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup, Magyi Kyun island*

Similar to Hon Son Cha island, in most cases climate change resilient energy system planning is more viable than BAU planning if climate change induced damages are expected to occur on the island. Compared to the evaluation scenario COEs, the COE of the *Climate_high* scenario is the lowest. Only three evaluation scenarios ($E_{10,25}$, $E_{15,25}$, and $E_{15,50}$) have lower COEs than the *Climate_all* scenario. In case of a critical climate change induced incident happening every 10 years or more frequently,

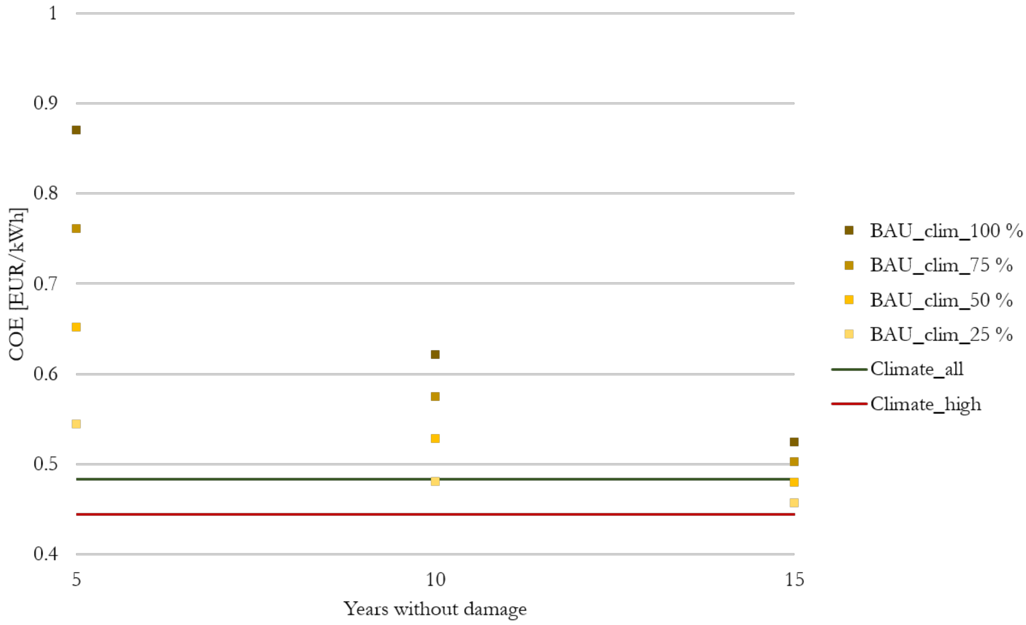

Figure 4.27: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup and climate demand, Magyi Kyun island*

climate resilient energy planning is economically more viable. If damage is happening less frequent it depends on the projected degree of damage: the higher the degree of damage, the more feasible it is to integrate climate change considerations into energy system planning. For 25 % damage, COEs of BAU system planning are lower, with damages of 100 % or 75 %, the climate scenarios show lower COEs. If half of the equipment or more needs repair and replacement, climate resilient planning is more viable in case of incidents happening every 10 years. If these events are happening every 15 years, this is the case if 75 % of the energy system needs repair and replacement.

Table 4.20 (following page) summarises the COEs for all evaluation scenarios and shows the four baseline scenarios for comparison. The evaluation for Magyi Kyun island reveals a strong tendency towards resilient energy system planning, if climate change induced incidents are likely to occur. The risk profile of the island (see Table 4.7) shows a severe flood risk, major temperature rise risk, minor cyclone, and insignificant sea-level rise risk. Climate resilient energy system planning is therefore recommended to be applied on Magyi Kyun island. Due to the high temperature rise, climate demand should be considered in energy system planning on the island. Flooding as well as cyclones might affect all selected components (solar, power house, inverter, grid, diesel generator). Therefore, it will be beneficial to account for suitable

Table 4.20: *Overview of 12 evaluation scenario results for BAU and Climate demand and comparison to 4 baseline scenarios - Magyi Kyun island*

Evaluation scenario COEs		
	BAU demand [EUR/kWh]	Clim. demand [EUR/kWh]
$E_{5,25}$	0.548	0.544
$E_{5,50}$	0.670	0.652
$E_{5,75}$	0.793	0.761
$E_{5,100}$	0.915	0.870
$E_{10,25}$	0.478	0.481
$E_{10,50}$	0.530	0.528
$E_{10,75}$	0.583	0.575
$E_{10,100}$	0.635	0.621
$E_{15,25}$	0.415	0.457
$E_{15,50}$	0.476	0.480
$E_{15,75}$	0.501	0.502
$E_{15,100}$	0.526	0.524
Baseline scenario COEs		
BAU	0.427	EUR/kWh
BAU_clim	0.435	EUR/kWh
Climate_high	0.444	EUR/kWh
Climate _all	0.483	EUR/kWh

adaptation measures from the very beginning. According to Table 4.4 especially for solar and grid infrastructure the difference in initial investment for BAU and resilient energy system planning will be significant (e.g. additional 11 % to protect against flooding incidents) and important to consider.

In contrast to Hon Son Cha island, where the COE of the *BAU_clim* scenario is lower than the *BAU* scenario for both - the originally modelled scenarios and the evaluation scenarios - the pattern is different for Magyi Kyun island. The *BAU* scenario has a lower COE than the *BAU_clim* scenario on Magyi Kyun island. Looking at the evaluation scenario COEs, (Table 4.20), most prices are lower for the BAU system setup considering climate demand (*BAU_clim*). This is the case for all evaluation scenarios considering damages every 5 years. In case of damages every 10 years, this applies to scenarios with higher degrees of damages (50 %, 75 %, and 100 %). For evaluation scenarios considering damages every 15 years, this only applies to one scenario ($E_{15,100}$). This pattern drives the conclusion that the higher the re-investment costs caused by damages, either through more frequent damages or through a higher degree of damage, the more beneficial is a higher demand (climate demand). This connects again to the fact that higher electricity sales in case of higher overall investment lead to lower COEs (see Function 3.18).

Comparison: Case Study Island 3 (Bulon Don, TH)

For Bulon Don, Figure 4.28 visualises the evaluation results for the BAU system setup and Figure 4.29 (following page) for the BAU system setup considering climate demand. Both figures can be found on the following page. Results of all evaluation scenarios and COEs of the four baseline scenarios are summarised in Table 4.21 (next but one page).

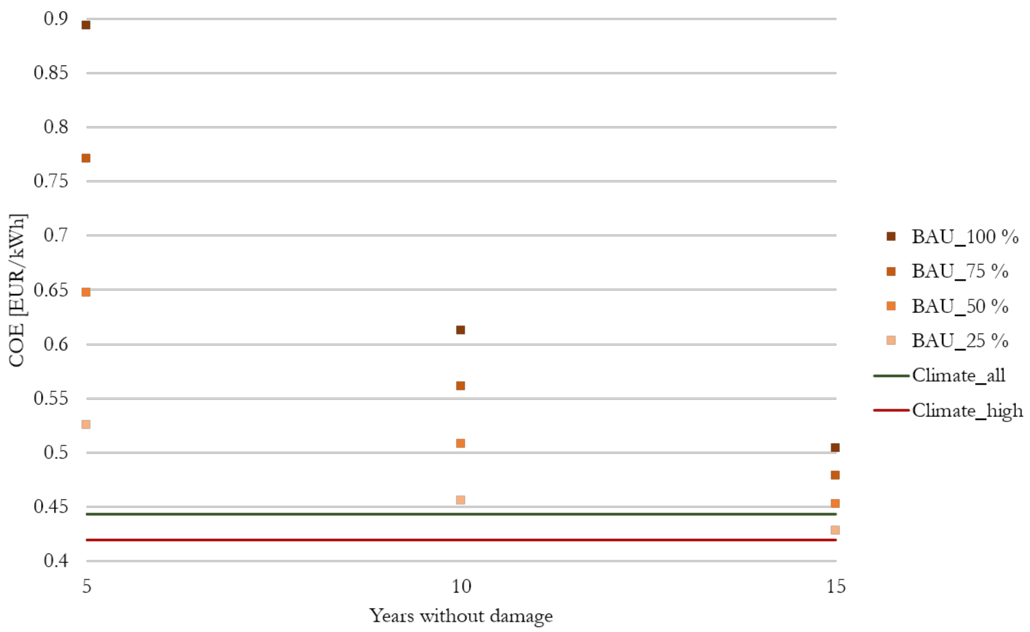

Figure 4.28: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup, Bulon Don island*

On the third case study island with the lowest COEs for the four baseline scenarios compared to the other two islands, resilient energy system planning is more viable than almost all calculated evaluation cases. Only if damages are occurring every 15 years with 25 % repair needs, the evaluation scenario $E_{15,25}$ has lower COEs than the

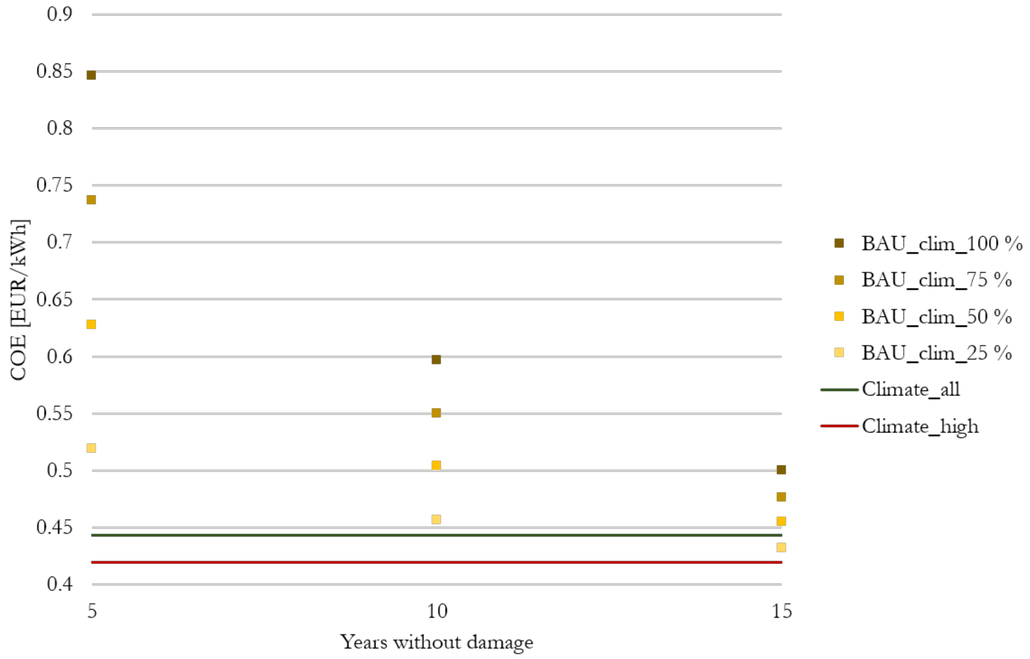

Figure 4.29: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup and climate demand, Bulon Don island*

Climate_all scenario. In all other cases it is reasonable to follow a climate resilient energy system planning approach on Bulon Don island if climate change induced incidents are expected to occur. Bulon Don has a moderate flood and temperature rise risk and a minor cyclone risk (see Table 4.8). Even though no severe or major risk occur, climate change resilient energy system planning for the island is recommended. It is still likely that flood incidents occur and demand is rising on the island due to temperature increase. Apart from this, the number of cyclones expected to arrive on the island over the next 50 years is 17, even though the risk is scaled to be minor (compared to other islands). This sums up to approximately 8 cyclones within a project duration of 25 years. Flooding and cyclones have the strongest impact on necessary infrastructure on the island such as solar generation and grid assets (see Table 4.4). To account for these beforehand will make energy system projects on the island more sustainable.

The pattern of lower evaluation scenario COEs if considering the climate demand on Bulon Don is similar to Magyi Kyun island.

Table 4.21: Overview of 12 evaluation scenario results for BAU and climate demand and comparison to 4 baseline scenarios - Bulon Don island

Evaluation scenario COEs		
	BAU demand [EUR/kWh]	Clim. demand [EUR/kWh]
$E_{5,25}$	0.526	0.519
$E_{5,50}$	0.648	0.628
$E_{5,75}$	0.771	0.737
$E_{5,100}$	0.894	0.846
$E_{10,25}$	0.456	0.457
$E_{10,50}$	0.508	0.504
$E_{10,75}$	0.561	0.550
$E_{10,100}$	0.613	0.597
$E_{15,25}$	0.428	0.432
$E_{15,50}$	0.453	0.455
$E_{15,75}$	0.479	0.477
$E_{15,100}$	0.504	0.500
Baseline scenario COEs		
BAU	0.403	EUR/kWh
BAU_clim	0.412	EUR/kWh
Climate_high	0.420	EUR/kWh
Climate _all	0.443	EUR/kWh

Sensitivity for Diesel Price

In order to understand the influences of different diesel prices, the evaluation scenarios are calculated for reduced diesel costs of 0.769 EUR/l (instead of 0.942 EUR/l). Results of the analysis are similar for all islands. Therefore, figures are only shown for the first case study island. Figure 4.30 (following page) shows the evaluation scenario COEs for the BAU system setup and Figure 4.31 (following page) visualises the results for the BAU system setup considering climate demand. The COE range on the y-axis is chosen to be the same as for the evaluation scenarios of Hon Son Cha with a diesel fuel price of 0.942 EUR/l.

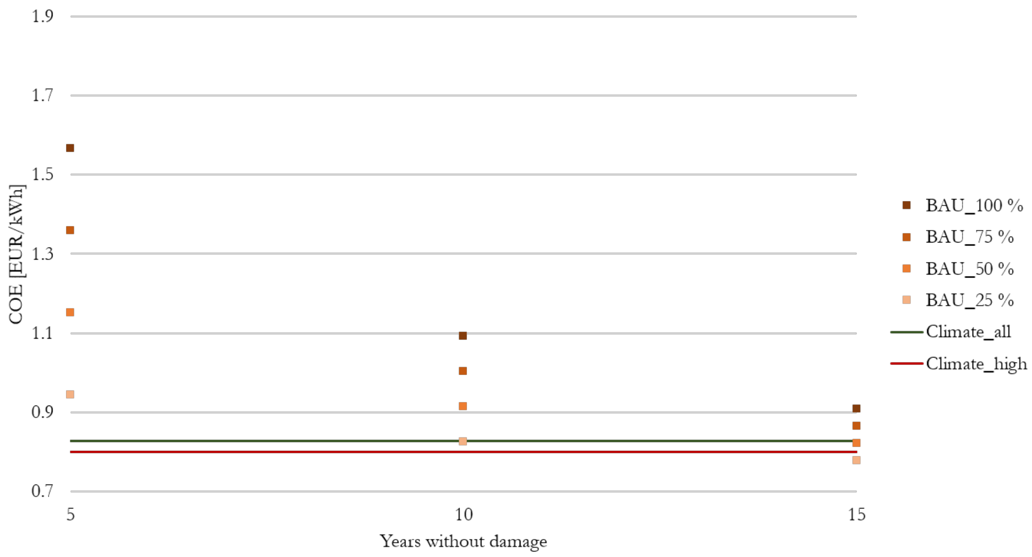

Figure 4.30: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup and reduced diesel fuel cost, Hon Son Cha island*

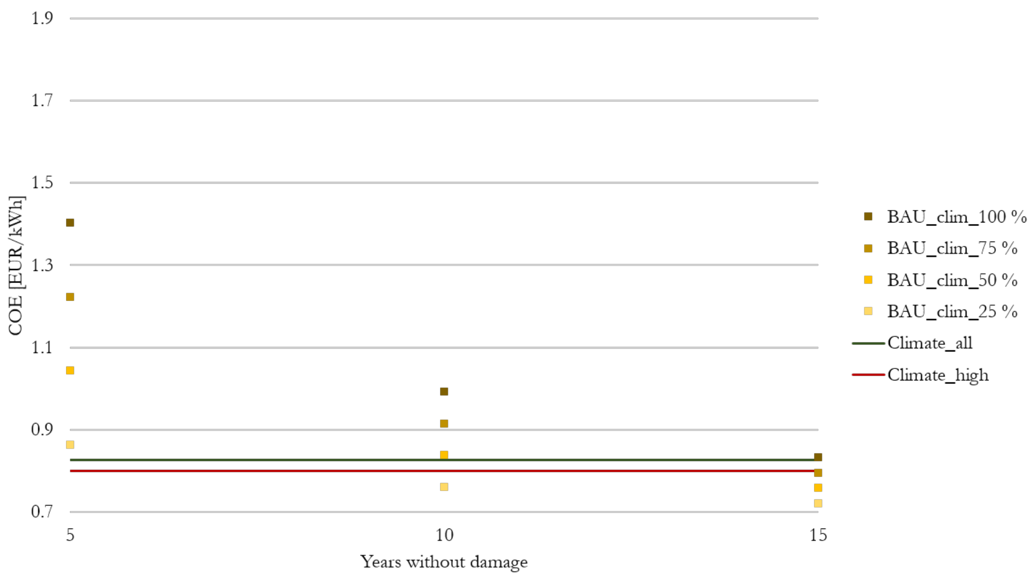

Figure 4.31: *COEs for different evaluation scenarios (5, 10, and 15 years without damage as well as 25 %, 50 %, 75 %, and 100 % damage of each component) for the BAU system setup, climate demand and reduced diesel fuel cost, Hon Son Cha island*

Table 4.22 (following page) summarises the evaluation scenario COEs for both diesel prices. Obviously, all COEs are lower for the reduced diesel price. While comparing the COEs for one frequency of damages (e.g. 5-years), it becomes apparent that the COEs are closer to each other (show less difference) in case of a reduced diesel price.

The likeliness that BAU system planning is more economic than climate resilient energy planning is increasing with reduced diesel prices: e.g. evaluation of the BAU system setup considering climate demand with a diesel fuel price of 0.769 EUR/l shows four cases of lower COEs than one of the climate scenarios out of which three show lower COEs for the *Climate_high* scenario compared to three and one for a diesel price of 0.942 EUR/l. Thus, diesel prices have an important influence on the feasibility of resilient energy system planning. Higher diesel prices cause a trend in favor of resilient energy system planning.

Table 4.22: *Overview of 12 evaluation scenario results for BAU and Climate demand for two different diesel prices - Hon Son Cha island*

Evaluation scenario	**Diesel price 0.942 EUR/l** BAU demand [EUR/kWh]	Clim. demand [EUR/kWh]	**Diesel price 0.769 EUR/l** BAU demand [EUR/kWh]	Clim. demand [EUR/kWh]
$E_{5,25}$	1.030	0.979	0.944	0.863
$E_{5,50}$	1.312	1.232	1.152	1.043
$E_{5,75}$	1.593	1.485	1.359	1.222
$E_{5,100}$	1.875	1.738	1.567	1.402
$E_{10,25}$	0.869	0.835	0.826	0.761
$E_{10,50}$	0.990	0.943	0.915	0.838
$E_{10,75}$	1.111	1.052	1.004	0.915
$E_{10,100}$	1.232	1.160	0.908	0.832
$E_{15,25}$	0.807	0.778	0.779	0.721
$E_{15,50}$	0.865	0.830	0.822	0.758
$E_{15,75}$	0.923	0.882	0.865	0.795
$E_{15,100}$	0.981	0.935	0.795	0.832

Cost of Power Outages

Another way to assess the prospects of climate resilient energy system planning is the comparison of additional investment costs for resilient energy systems with projected costs of outages in case of climate change induced system failure of BAU setups. Power outage times caused by climate change induced threats on Southeast Asian islands as stated by interviewees are listed in Table 4.23 (following page, limited to answers given including power outage times). System outage times range from few hours to 5 month with the majority of answers given around 1 week.

Table 4.23: *Overview of damages and outage times as stated by the interviewees, limited to answers given including a system outage time*

Component	**Threat**	**Damage**	**Outage time**	**No. interviewee**
Solar	Storm	Lightning strike	1-2 weeks	7
		Lightning strike	1-5 month	19
		Panels blown away and debris is hitting remaining panels causing cracks	1 week	20
	Temperature	Overheating of charge controller	1 week	11
Hydro	Flood	Damages to civil works	1-2 weeks	20
Wind	Storm	Lightning strike	Several weeks	20
Grid	Storm	Unstable poles and trees falling on grid lines leading to grid break-down	Few hours	15
Power house, inverter & batteries	Flood	damage to power house and equipment (short circuits)	2 weeks	20

Table 4.24 (following page) summarises the total investment costs including capital, operation and maintenance, fuel, and salvage costs for the *BAU_clim* and *Climate_high* scenario and their difference for all islands to be compared to the estimated cost of outages. The *BAU_clim* scenario is listed, because demand increases (caused by e.g. increasing temperatures) are considered to be likely. The *Climate_high* scenario covers higher investment costs for only the most severe climate change risks on the islands, which is more likely to be implemented than the *Climate_all* scenario considering all occurring risk causing high upfront investments. Therefore, the *Climate_high* scenario is selected for comparison.

Table 4.24: *Total expected investment cost (including capital, operation and maintenance, fuel and salvage cost) for two selected scenarios (BAU_clim and Climate_high) and all case study islands*

Island	**Total investment BAU_clim** [EUR]	**Total investment Climate_high** [EUR]	**Difference** [EUR]
Hon Son Cha	43,180	49,347	6,167
Magyi Kyun	830,403	847,909	17,506
Bulon Don	392,839	401,124	8,285

To relate the outage times with estimates on cost of power outages (GDP per capita) and compare these costs to the differences of investment cost for each case study island, the number of people on the islands have to be estimated. As mentioned in Section 4.3.2, Magyi Kyun has an estimated number of 200 households and Bulon Don of 80 households. Hon Son Cha has currently no permanent residents and is therefore not further considered. According to Esri, the average number of people per household is 4.2 in Myanmar and 3.1 in Thailand [122, 123]. This results in 840 people living on Magyi Kyun island and 248 on Bulon Don.

Applying a GDP loss of approximately 24.5 Ph.Pesos (0.017 Euro) per hour per capita caused by power outages as mentioned in Section 3.3.3, this translates to GDP losses of approximately:

- 43 Euro (e.g. 3 hours), 2,399 Euro (1 week) and 52,122 Euro (5 month) on Magyi Kyun island, and
- 13 Euro (e.g. 3 hours), 708 Euro (1 week) and 15,388 Euro (5 month)on Bulon Don island.

Comparing the difference of investment costs between BAU and climate resilient planning to the estimated cost of an outage, it can be seen that resilient energy system planning pays off when outages are frequent or long-lasting: After 1,226 hours (51 days) of power outages on Magyi Kyun, the investment difference is reached, and after 1,965 hours (82 days) for Bulon Don. Because the cost of power outages increases with the number of people living on the island, planning for a resilient energy system is especially recommended for densely populated, remote islands.

Resilient energy system planning reduces the probability of power outages caused by environmental disruptions and thus minimises the losses connected to outages. Disruptions based on environmental impacts are categorised as unexpected disruptions and account for even higher outage costs as usually calculated (e.g. for Thailand a study showed up to four times higher outage costs caused by unexpected outages) [114]. This makes resilient energy system planning even more appealing to planners of energy systems in regions that are at high risk of climate change impacts.

Outages of few hours have no strong economic impact. However, social impacts might be high and have to be further analysed. For example, benefits resulting from reliable electricity access as mentioned in Section 2.3.4 are undermined by electricity system outages. Longer outage duration, which is often the case for remote islands due to poor accessibility, and complicated transport routes and landing options, imply an economic - and most likely social - benefit of resilient energy system planning.

4.4 Discussion of Limitations

The presented research aims to provide a first overview and approach to integrate climate change risk considerations into off-grid energy system modelling. The financial figures provided have a comparative rather than a full feasibility study character. The processing of both core topics shows limitations that are discussed in the following.

4.4.1 Climate Change Risk Assessment

Datasets and processing. First of all, the data coverage for conducting the climate change risk assessment is limited. Therefore, not all Southeast Asian islands are considered. Another challenge arises from the different resolution and geographic allocation of applied datasets. Data points of different datasets might not match and create inaccuracies that are difficult to detect. The applied methodology is a simplified model to create an overview of occurring climate change risks. However, climate change risk assessments are a complex task and the simplified approach used within this research is not able to grasp every aspect of it. For example, it does not reflect the impact of seasonality on e.g. temperature and precipitation developments (indicating flood and drought risk). Drought and flood risk are dependent on many different factors and are difficult to fully assess. Only a limited number of these factors were considered within this research. This might be one reason why there is no drought risk detected for any of the observed islands within this research, even though droughts are expected to play a role in some parts of Southeast Asia (see hazard hotspots in Section 2.2.2).

Clustering. The cluster analysis served to create an overview of risk patterns and determine characteristic islands for further analysis. The above mentioned challenges to process and combine different datasets also affect the cluster analysis. The boxplots (see Figure 4.11) reveal a high number of outlier (especially for sea-level rise) and median and first quartile lines are difficult to distinguish (sea-level rise only). The analysis highlights that an improvement of the accuracy of data - especially for sea-level rise - is necessary.

Scaling. Another weakness is the weighting of the four analysed climate change risks. The scaling is applied by looking at the full (global) range of each dataset and distribute this range in equal parts to the Likert scale. This approach does not consider the difference in consequences for island communities e.g. if the temperature is rising by 1.38 - 1.5 °C, HDI is above 1.5 (severe flood risk), they face land loss of 80 - 100 % or the occurrence of 280 - 350 cyclones. All these values are assigned to the highest risk scale (5). A more detailed impact assessment of each risk to develop a more appropriate weighting of these risks is recommended for further research.

Despite these limitations, the basic findings of the climate change risk assessment match well with common scientific findings. The geographical location of island within Cluster 1 characterised by a high cyclone risk for example is in line with one of the global cyclone basis (Western Pacific) [119]. Furthermore, the high flood risk of islands within Cluster 2 aligns well with Köppen-Geiger's “tropical monsoon” classification characterised by periods of heavy rainfall [120]. The low flood risk of Cluster 3 islands is also represented in their “tropical rainforest” classification [120]. These areas are characterised by high quantities of rainfall, which are often absorbed by vegetation.

4.4.2 Resilient Energy System Planning

Data acquisition. Empirical research was necessary in order to create a data basis for further assessment. Even though a special focus was laid in creating a representative picture of knowledge and expertise about resilient energy system planning on Southeast Asian islands by approaching people with divers backgrounds, the acquired data serves as a first overview only. More detailed research is needed to create a solid and holistic data basis. Especially the missing link of identified adaptation measures to extra investment costs to implement these specific measures is a weakness. For now, the adaptation measure list and the estimated rise in investment costs to protect equipment against the impacts of different climate change risks is detached. The extra investment costs are generalised figures to get a first impression. Linking specific measures and related cost was not done in the expert interviewees to not overwhelm the interviewees with a very detailed questionnaire, a lot of repeating questions, and interview time exceeding one to one-and-a-half hours. In addition, the obtained data includes a range of values as presented in Table 4.4 and Table 4.5. Due to the high number of calculations per island (modelling and evaluation scenarios), only the mean values are considered. The full range of answers and estimations is reflected on a limited scale and needs further assessment.

Evaluation. The evaluation approach is a simplified method to reflect occurring frequencies and severity of damages caused by climate change induced incidents. This approach assumes the same damage for each system component after an incident happened and does not reflect irregularly occurring damages. As mentioned in Section 3.3.3, the evaluation calculation via HOMER is not possible and therefore a dynamic cash flow table was created. This approach allows to reflect partly destroyed equipment and persisting equipment at the same time. However, the salvage and replacement schedule is obtained from the original HOMER cash flow model as proxy. The real salvage and replacement figures might differ, as parts of the equipment are being replaced or repaired earlier (due to climate change induced damages). Thus, the developed approach serves as first assessment to the evaluation only. The calculated cost of outages and their relation to cost differences in BAU and climate resilient planning can be seen as approximation only. There was no detailed analysis of economic activities and social structures available for the case study islands. The exact figures to calculate the cost of outage might vary between the islands and need to be studied more thoroughly.

HOMER input parameter. The analysis (modelling and evaluation scenarios) depends on COE comparison. The value of COEs is dependant on all input criteria entered to HOMER. These values are determined based on current fuel prices, past mini-grid studies in the region, and the expert interviews. Changes in input criteria are leading to different COE results. Therefore, the analysis is subject to sensitivity of changing prices of components, fuel, or load profiles. In addition, the load profiles for each case study island are broad estimations, which served the purpose of this research. However, these demand estimations do not consider cultural, contextual, and site-specific parameters. A more detailed analysis of demands and time of usage is necessary to depict the local needs more precisely. A climate change impact assessment for biomass as another relevant generation source on some of the islands is also an interesting topic to cover for further research and include in set of input parameters.

Scope. Increasing the resilience of energy systems is not only a technical task as the interviews confirmed. A more holistic approach to the topic including social, political, and institutional factors is needed. Considering local needs and power dynamics is important to create and sustain resilient energy systems and their evolving benefits for the communities. All these non-technical factors were not within the scope of this research. As a result, the developed approach covers technical dimensions only and should be seen and communicated accordingly.

Although there are limitations, the approach developed and results are sufficient to legitimise and initiate further research in this direction. It has been shown that resilient energy system planning is worthwhile to consider and should be further researched. Basic assumptions made in this research led to reasonable COEs if compared to other studies dealing with COE calculation of mini-grids in rural areas in the Global South and on islands like those conducted by Zebra et al. (2021) or Berendes et al. (2018) [124, 125].

Chapter 5

Conclusion and Outlook

The final part of this thesis connects the results of both topics - climate change risk assessment and resilient energy system planning for Southeast Asian islands - and summarises the main findings. It looks back at the research questions posed at the beginning of this thesis (Section 1) and gives a brief overview on the answers found during the course of this research. Based on this, research and implementation recommendations are defined.

5.1 Summary

Both core topics of this research are strongly connected: climate resilient energy system planning is not possible without adequate climate change risk assessment, and climate change risk assessment cannot provide benefits without resilient energy system planning. For both topics, a large part of the work was data collection and acquisition. To analyse climate change risks in the research area, suitable datasets available for all countries to assess the main risks had to be identified and processed. The missing data to support climate change resilient energy system planning in an off-grid context led to the necessity to conduct expert interviews. After data acquisition, both topics required different approaches and tools to be assessed. Climate change risks were analysed by the application of QGIS and the statistical software R together with basic Excel operations. The adaptation data was processed mainly by calculating statistical parameters based on Excel. Finally, the results were applied with HOMER to model common and resilient RE-diesel mini-grids for three case study islands. To analyse the findings, an evaluation simulating the occurrence of climate change induced threats in terms of frequency and severity was conducted.

The detailed summary of results is following the structure of the research questions posed.

Research Question 1: Which climate change risks affect Southeast Asian island communities and their energy infrastructure and to what extent?

1.1 Which climate risks have an impact on island energy systems?

A literature review revealed four main climate change hazards impacting (island) energy systems, namely temperature increase, extreme weather events (e.g. cyclones), fluctuation in precipitation patterns (leading to droughts and floods), and sea-level rise (see Section 2.3.5). These hazards affect energy systems on different levels. Some lead to direct damages on the energy system's components, like storms or floods and landslides caused by intense rainfalls, while temperature increase leads to higher projected demands (e.g. caused by increasing cooling needs) and decreased system efficiency. Sea-level rise might flood and damage system components close to shorelines or lead to higher salt-corrosion of equipment decreasing their lifetime. Within this research, all four climate change risks were considered for further analysis.

1.2 Which of these climate change risks are occurring on Southeast Asian islands and in what degree of intensity?

Climate change risk assessment for the study area of Southeast Asian islands confirmed that all of the above mentioned climate change hazards occur on Southeast Asian islands (see Section 4.2). In order to reflect the risks and their intensity in developed energy system modelling scenarios, a risk scaling based on the Likert scale (1-5 from slight to severe risk) was applied. The scaling made the four assessed risks with different units comparable. Projected temperature rise of the region's islands ranges from 0.98 °C to 1.48 °C. The majority of islands will face a temperature rise between 1.3 - 1.4 °C. According to the selected approach to assess flood and drought risk (based on the Hydrological Drought Index), flood risk dominates and occurs on all islands ranging from slight to severe risk. However, most islands (7,671 out of 11,083) are facing a severe flood risk. Even though the majority of islands (6,717 out of 11,083 islands) shows no risk caused by sea-level rise, there are 4,366 islands at risk from sea-level rise. For 880 islands, the situation is very dramatic as they are likely to loose more than 80 % of their land area. All islands are affected by cyclone risk. The majority (6,512 islands) will face up to 70 cyclones within a 50-years-period. 464 islands are even projected to be challenged by 211 to 267 cyclones within the same time period. These findings confirm that Southeast Asian island communities are heavily affected by the impacts of climate change underlining the importance to implement adaptation measures for the communities and their critical infrastructure.

1.3 Can climate change risk profiles and patterns be identified for these islands?

To detect climate change risk patterns of the Southeast Asian island landscape, a cluster analysis was performed (see Section 4.2.5). Three risk clusters were determined reflecting similar risk patterns of islands within one cluster. The first cluster groups 1,731 island together, which are heavily affected by cyclone risk. Islands within this cluster are situated in the Philippines with some located on the central East coast of Vietnam, the Andaman and Nicobar islands, East Timor, and islands situated in South-Eastern Indonesia. The geographical grouping of islands within Cluster 1 is visible and relates well with one of the seven global cyclone basins being situated in Southeast Asia. Cluster 2 consists of 3,243 mostly small sized islands affected by sea-level rise, flooding, and increasing temperatures (highest scoring compared to other clusters) as well as cyclones (second highest scoring). Islands within this cluster are projected to loose a mean value of 28 % of their land area due to sea-level rise (compared to 3 % and 6 % of the other clusters). The small size of the islands grouped within this cluster is characteristic and explains the high proportion of land loss compared to the other clusters. The islands of Cluster 2 are mostly situated along the coastlines of Myanmar and Thailand and are to a large extend also part of the typical cyclone basin (outer zones) explaining their high cyclone risk. With 6,109 islands, Cluster 3 groups the largest number of islands. Islands within this cluster are situated in the central zones of Southeast Asia and show low, but measurable risks for all considered climate change hazards. The applied PAM method provided a characteristic medoid (island) for each cluster: The medoid island for Cluster 1 is a rock island, situated close to the East coast of central Vietnam, Maygi Kyun in South-Western Myanmar is the medoid island of Cluster 2 and medoid island of Cluster 3 is Bulon Pai, an island located in the Andaman Sea in Southern Thailand. As the first and third medoid islands are not inhabited and settlements are a crucial factor to assess demands and design energy systems, their closest neighbour islands sharing a similar risk profile served as case study islands for further analysis, namely Hon Son Cha (Cluster 1) and Bulon Don (Cluster 3).

Research Question 2: How can these island communities be supplied by technically resilient energy systems considering the identified climate risks?

2.1 Which technical measures can increase the resilience of island energy systems to climate change and at what cost?

To facilitate the integration of climate change risk considerations into energy system planning, measures to decrease the impacts of the defined hazards and related extra investment costs to implement these measures were studied. The impacts on energy systems were considered as damage of equipment causing repair needs and increased cost over project lifetime and as increased electricity demand (base and peak loads) as result of rising temperature. While literature review revealed a basic overview of measures to increase the resilience of off-grid energy systems, there was no data on cost structures or demand increase to guide their implementation. With the help of empirical research (expert interviews), I confirmed the necessity to implement climate change resilient energy system planning on Southeast Asian islands and quantified the costs and demand increases to reflect climate change impacts in energy system planning.

As a first result, the interviews showed the need to implement and anchor measures on a social, political and technical level in order to increase the resilience of island energy systems and to strengthen participatory approaches. One key result of the interviews is a detailed overview of existing adaptation measures to protect energy systems against current and future climate change hazards (see Appendix A.4). Measures relate to one or more of the identified climate change risks and can be applied to single components or the energy system as a whole. Another important finding is the quantification of incremental investment costs to implement these adaptation measures (see Table 4.4) and estimated demand increases (see Table 4.5). According to the interviewees, measures to protect against cyclones are causing the highest cost increase (ranging from 5 % to 22 %, mean value) followed by those protecting against the impacts of floods (ranging from 3 % to 18 %, mean value). Looking at the generation technologies, hydro (5 % to 18 %) and wind power (4 % to 14 %) require more additional investment to increase their resilience than solar (9 % to 11 %) and diesel (5 % to 9 %) generation. Grid infrastructure is rated to lead to the highest additional investment costs if protected against the impacts of cyclones (22 %). These figures facilitate the assessment of projected investment costs for resilient energy system planning. To reflect the impact of increasing temperature on energy system planning, the respondents were also asked to rate the potential increase of peak and base loads. Both were estimated to increase by 13 % (mean value), a detailed analysis of responses is shown in Table 4.5. This estimation enables the adjustment of load profiles to reflect future demand growth caused by the impacts of climate change and thus contribute to long-term system stability.

2.2 How can these measures and related costs be implemented in modelling resilient energy system scenarios?

In order to reflect these findings in energy system modelling, a translation of risk data and integration of adjusted demand and investment costs is necessary. This is the point where both core topics of my research - climate change risk assessment and resilient energy planning - are merged. The general idea is to transfer site-specific climate change risks into common energy system modelling inputs. Therefore, cyclone, sea-level rise, and flood risk are considered by adding investment costs to each system component to protect these against the impact of each risk (adjusted CAPEX cost). Increasing temperature is reflected by an increased load profile (climate demand). Based on four different scenarios (*BAU*, *BAU_clim*, *Climate_high*, *Climate_all*) as described in Section 3.3.2, energy systems were simulated and optimised for three different case study islands (determined in research question 1.3). The *BAU_clim* scenario represents business as usual planning in case of rising demands due to climate change (climate demand), the *Climate_high* scenario considers measures to reduce site-specific climate change impacts reflected by adjusted CAPEX with a risk scale of 3-5 (moderate to severe risks) and the *Climate_all* applies measures for all occurring risks (scale 1-5, insignificant to severe risk). After analysing which risks will be considered for the three case study islands, the respective extra investment costs as determined in the expert interviews (research question 2.1) are applied. Each system component received an increased investment costs (to be climate resilient), which served as input parameter for energy system modelling within HOMER. In addition, the demand was adjusted according to the demand increase caused by rising temperatures as mentioned above (climate demand).

The three case study islands differ in their risk profile as well as in their general characteristics: The first case study island Hon Son Cha (Vietnam) is a medium sized and scarcely populated island with some touristic activity. Magyi Kyun (Myanmar) - as second case study island - is a large island with a bigger settlement and agricultural activity. The third case study island is the small sized island of Bulon Don (Thailand) with no touristic or agricultural activity and a small settlement.

After modelling the energy systems for these case study islands according to the above mentioned scenarios, the following findings became apparent:

- **COE comparison - BAU and climate demand**: The overall system setup of the *BAU* and *BAU_clim* scenarios remains the same for the solar and battery capacities while demand is increasing (climate demand), which leads to the need of higher diesel generator capacities, higher fuel consumption, and lower RE shares. However, the COE develops differently for higher and lower demand islands: The low demand on Hon Son Cha results in low electricity sales while the cost distribution of the energy system shows a high proportion of cost for general infrastructure like power house and grid (with 44 % the highest proportion of all components). This results in an unfavorable proportion of NPV and electricity sales, which is the basis for COE calculation. On Hon Son Cha, the slightly higher demand in the *BAU_clim* scenario is thus beneficial and causes a lower COE for the *BAU_clim* scenario (0.729 EUR/kWh) than for the *BAU* scenario (0.749 EUR/kWh). The other two islands have a significant demand and their cost distribution shows a lower proportion of overall infrastructure cost (with approximately 5 % the lowest proportion of all components). Here, the *BAU* scenario has lower COEs (0.427 EUR/kWh for Magyi Kyun and 0.403 EUR/kWh for Bulon Don) than the *BAU_clim* scenario as the increased demand leads to increased diesel consumption.

- **COE comparison - *Climate_high* and *Climate_all* scenario**: Due to significant higher investment costs for the *Climate_all* scenario, the COE for all case study islands is slightly higher for the *Climate_all* system than for the *Climate_high* scenario. However, the difference between both COEs depends on the risk profile of each island and the extra investment costs that need to be considered. They range from 0.028 EUR/kWh (Hon Son Cha) to 0.039 EUR/kWh (Magyi Kyun) and 0.023 EUR/kWh (Bulon Don).

- **COE comparison - BAU and climate scenarios**: For all islands, COEs of BAU scenarios are lower than for the climate scenarios. If looking at the lowest difference, they range from 0.08 EUR/kWh (Hon Son Cha) to 0.01 EUR/kWh (Magyi Kyun and Bulon Don). If looking at the highest difference, they range from 0.13 EUR/kWh (Hon Son Cha) to 0.05 EUR/kW (Magyi Kyun) and 0.04 EUR/kW (Bulon Don). Due to the comparatively small differences in COEs between BAU and climate-resilient planning, the climate-resilient energy system planning approach is particularly attractive for Bulon Don and Magyi Kyun island.

- **COE comparison - all islands**: There is a significant difference between COEs of the islands. While Magyi Kyun and Bulon Don are within the same range (approximately 0.4 - 0.5 EUR/kWh), Hon Son Cha has almost twice as high COEs (0.7 - 0.9 EUR/kWh). This is explained by the high investment costs in combination with low electricity sales on Hon Son Cha island. Economies of scale do not apply to this island. Bulon Don has the lowest COEs of all islands (0.024 - 0.04 EUR/kWh lower than Magyi Kyun island). The reason of slightly lower COEs for Bulon Don can be detected in the cash flow model of Magyi Kyun. The energy system on the island has higher proportional operation, maintenance, and fuel costs than on Bulon Don island.

The analysis demonstrates the manageability of the approach as comprehensible results were created. Integrating climate change risks into energy system planning by considering these in the definition of common energy system modelling input criteria is a viable and transferable approach.

2.3 Under what circumstances is resilient energy system planning beneficial?

To understand which conditions make resilient energy system planning viable, evaluation scenarios were defined. The aim is to compare both climate scenarios with both BAU scenarios given the probability that climate change induced threats will affect the BAU systems causing damage. The frequency as well as the severity of damage was attempted to depict in the developed evaluation scenarios. Damage frequency was set to every 5, 10, and 15 years of project duration and for each of these cases, different severity of damage were applied (25 %, 50 %, 75 %, and 100 % of damage for each system component). The evaluation showed two interesting facts: In most cases both climate scenarios have lower COE than the calculated evaluation scenarios making resilient energy system planning more viable if climate change induced hazards are likely to occur. The lower the damage frequency in combination with less damage severity, the more likely the calculated evaluation scenarios showed lower COEs than the climate scenarios, indicating BAU planning is more viable (which is only the case for up to three of nine evaluation scenarios). The other interesting fact is that the lower the frequency of damage, the less important is the severity of damages. Evaluation calculation for varying diesel fuel prices revealed that higher diesel prices show a trend in favor of resilient energy system planning. In addition, COEs for the same damage frequency are less scattered for lower diesel prices meaning that the difference between COEs for various severity of damages is less. In the following the main results per island are summarised.

- **Hon Son Cha**: For eight out of nine (BAU demand) and six out of nine (Climate demand) cases, the climate scenarios shows lower COEs than the evaluation scenarios making climate resilient energy system planning more viable in climate change threatened areas like Hon Son Cha island. The pattern of lower COEs for the *BAU_clim* than for the *BAU* scenario persists for all evaluation scenarios.

- **Magyi Kyun**: On Magyi Kyun island, the *Climate_high* scenario has the lowest COE when compared to the evaluation scenarios and only three evaluation scenarios ($E_{10,25}$, $E_{15,25}$, and $E_{15,50}$) have lower COEs than the *Climate_all* scenario. Climate resilient energy system planning is thus highly feasible on the island. In case of a critical climate change induced incident happening every 10 years or more frequently, climate resilient energy planning is in general economically more viable. If damage is happening less frequent it depends on the projected degree of damage: the higher the degree of damage, the more reasonable it is to integrate climate change considerations into energy system planning from the very beginning.

- **Bulon Don**: On the third case study island, only one evaluation scenario ($E_{15,25}$) shows lower COEs than one of the climate scenarios (*Climate_all*). If damages are occurring every 15 years or less often, destroying approximately 25 % of the equipment, BAU system planning is more reasonable than climate resilient planning. In all other cases it is recommended to follow a climate resilient energy system planning approach.

Climate resilient energy system planning reduces the likelihood of power outages due to disturbances caused by climate related shocks and stresses. It thus minimises the losses associated with these outages. Comparing the difference in investment costs between BAU and climate resilient planning to the estimated costs of power outages on the case study islands, resilient energy system planning is more feasible if outages of 23 to 66 days occur on the islands. According to the interviewees, these outage times are not rare cases.

The evaluation highlights that most disruptions of the energy system will have a very strong economic impact leading to high electricity prices in the long run. For the majority of the evaluated cases, resilient energy system planning proofs to be viable. In areas where climate change impacts are expected to be frequent and/or severe, planning for a climate-resilient energy systems not only has economic benefits, but the positive impacts of electrification on communities are more likely to persist in the face of climate change.

5.2 Research and Implementation Recommendations

Some of the limitations identified for this research as well as the idea to transfer the applied research to other regions heavily threatened by climate change results in the definition of further research needs that are listed within this section. Recommendations are also provided on how to put the results of this research into practice.

Climate Change Risk Assessment

Climate change risk assessments are a complex task and many climate change impacts interrelate with each other. The assessment conducted in this research serves as first attempt to understand the risk profiles of Southeast Asian island communities. A more detailed climate change risk analysis is recommended which shall include:

- The effect of seasonality for assessing temperature rise, flood and drought risk,
- The impact of topography, soil and vegetation on flood and drought risk,
- The assessment of site specific landslide risk based on topography, soil and flood risk, and
- The assessment and comparison of sea-level rise risk based on different sea-level rise projections, data, and currently updated elevation models (CoastalDEM, December 2021) to improve accuracy.

Most datasets applied are based on RCPs (temperature, precipitation, sea-level rise projection). Therefore, the inclusion and selection of data based on various RCPs opens a more holistic approach and assessment of what will happen, if certain climate agreements and goals are not achieved and will - most likely - underline the urgency to act. The climate change risk assessment conducted in this research is based on data and models developed for and applied in IPCC's Fifth Assessment Report (2014). Over the course of my research, the Sixth Assessment Report got published (2022) and might provide additional insights and updated projections relevant for further analysis, even though RCPs remained the same.

An impact assessment of the analysed hazards on the islands facilitates a more appropriate scaling and weighting. This may lead to the definition of more reasonable evaluation scenarios considering the different nature and consequences of cyclones, sea-level rise, temperature increase, flood, and drought risk for island communities and their energy systems.

Resilient Energy System Modelling

The energy system modelling and evaluation is based on mean values derived from the expert interviews. It is recommended to calculate and compare modelling and evaluation results for other ranges of adjusted CAPEX and demand input (e.g. top third values, majority mean value, minimum, and maximum values) to create a more holistic picture. It is also beneficial to implement a second round of interviews and link identified adaptation measures directly to expected extra investment costs and receive feedback from a wider range of interviewees. In addition, a detailed sensitivity analysis of all input criteria is recommended. For further analysis, a deeper knowledge of local needs and demands is also recommended to optimally design and model the island energy systems.

Scope Extension & Transferability

The general approach of this research is transferable to other regions for the following reasons. The data used for the climate change risk assessment is part of global datasets and thus available for other regions. The energy system modelling input parameters as derived from the expert interview, however, are only transferable to a limited extent. Most interviewees are experts for energy systems in Southeast Asia and their regional characteristics. Thus, the interviews have to be extended to other regions and interviewees with similarly diverse backgrounds. While working on this thesis and speaking to many experts, the need for a solid database as well as for a convenient tool to integrate climate change risk considerations into off-grid energy system planning became apparent. The first step should be to create a (global) database for suitable adaptation measures linked to one or multiple climate change hazards and related extra investment costs to implement these. At the same time, the database could serve as monitoring and evaluation tool where practitioners are able to enter their experiences and recommendations. This enables global learning and experience sharing and will fill - step by step - the existing data gap. In a second step, functions to enable the integration of these measures in energy system modelling tools are necessary. It is recommended to integrate e.g. check-boxes to select different measures to increase resilience and provide economic default data to consider these or the option to include potential damages in sensitivity analyses for common energy system modelling tools.

Recommendations to Policy Makers and Implementers

With exacerbating climate change, consideration of this change will become increasingly important for energy system planning. This research suggest that implementation of the developed approach will be beneficial for areas at high risk of climate change impacts. Energy system planning needs to become a multi-sectoral approach that considers the various impacts of climate change on communities and their infrastructure. Policy makers and energy planners should take these findings into account and create an enabling framework. Incorporating climate change considerations into energy system planning must be approached from multiple angles:

- A mandatory climate change risk assessment, embodied in energy system planning standards and guidelines, can provide an overview of site-specific risks and guide the selection of appropriate mitigation measures.

- Adapting energy systems to site-specific risk profiles is costly and requires additional funding. Therefore, climate-resilient energy systems require the implementation of specific financial support programs, as they only pay off on the long run.

- Initial energy infrastructure is often supported in whole or in part by public investment and financing. Therefore, policymakers have the opportunity to set the rules for public procurement for such systems and incorporate appropriate adaptation requirements.

- It is also recommended that climate change considerations be incorporated into energy system planning tools to address the specific long-term value of resilient energy systems as opposed to commonly applied least-cost planning to mainstream resilient energy system planning and facilitate decision-making.

These initial steps will provide the foundation for climate-resilient energy system planning in the off-grid sector and support the further development of holistic infrastructure planning.

5.3 Final Statement

The research aim to enable climate change resilient off-grid energy system planning was achieved by developing and applying a first approach based on literature review, data analysis and empirical research. Four different climate change induced risks were identified to impact current and future energy systems and were considered for further analysis. Climate change risk assessment showed significant risks for Southeast Asian islands, their communities and (future) energy systems. Climate change risks vary within the region, but patterns and characteristics can be detected: there is a strong geographically assignable risk for cyclones, a high sea-level rise risk for smaller islands (loosing higher percentages of land) or higher flood risk for islands outside of tropical rainforest climate classifications. Site-specific climate change risk profiles and scales were obtained for all islands included in this analysis. After this, a list of adaptation measures and related extra investment costs to reduce the impacts of site-specific climate change risks on off-grid energy systems as well as climate change adapted demand structures were compiled based on the expertise of people interviewed. Energy modelling scenarios were developed to reflect different degrees of climate resilient planning and enable the comparison with BAU planning. These scenarios were calculated for three case study islands being representative for three different climate change risk cluster. Evaluation of these scenarios showed that climate resilient energy system planning is viable for most cases. The higher the frequency and severity of damages, the more feasible becomes climate resilient system planning. This research creates a first overview of potential benefits and applicability of resilient energy system planning and provides an approach to integrate climate change risk analysis into energy system planning. However, further research on this topic remains necessary to validate, strengthen and mainstream the developed approach. Results underline the importance of climate risk assessment and resilient energy system planning for a climate change threatened region like Southeast Asia. The approach developed improves the long-term reliability of energy supply to Southeast Asian island communities, increasing their overall resilience.

Acknowledgement

First of all, I wish to thank the Heinrich Böll Foundation for financing this PhD project. The scholarship allowed an independent and flexible research on a topic of scientific and personal importance.

Additionally, I would like to thank my two supervisors Prof. Dr. Frank Behrendt (TU Berlin) and Prof. Dr. Christoph Menke (FH Trier) who guided me through this research and gave valuable feedback and support.

I want to express my special gratitude to Dr. Philipp Blechinger (Reiner Lemoine Institut) who accompanied me in all my ups and downs and kept me motivated. Thank you for all your valuable feedback, comments, critical questions and trust. I am grateful that I was able to take my time, when I needed it most. Special thanks to Reiner Lemoine Institut which gave me the best framework and conditions I could think of. Thanks to all RLI's who supported me!

This research would not have been the same without the support of Karoline Gerbatsch, Tim Ronan Britton and Jean-Marie Chukwuma who wrote their Bachelor and Master Theses within the framework of my research. All of you contributed a lot to this work and I enjoyed working with you - it taught me a lot.

I would like to thank Moritz Krüger for his emotional support and backing as well as endless reading and commenting! For great fellow-PhD companionship I would like to thank Zakia Soomauroo. I am especially grateful to Clara Jütte, Ulli Lich, Avia Linke, Catherina Cader, Caroline Möller, Adnan Alakori and Andrés Andrade Velásquez who took the time and effort to read, correct and comment this thesis.

Thanks to my family and friends who were always there for me.

And last but not least I want to acknowledge all the powerful women out there and acknowledge the power in ourselves - the power that only we are able to rouse.

Bibliography

[1] Zhi Hua Lee, Sumathi Sethupathi, Keat Teong Lee, Subhash Bhatia, and Abdul Rahman Mohamed. An overview on global warming in Southeast Asia: CO2 emission status, efforts done, and barriers. *Renewable and Sustainable Energy Reviews*, 28:71–81, 2013. doi:10.1016/j.rser.2013.07.055.

[2] World Economic Forum (WEF). The Global Risks Report 2021. 16th edition, WEF, 2021. URL: http://wef.ch/risks2021.

[3] Laura T. David, Rommel Maneja, Beverly Goh, Felino Lansigan, Pich Sereywath, Ivonne M. Radjawane, Bernardette M. Manjaji Matsumoto, Pitiwong Tantichodok, Anond Snidvong, Nguyen Hoang Tri, Kim Anh Thi Nguyen, Yoshiki Saito, and Jochen Hinkel. Sea level rise vulnerability of Southeast Asian coasts. *Inprint of Land-Ocean Interactions in the Coastal Zone Project*, 2008. URL: https://www.researchgate.net/profile/Beverly-Goh/publication/281267072_Sea_Level_Rise_Vulnerability_of_Southeast_Asian_Coasts/links/55dd78e008ae591b309ad677/Sea-Level-Rise-Vulnerability-of-Southeast-Asian-Coasts.pdf?origin=publication_detail.

[4] Yen Yi Loo, Lawal Billa, and Ajit Singh. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, 6(6):817–823, 2015. doi:10.1016/j.gsf.2014.02.009.

[5] Peter van der Keur, Caroline van Bers, Hans Jürgen Henriksen, Hari Krishna Nibanupudi, Shobha Yadav, Rina Wijaya, Andreas Subiyono, Nandan Mukerjee, Hans-Jakob Hausmann, Matt Hare, Catharien Terwisscha van Scheltinga, Gregory Pearn, and Fons Jaspers. Identification and analysis of uncertainty in disaster risk reduction and climate change adaptation in South and Southeast Asia. *International Journal of Disaster Risk Reduction*, 16:208–214, 2016. doi:10.1016/j.ijdrr.2016.03.002.

[6] Hans-Joachim Heintze, Barbara Küppers, Holger Mann, Frank Mischo, Peter Mucke, Tanja Pazdzierny, Ruben Prütz, Katrin Radtke, Friederike Strube, and Daniel Weller. Weltrisikobericht 2018. Fokus Kinderschutz und Kinderrechte. Technical report, Bündnis Entwicklung

Hilft, Ruhr-Universität Bochum – Institut für Friedenssicherungsrecht und Humanitäres Völkerrecht (IFHV), Bonn, Germany, 2018. URL: https://www.welthungerhilfe.de/fileadmin/pictures/publications/de/studies-analysis/2018-WeltRisikoBericht2018_BEH-final.pdf.

[7] National Intelligence Council (NIC). Southeast Asia and Pacific islands: The impact of climate change to 2030 - a commissioned research report. Technical report, Report by Joint Global Change Research Institute, Battelle Memorial Institute, Pacific Northwest Division, Scitor Corporation on behalf of NIC, Special Report, NIC 2009-006D, 2009. URL: https://www.dni.gov/files/documents/climate2030_southeast_asia_pacific_islands.pdf.

[8] Nisrina Setyo Darmanto, Alvin Christopher Galang Varquez, Natsumi Kawano, and Manabu Kanda. Future urban climate projection in a tropical megacity based on global climate change and local urbanization scenarios. *Urban Climate*, 29:100482, 2019. doi:10.1016/j.uclim.2019.100482.

[9] P. Blechinger, C. Cader, P. Bertheau, H. Huyskens, R. Seguin, and C. Breyer. Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands. *Energy Policy*, 98:674–687, 2016. doi:10.1016/j.enpol.2016.03.043.

[10] International Energy Agency (IEA). *Southeast Asia Energy Outlook 2017*. IEA / Organisation for Economioc Co-operation on Development (OECD), France, Paris, 2017. URL: https://read.oecd-ilibrary.org/energy/southeast-asia-energy-outlook-2017_9789264285576-en#page1.

[11] Gambhir A, Drouet L, McCollum D, Napp T, Bernie D, and Hawkes A. Assessing the feasibility of global long-term mitigation scenarios. *Energies*, 10(1), 2017. doi:10.3390/en10010089.

[12] Climatescope. 3rd Quartal 2018 - off-grid and mini-grid market outlook. Technical report, BloombergNEF, 2018. http://2017.global-climatescope.org/en/off-grid-quarterly/q3-2018/. URL: https://medium.com/climatescope/3q-2018-off-grid-and-mini-grid-market-outlook-70ed47656c31.

[13] Zumar M.A. Bundhoo, Kalim U. Shah, and Dinesh Surroop. Climate proofing island energy infrastructure systems: Framing resilience based policy interventions. *Utilities Policy, ScienceDirect*, 55:41–51, 2018. URL: https://www.sciencedirect.com/science/article/abs/pii/S0957178718300778, doi:10.1016/j.jup.2018.09.005.

[14] Nipunika Perera, Emily Boyd, Gill Wilkins, and Ruth Phillips Itty. Literature review on energy access and adaptation to climate change. Technical report, Evidence on Demand, 2015. doi:10.12774/eod_cr.may2015.pereran.

[15] Peter Campbell Johnston, Jose Frazier Gomez, and Benoit Laplante. Climate risk and adaptation in the electric power sector. Technical report, Asian Development Bank, Manila, Philippines, 2012. URL: https://www.adb.org/sites/default/files/publication/29889/climate-risks-adaptation-power-sector.pdf.

[16] Global Climate Action. Climate action pathway, climate resilience, executive summary. Technical report, United Nation FCCC, 2020. URL: https://unfccc.int/sites/default/files/resource/ExecSumm_Resilience_0.pdf.

[17] Pernille Seljom, Eva Rosenberg, Audun Fidje, Jan Erik Haugen, Michaela Meir, John Rekstad, and Thore Jarlset. Modelling the effects of climate change on the energy system — a case study of Norway. *Energy policy*, 39(11):7310–7321, 2011. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421511006513, doi:10.1016/j.enpol.2011.08.054.

[18] Hagen Koch, Stefan Vögele, Fred F Hattermann, and Shaochun Huang. The impact of climate change and variability on the generation of electrical power. *Meteorologische Zeitschrift*, 24(2):173, 2015. doi:10.1127/metz/2015/0530.

[19] Jim Blackburn Christina Copeland Sara Law Joan M. Ogden Amy Myers Jaffe, Joshua Busby and Paul A. Griffin. *Impact of Climate Risk on the Energy System: Examining the Financial, Security, and Technology Dimensions.* Council on Foreign Relations, 2019. URL: https://cdn.cfr.org/sites/default/files/report_pdf/Impact%20of%20Climate%20Risk%20on%20the%20Energy%20System_0.pdf.

[20] Nnaemeka Vincent Emodi, Taha Chaiechi, and ABM Rabiul Alam Beg. A techno-economic and environmental assessment of long-term energy policies and climate variability impact on the energy system. *Energy Policy*, 128:329–346, 2019. doi:10.1016/j.enpol.2019.01.011.

[21] Jane Ebinger and Walter Vergara. *Climate Impacts on Energy Systems.* The World Bank, 2011. URL: https://elibrary.worldbank.org/doi/abs/10.1596/978-0-8213-8697, doi:10.1596/978-0-8213-8697.

[22] Roberto Schaeffer, Alexandre Salem Szklo, André Frossard Pereira de Lucena, Bruno Soares Moreira Cesar Borba, Larissa Pinheiro Pupo Nogueira, Fernanda Pereira Fleming, Alberto Troccoli, Mike Harrison, and Mohammed Sadeck Boulahya. Energy sector vulnerability to climate change: A review. *Energy*, 38(1):1–12, 2012. doi:10.1016/j.energy.2011.11.056.

[23] C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group ii to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical

report, IPCC, 2014. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf.

[24] Piya Abeygunawardena, Yogesh Vyas, Philipp Knill, Tim Foy, Melissa Harrold, Paul Steele, Thomas Tanner, Danielle Hirsch, Maresa Oosterman, Jaap Rooimans, Marc Debois, Maria Lamin, Holger Liptow, Elisabeth Mausolf, Roda Verheyen, Shardul Agrawala, Georg Caspary, Ramy Paris, Arun Kashyap, Arun Sharma, Ajay Mathur, Mahesh Sharma, and Frank Sperling. Poverty and climate change. Reducing the vulnerability of the poor through adaptation. Technical report, World Bank, Washington, D.C., 2009. URL: https://documents1.worldbank.org/curated/en/534871468155709473/pdf/521760WP0pover1e0Box35554B01PUBLIC1.pdf.

[25] Department for International Development (DFID). Defining disaster resilience: A DFID approach paper. Technical report, DFID London UK, 2011. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/186874/defining-disaster-resilience-approach-paper.pdf.

[26] Brian Walker, C. S. Holling, Stephen R. Carpenter, and Ann Kinzig. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society*, 2004. URL: https://www.ecologyandsociety.org/vol9/iss2/art5/.

[27] Fiona Miller, Henny Osbahr, Emily Boyd, Frank Thomalla, Sukaina Bharwani, Gina Ziervogel, Brian Walker, Jörn Birkmann, Sander van der Leeuw, Johan Rockström, Jochen Hinkel, Tom Downing, Carl Folke, and Donald Nelson. Resilience and vulnerability: Complementary or conflicting concepts? *Ecology and Society*, 15(3), 2010. URL: https://www.ecologyandsociety.org/vol15/iss3/art11/, doi:10.5751/es-03378-150311.

[28] Nick Brooks, Eunica Aure, and Martin Whiteside. Final report: Assessing the impact of ICF programmes on household and community resilience to climate variability and climate change. Technical report, Department for International Development (DFID), 2014. doi:10.12774/eod_cr.june2014.brooksetal.

[29] United Nations (UN), editor. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, UN, 2012. URL: https://www.ebook.de/de/product/19222721/united_nations_managing_the_risks_of_extreme_events_and_disasters_to_advance_climate_change_adaptation.html.

[30] Adelle Thomas, Rose Martyr-Koller, and Patrick Pringle. Climate change and small islands: more scientific evidence of high risks. *Climate Analytics Blog*, 2020. URL: https://climateanalytics.org/blog/2020/climate-change-and-small-islands-more-scientific-evidence-of-high-risks/.

[31] World Data. Country data and statistics - islands per country. Worlddata.info. URL: https://www.worlddata.info/.

[32] Andaman and Nicobar Administration. Andaman and Nicobar Islands. https://www.andaman.gov.in, 2020. URL: https://www.andaman.gov.in/about.

[33] World Atlas. Which countries have the most islands? Article - WorldAltlas.com, 2021. URL: https://www.worldatlas.com/articles/which-countries-have-the-most-islands.html.

[34] Herminia Francisco Arief Anshory Yusuf. Climate change vulnerability mapping for Southeast Asia. Technical report, Economy and Environment Program for Southeast Asia (EEPSEA), 2009. URL: https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/asia-amp-indian-ocean/southeast-asia-amp-philippines/Yusuf--Francisco.--2009.---CC-Vulnerability-for-Southeast-Asia.pdf.

[35] Sanaz Moghim and Roja Kaveh Garna. Countries classification by environmental resilience. *Journal of Environmental Management*, 230:345–354, 2019. URL: https://www.sciencedirect.com/science/article/pii/S0301479718311009, doi:10.1016/j.jenvman.2018.09.090.

[36] International Energy Agency. Defining energy access: 2020 methodology. *IEA*, 2020. URL: https://www.iea.org/articles/defining-energy-access-2020-methodology.

[37] Mikul Bhatia and Nicolina Angelou. Beyond connections: Energy access redefined. Technical report, Energy Sector Management Assistance Program (ESMAP), The World Bank, 2015. URL: https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y.

[38] Michael Franz, Nico Peterschmidt, Michael Rohrer, and Bozhil Kondev. Mini-grid policy toolkit. Technical report, European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF), Eschborn, 2014. URL: http://euei-pdf.org/thematic-studies/mini-grid-policy-toolkit.

[39] Douglas R. Burnett, Robert Beckman, and Tara M. Davenport. *Submarine Cables: The Handbook of Law and Policy.* Martinus Nijhoff, 2013. URL: https://www.ebook.de/de/product/21590377/submarine_cables_the_handbook_of_law_and_policy.html.

[40] Christina Stuart. Energy and climate change adaptation in developing countries. Technical report, EUEI PDF, 2017.

[41] Paul Bertheau and Catherina Cader. Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options. *Applied Energy*, 251:113393, 2019. doi:10.1016/j.apenergy.2019.113393.

[42] Yonghong Kuang, Yongjun Zhang, Bin Zhou, Canbing Li, Yijia Cao, Lijuan Li, and Long Zeng. A review of renewable energy utilization in islands. *Renewable and Sustainable Energy Reviews*, 59:504–513, 2016. doi:10.1016/j.rser.2016.01.014.

[43] Matthew Dornan. Access to electricity in Small Island Developing States of the Pacific: Issues and challenges. *Renewable and Sustainable Energy Reviews*, 31:726 – 735, 2014. URL: http://www.sciencedirect.com/science/article/pii/S1364032113008514, doi:https://doi.org/10.1016/j.rser.2013.12.037.

[44] Ricardo Oliveira Billy Roberts Thomas Bowen Nathan Lee, Francisco Flores-Espino and Jessica Katz. Exploring renewable energy opportunities in select Southeast Asian countries. Technical report, NREL, 2020. URL: https://www.nrel.gov/docs/fy19osti/71814.pdf.

[45] David Hayes. Asian renewables: South East Asia regional overview. *reFocus*, 5(3):48–51, 2004. doi:10.1016/S1471-0846(04)00145-3.

[46] Global Energy Assessment Writing Team. Global energy assessment. Technical report, Cambridge University Press, 2012. URL: https://ideas.repec.org/b/cup/cbooks/9780521182935.html.

[47] United Nations. Affordable and clean energy: Why it matters. UN - Sustainable Development Goals, 2020. URL: https://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/7_Why-It-Matters-2020.pdf.

[48] Sarah Best. Growing power: Exploring energy needs in smallholder agriculture. *International Institute for Environment and Development (IIED)*, Discussion Paper April 2014, 2014. URL: https://pubs.iied.org/sites/default/files/pdfs/migrate/16562IIED.pdf.

[49] Rabia Ferroukhi, Divyam Nagpal, Alvaro Lopez-Peña, Troy Hodges, Rabi H. Mohtar, Bassel Daher, Samia Mohtar, and Martin Keulertz. Renewable energy in the water, energy & food nexus. Technical report, IRENA, 2015. URL: file:///C:/Users/KATRIN~1.LAM/AppData/Local/Temp/IRENA_Water_Energy_Food_Nexus_2015.pdf.

[50] Olivia Gippner, Saroj Dhakal, and Benjamin K. Sovacool. Microhydro electrification and climate change adaptation in Nepal: Socioeconomic lessons from the Rural Energy Development Program (REDP). *Mitigation and Adaptation Strategies for Global Change*, 18(4):407–427, 2012. doi:10.1007/s11027-012-9367-5.

[51] Jennifer Cronin, Gabrial Anandarajah, and Olivier Dessens. Climate change impacts on the energy system: A review of trends and gaps. *Climatic change*, 151(2):79–93, 2018. URL: https://link.springer.com/article/10.1007/s10584-018-2265-4.

[52] Leon Clarke, Kejun Jiang, Keigo Akimoto, Mustafa Babiker, Geoffrey Blanford, Karen Fisher-Vanden, J-C Hourcade, Volker Krey, Elmar Kriegler, and Andreas Löschel. Assessing transformation pathways. 2014. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter6.pdf.

[53] Pablo E Carvajal, Francis GN Li, Rafael Soria, Jennifer Cronin, Gabrial Anandarajah, and Yacob Mulugetta. Large hydropower, decarbonisation and climate change uncertainty: Modelling power sector pathways for Ecuador. *Energy Strategy Reviews*, 23:86–99, 2019. doi:10.1016/j.esr.2018.12.008.

[54] Carla Teotónio, Patrícia Fortes, Peter Roebeling, Miguel Rodriguez, and Margarita Robaina-Alves. Assessing the impacts of climate change on hydropower generation and the power sector in Portugal: A partial equilibrium approach. *Renewable and Sustainable Energy Reviews*, 74:788–799, 2017.

[55] Charles Fant, C Adam Schlosser, and Kenneth Strzepek. The impact of climate change on wind and solar resources in southern Africa. *Applied Energy*, 161:556–564, 2016. URL: https://www.sciencedirect.com/science/article/pii/S0306261915003268, doi:10.1016/j.apenergy.2015.03.042.

[56] Théoneste Uhorakeye and Bernd Möller. Assessment of a climate-resilient and low-carbon power supply scenario for Rwanda. *International Journal of Sustainable Energy Planning and Management*, 17:45–60, 2018. URL: https://journals.aau.dk/index.php/sepm/article/view/2055/1871, doi:10.5278/ijsepm.2018.17.5.

[57] Afees A Salisu and Taofeek O Ayinde. Modeling energy demand: Some emerging issues. *Renewable and Sustainable Energy Reviews*, 54:1470–1480, 2016. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032115012009, doi:10.1016/j.rser.2015.10.121.

[58] Maryse Labriet, Markus Biberacher, Philip B Holden, Neil R Edwards, Amit Kanudia, and Richard Loulou. Assessing climate impacts on the energy sector with TIAM-WORLD: Focus on heating and cooling and hydropower potential. In *Informing Energy and Climate Policies Using Energy Systems Models*, pages 389–409. Springer, 2015. URL: https://link.springer.com/chapter/10.1007/978-3-319-16540-0_21, doi:10.1007/978-3-319-16540-0_21.

[59] Pravin Karki, Laura Bonzanigo, Haruhisa Ohtsuka, and Sanjay Pahuja. Toward climate-resilient hydropower in South Asia. 2016. URL: https://openknowledge.worldbank.org/handle/10986/24254.

[60] M Bernardino and C Guedes Soares. Assessing climate change effect in offshore wind power in the north of Portugal. In *Progress in Renewable Energies Offshore: Proceedings of the 2nd International Conference on Renewable Energies Offshore (RENEW2016), Lisbon, Portugal, 24-26 October 2016*, page 111. CRC Press, 2016. URL: http://www.centec.tecnico.ulisboa.pt/en/centec/publications.aspx?publicationid=2270.

[61] Kamia Handayani, Tatiana Filatova, and Yoram Krozer. The vulnerability of the power sector to climate variability and change: Evidence from Indonesia. *Energies*, 12(19):3640, 2019. URL: https://mdpi-res.com/d_attachment/energies/energies-12-03640/article_deploy/energies-12-03640.pdf, doi:10.3390/en12193640.

[62] Icon: PK Vectorstall. Chart. In the Industry-K (Line and Glyph) Collection, 2021. URL: https://thenounproject.com/search/?q=temperature+increase&i=3721339#.

[63] Icon: Nikolay Necheuhin. Rain. The Noun Project, 2021. URL: https://thenounproject.com/search/?q=temperature+increase&i=3721339#.

[64] Icon: Bakunetsu Kaito. Storm. The Noun Project, 2021. URL: https://thenounproject.com/search/?q=temperature+increase&i=3721339#.

[65] Icon: dDara. Sea level. The Noun Project, 2021. URL: https://thenounproject.com/search/?q=temperature+increase&i=3721339#.

[66] Asian Development Bank, editor. *Guidelines for Climate Proofing Investment in the Energy Sector*. Asian Development Bank, 2013. URL: https://www.adb.org/sites/default/files/institutional-document/33896/files/guidelines-climate-proofing-investment-energy-sector.pdf.

[67] Elizabeth Cecelski. The role of women in sustainable energy development. *National Renewable Energy Laboratory (NREL), Energy, Environment & Development*, NREL/SR-550-26889, 2000. URL: https://www.nrel.gov/docs/fy00osti/26889.pdf.

[68] Muzibur Rahman and Somik Ghosh. Increasing resilience by the participatory planning approach. In *Construction Research Congress 2016*. American Society of Civil Engineers, 2016. doi:10.1061/9780784479827.154.

[69] Dina Stober, Monika Suškevičs, Sebastian Eiter, Stefanie Müller, Stanislav Martinát, and Matthias Buchecker. What is the quality of participatory renewable energy planning in Europe? A comparative analysis of innovative practices in 25 projects. *Energy Research & Social Science*, 71:101804, 2021. doi:10.1016/j.erss.2020.101804.

[70] Nadja Kabisch, Horst Korn, Jutta Stadler, and Aletta Bonn, editors. *Nature-Based Solutions to Climate Change Adaptation in Urban Areas*. Springer International Publishing, 2017. doi:10.1007/978-3-319-56091-5.

[71] Esther Duflo. Women empowerment and economic development. *Journal of Economic Literature*, 50(4):1051–1079, 2012. doi:10.1257/jel.50.4.1051.

[72] Lorraine Corner. Women's participation in decision-making and leadership - a global perspective. *Conference on Women in Decision-Making in Cooperatives - Asian Women in Co-operative Development Forum (ACWF)*, 1997. URL: https://iknowpolitics.org/sites/default/files/decision-making26leadership_global.pdf.

[73] "R Core Team". R: A language and environment for statistical computing. URL: https://www.R-project.org.

[74] QGIS. QGIS Geographic Information System, version 3.4 "Madeira". *QGIS Development Team, https://www.qgis.org/de/site/*, 2018. URL: http://qgis.osgeo.org.

[75] GADM. GADM database of Global Administrative Areas - version 3.6. *Database of Global Administrative Areas*, https://gadm.org/, 2020. https://gadm.org/. URL: http://gadm.org/home.

[76] Sander Brinkman Eduardo Calvo Tim Carter Jae Edmonds Ismail Elgizouli Seita Emori Lin Erda Kathy Hibbard Roger Jones Mikiko Kainuma Jessica Kelleher Jean Francois Lamarque Martin Manning Ben Matthews Jerry Meehl Leo Meyer John Mitchell Nebojsa Nakicenovic Brian O'Neill Ramon Pichs Keywan Riahi Steven Rose Paul Runci Ron Stouffer Detlef van Vuuren John Weyant Tom Wilbanks Jean Pascal van Ypersele Richard Moss, Mustafa Babiker and Monika Zurek. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. *Intergovernmental Panel on Climate Change*, 2008. URL: https://archive.ipcc.ch/pdf/supporting-material/expert-meeting-report-scenarios.pdf.

[77] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, Christoph von Stechow, T. Zwickel, and J. C. Minx. IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, IPCC, 2014. URL: http://www.ipcc.ch/report/ar5/wg3/.

[78] Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy. RCP8.5 tracks cumulative CO2 emissions. *Proceedings of the National Academy of Sciences*, 117(33):19656–19657, 2020. doi:10.1073/pnas.2007117117.

[79] Detlef P. van Vuuren, Elke Stehfest, Michel G. J. den Elzen, Tom Kram, Jasper van Vliet, Sebastiaan Deetman, Morna Isaac, Kees Klein Goldewijk, Andries Hof, Angelica Mendoza Beltran, Rineke Oostenrijk, and Bas van Ruijven. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, 109(1-2):95–116, 2011. doi:10.1007/s10584-011-0152-3.

[80] Stephen E. Fick and Robert J. Hijmans. Worldclim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12):4302–4315, 2017. doi:10.1002/joc.5086.

[81] Suchada Kamworapan and Chinnawat Surussavadee. Evaluation of CMIP5 global climate models for simulating climatological temperature and precipitation for Southeast Asia. *Advances in Meteorology*, 2019:1–18, 2019. doi:10.1155/2019/1067365.

[82] Richard G. Allen, Luis S. Pereira, Dirk Raes, and Martin Smith. FAO irrigation and drainage paper No. 56: Crop evapotranspiration. Technical report, FAO, 1998. URL: https://www.researchgate.net/publication/235704197_Crop_evapotranspiration-Guidelines_for_computing_crop_water_requirements-FAO_Irrigation_and_drainage_paper_56#fullTextFileContent.

[83] George H. Hargreaves. Defining and using reference evapotranspiration. 120(6):1132–1139, 1994. doi:10.1061/(asce)0733-9437(1994)120:6(1132).

[84] Antonio Trabucco and Robert J. Zomer. Global high-resolution soil-water balance, 2019. URL: https://cgiarcsi.community/data/global-high-resolution-soil-water-balance/, doi:10.6084/M9.FIGSHARE.7707605.V3.

[85] A. Trabucco and R. Zomer. Global-aridity and global-PET database. CGIAR-CSI, 2007. URL: https://cgiarcsi.community/data/global-aridity-and-pet-database/.

[86] SATH. Hydrological drought index. Technical report, Satellite Hydrology Project (SATH). URL: http://www.sath.abn.ne/Factsheets/Factsheet_SATH_UK_HDI.pdf.

[87] Richard Allan, L. Pereira, and Martin Smith. *Crop evapotranspiration Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*, volume 56. 1998. URL: https://www.researchgate.net/publication/235704197_Crop_evapotranspiration-Guidelines_for_computing_crop_water_requirements-FAO_Irrigation_and_drainage_paper_56.

[88] Scott A. Kulp and Benjamin H. Strauss. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, 10(1), 2019. doi:10.1038/s41467-019-12808-z.

[89] Climate Central. Flooded Future: Global vulnerability to sea level rise worse than previously understood. Technical report, Climate Central, 2019. URL: https://www.climatecentral.org/pdfs/2019CoastalDEMReport.pdf.

[90] Robert E. Kopp, Radley M. Horton, Christopher M. Little, Jerry X. Mitrovica, Michael Oppenheimer, D. J. Rasmussen, Benjamin H. Strauss, and Claudia Tebaldi. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, 2(8):383–406, 2014. doi:10.1002/2014ef000239.

[91] Ali Yunus, Ram Avtar, Steven Kraines, Masumi Yamamuro, Fredrik Lindberg, and C. Grimmond. Uncertainties in tidally adjusted estimates of sea level rise flooding (bathtub model) for the greater London. 8(5):366, 2016. doi:10.3390/rs8050366.

[92] B.C. Glavovic J. Hinkel R. van de Wal A.K. Magnan A. Abd-Elgawad R. Cai M. Cifuentes-Jara R.M. DeConto T. Ghosh J. Hay F. Isla B. Marzeion B. Meyssignac Oppenheimer, M. and Z. Sebesvari. Sea level rise and implications for low-lying islands, coasts and communities. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, 2019. URL: https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/08_SROCC_Ch04_FINAL.pdf.

[93] WorldBank. Global cyclone hazard 50 year return period. WorldBank, 2015. Published (Ver.2186031). URL: https://datacatalog.worldbank.org/dataset/global-cyclone-hazard.

[94] United Nations Office for Disaster Risk Reduction (UNISDR). The pocket GAR 2015. Making development sustainable: The future of disaster risk management. Technical report, UNISDR, Geneva, Switzerland, 2015. URL: https://archive-ouverte.unige.ch/files/downloads/0/0/0/7/8/2/9/9/unige_78299_attachment01.pdf.

[95] WorldClim. Worldclim 1.4 dataset current conditions: 2050 (average for 1960 - 1990) and RCP45 - 30 arcsec. WorldClim Data Platform, 2017. URL: https://www.worldclim.org/data/v1.4/worldclim14.html.

[96] WorldClim. Worldclim 1.4 dataset future conditions: 2050 (average for 2041-2060) and rcp45 - 30 arcsec. WorldClim Data Platform, 2017. URL: https://www.worldclim.org/data/v1.4/cmip5_30s.html.

[97] Valipour Alireza, Yadollahi Mohammadreza, Rosli Mohamad Zin, Nordin Yahaya, and Norhazilan Md. Noor. An enhanced multi-objective optimization approach for risk allocation in public–private partnership projects: a case study of Malaysia. 41(2):164–177, 2014. doi:10.1139/cjce-2013-0342.

[98] Michael Wiedenbeck and Cornelia Züll. Clusteranalyse. pages 525–552. Verlag für Sozialwissenschaften, 2010. doi:10.1007/978-3-531-92038-2_21.

[99] Katrin Lammers, Paul Bertheau, and Philipp Blechinger. Exploring requirements for sustainable energy supply planning with regard to climate resilience of Southeast Asian islands. *Energy Policy*, 146:111770, 2020. doi:10.1016/j.enpol.2020.111770.

[100] Luis Angel García-Escudero, Alfonso Gordaliza, Carlos Matrán, and Agustín Mayo-Iscar. A review of robust clustering methods. 4(2-3):89–109, 2010. doi:10.1007/s11634-010-0064-5.

[101] Naomi C. Brownstein, Andreas Adolfsson, and Margareta Ackerman. Descriptive statistics and visualization of data from the R datasets package with implications for clusterability. *Data in Brief*, 25:104004, 2019. doi:10.1016/j.dib.2019.104004.

[102] Leonard Kaufman and Peter J. Rousseeuw. Partitioning around medoids (program PAM). In *Finding Groups in Data: An Introduction to Cluster Analysis*, Wiley Series in Probability and Statistics, pages 68–125. John Wiley & Sons, Inc., 1990. doi:10.1002/9780470316801.ch2.

[103] Samuel Watchueng, Adrien Jacob, and Romain Frandji. Planning tools and methodologies for rural electrification. In *Tools and technologies for rural electrification*, 2010. URL: https://www.wame2030.org/files/catalogue/2019/4/CLUBER_3_outilplanif_gb_bd_1.pdf.

[104] Offgridders. Offgridders simulates user-defined electricity supply system, 2021. URL: https://offgridders.readthedocs.io/en/latest/Home.html.

[105] Tom Lambert, Paul Gilman, and Peter Lilienthal. Micropower system modeling with Homer. pages 379–418. John Wiley & Sons, Inc., 2006. doi:10.1002/0471755621.ch15.

[106] Andreas Witzel. Das problemzentrierte Interview, in, Jüttemann, G.(Hg.). *Qualitative Forschung in der Psychologie*, 1985. doi:10.1007/978-3-8349-9258-1_29.

[107] Catherine Marshall and Gretchen B Rossman. *Designing qualitative research.* Sage publications, 2014. URL: https://us.sagepub.com/hi/nam/designing-qualitative-research/book274291.

[108] David Kergel. Qualitative Sozialforschung. pages 43–76. Springer Fachmedien Wiesbaden, 2017. doi:10.1007/978-3-658-18587-9_3.

[109] Homer Energy. HOMER-hybrid renewable and distributed generation system design software, 2021. URL: http://www.homerenergy.com.

[110] Shady Abdel Aleem, Mohd Mohd Rozlan, and Ahmed Zobaa. The optimisation of stand-alone hybrid renewable energy systems using HOMER. *International Review of Electrical Engineering*, 6, 2011. URL:

https://www.researchgate.net/publication/259176242_The_Optimisation_of_Stand-Alone_Hybrid_Renewable_Energy_Systems_Using_HOMER.

[111] Jann Michael Weinand, Fabian Scheller, and Russell McKenna. Reviewing energy system modelling of decentralized energy autonomy. *Energy*, 203:117817, 2020. doi:10.1016/j.energy.2020.117817.

[112] Tensay Hadush Meles. Impact of power outages on households in developing countries: Evidence from Ethiopia. *Energy Economics*, 91:104882, 2020. doi:10.1016/j.eneco.2020.104882.

[113] Lamessa Tariku Abdisa. Power outages, its economic cost and firm performance: Evidence from Ethiopia. *MPRA Paper*, 2018. URL: https://mpra.ub.uni-muenchen.de/88217/.

[114] W. Pattaraprakorn P. Teansri, R. Bhasaputra and P. Bhasaputra. Outage cost of industries in Thailand by considering Thailand Standard Industrial Classification. *GMSARN International Journal*, 2010. URL: http://gmsarnjournal.com/home/wp-content/uploads/2015/08/vol4no1-5.pdf.

[115] Siriprapa Panya, Woraratana Pattaraprakorn, Thanet Detmote, Panuwat Teansri, and Pornrapeepat Bhasaputra. Economic impact of power outage in Thailand: Industry perspectives. In *Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010)*, pages 1–7, 2010. doi:10.1109/ESD.2010.5598792.

[116] David Barua Yap II. Policy brief on energy: The costs of power outages in the Philippines. *Office of Senator Win Gatchalian*, 2016. URL: https://wingatchalian.com/wp-content/uploads/2017/01/Policy-Brief_Cost-of-Power-Outages.pdf.

[117] City Population. Philippines: Mindanao: Population census 2020-05-01, 2020. URL: https://www.citypopulation.de/en/philippines/mindanao/admin/.

[118] Scott Kulp and Benjamin H. Strauss. Global DEM errors underpredict coastal vulnerability to sea level rise and flooding. *Frontiers in Earth Science*, 4, 2016. doi:10.3389/feart.2016.00036.

[119] Nadia Bloemendaal, Ivan D. Haigh, Hans de Moel, Sanne Muis, Reindert J. Haarsma, and Jeroen C. J. H. Aerts. Generation of a global synthetic tropical cyclone hazard dataset using STORM. *Scientific Data*, 7(1), 2020. doi:10.1038/s41597-020-0381-2.

[120] Hylke E. Beck, Niklaus E. Zimmermann, Tim R. McVicar, Noemi Vergopolan, Alexis Berg, and Eric F. Wood. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5(1), 2018. doi:10.1038/sdata.2018.214.

[121] ILF Consulting Engineers (Asia). Hybridization of islands, Thailand. Feasibility study Koh Bulon Don. Technical report, ILF and GIZ, 2017. URL: https://www.thai-german-cooperation.info/admin/uploads/publication/1abee3f638e3d26c361e10c9a25a2c8fen.pdf.

[122] Michael Bauer Research GmbH Esri. Myanmar average household size. Map Service, 2020. URL: https://www.arcgis.com/home/item.html?id=2ddfa19b912f4d0f85c9246d88b05793.

[123] Michael Bauer Research GmbH Esri. Thailand average household size. Map Service, 2020. URL: https://www.arcgis.com/home/item.html?id=8658f09cf1ae4a44aaa813fbb687b59f.

[124] Emília Inês Come Zebra, Henny J. van der Windt, Geraldo Nhumaio, and André P.C. Faaij. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*, 144:111036, 2021. doi:10.1016/j.rser.2021.111036.

[125] Sarah Berendes, Paul Bertheau, and Philipp Blechinger. Sizing and optimization of hybrid mini-grids with microgrids - an open-source modelling tool. *3rd International Hybrid Power Systems Workshop*, 2018. URL: https://hybridpowersystems.org/wp-content/uploads/sites/9/2018/05/2B_1_TENE18_062_paper_Berendes_Sarah.pdf.

[126] Michael Bauer Research GmbH Esri. Vietnam average household size. Map Service, 2020. URL: https://www.arcgis.com/home/item.html?id=80ffd900e5284873995b4e4ffb0e1d62.

[127] Rebekah Shirley and Daniel Kammen. Energy planning and development in Malaysian Borneo: Assessing the benefits of distributed technologies versus large scale energy mega-projects. *Energy Strategy Reviews*, 8:15–29, 2015. doi:10.1016/j.esr.2015.07.001.

[128] Chris Greacen Bernard Tenenbaum and Dipti Vaghela. Mini-grids and arrival of the main grid - lessons learnt from Cambodia, Sri Lanka and Indonesia. Technical report, ESMAP, 2017. URL: https://openknowledge.worldbank.org/handle/10986/29018.

[129] M.H. Ashourian, S.M. Cherati, A.A. Mohd Zin, N. Niknam, A.S. Mokhtar, and M. Anwari. Optimal green energy management for island resorts in Malaysia. *Renewable Energy*, 51:36–45, 2013. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960148112005265, doi:10.1016/j.renene.2012.08.056.

[130] George William Hong and Naoya Abe. Sustainability assessment of renewable energy projects for off-grid rural electrification: The Pangan-an island case in the Philippines. *Renewable and Sustainable Energy Reviews*, 16(1):54–64, 2012. doi:10.1016/j.rser.2011.07.136.

[131] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Renewable energy hybrid grid systems for Thai islands - project report. Technical report, GIZ, 2018. URL: http://www.thai-german-cooperation.info/download/public-report_5s.pdf.

[132] Francesco Fuso Nerini, Roger Dargaville, Mark Howells, and Morgan Bazilian. Estimating the cost of energy access: The case of the village of Suro Craic in Timor Leste. *Energy*, 79:385–397, 2015. doi:10.1016/j.energy.2014.11.025.

[133] Tanai Potisat, Dan Pezim, and Gabriel Veilleux. Koh Jik Recharge. Online - https://www.kohjikrecharge.com/, 2018. URL: https://www.kohjikrecharge.com/.

Appendix A

Appendix

A.1 Island Case Study Review

I started my research in analysing the research gap. I found literature stating the missing link between energy planning and climate change impact (e.g. [14, 22]). Focusing on Southeast Asian islands, I 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 [127]. For the studies I identified, 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, I 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”

I limited the 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, I 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. I thus identified 5 studies including 13 cases (locations) out of the previously screened papers (abstract reading and keyword search). I also included 4 additional cases from my personal project experience in Thailand. A detailed overview of all included case studies in given in the tables below.

Table A.1: Overview of island case studies identified in literature review, part I

INDONESIA					
Name	Size	Location	Type of electricity access	Current power source	Source
Curugagung Village	121 HHs	-6.627132, 107.682756	Mini-grid and grid	Hydro power and grid	[128]
Dompyong Village	40 HHs	-7.92623, 111.7078	Mini-grid and grid	Hydro power and grid	[128]
Seloliman Village	45 HHs	-7.5955, 112.59304	Mini-grid and grid	Hydro power and grid	[128]
Santong Village	N/A	-8.39427, 116.34265	Mini-grid and grid	Hydro power and grid	[128]
Salido-Kecil Village	20 HHs	-1.24801, 100.64217	Mini-grid and grid	Hydro power and grid	[128]
Kabupaten Mojokerto Village	25 HHs	-7.59722, 112.58249	Mini-grid and grid	Hydro power and grid	[128]
Sumba Island, Bakuhau	305 HHs	-9.69934, 119.97405	Mini-grid and grid	Hydro power and grid	[128]

Table A.2: *Overview of island case studies identified in literature review, part II*

MALAYSIA					
Name	Size	Location	Type of electricity access	Current power source	Source
Juara village	30 chalets	2.796247, 104.203634	N/A	N/A	[129]
Pulau Perhentian	N/A	5.90097, 102.75147	Mini-grid	200 kW diesel generator	[129]
Terumbu Layang	N/A	7.3736, 113.82872	Mini-grid	150 kW wind turbine	[129]
Sarawak State	2.47 mil. people	1.55327, 110.35921	Grid	Diesel, coal, natural gas and hydro power	[127]
PHILIPPINES					
Name	Size	Location	Type of electricity access	Current power source	Source
Pangan-an island	375 HHs	10.220132, 124.039032	Mini-grid and private diesel generators	PV, diesel and battery	[130]

Table A.3: Overview of island case studies identified in literature review, part III

THAILAND					
Name	Size	Location	Type of electricity access	Current power source	Source
Bulon Don island	81 HHs	6.856191, 99.593076	SHS and private HH diesel generators	PV, diesel, battery	[131]
Bulon Lae island	79 HHs, 11 resorts	6.829273, 99.535025	SHS and private HH diesel generators	PV, diesel, battery	[131]
Jik island	400 people	12.292714, 102.238743	Mini-grid	PV, diesel, battery	[133]
Mak Noi island	250 HHs	8.287294, 98.586723	SHS and private diesel mini-grids	PV, diesel, battery	[121]
TIMOR-LESTE					
Name	Size	Location	Type of electricity access	Current power source	Source
Suro Craic Village	350 HHs	-9.059372, 125.545073	SHS and private diesel generators	PV and diesel	[132]

A.2 Digital Files

Under the following link, the accompanying digital files important to understand and follow this research, is provided:

https://dataverse.harvard.edu/dataverse/ResEnergySEA

They are divided by the two overarching topics of this research (I: Climate change risk assessment and II: Resilient energy system planning) and include:

- QGIS, R and Excel files supporting the climate change risk assessment (I),
- Expert interview evaluation documents (II),
- HOMER files to all modelled scenarios for three case study islands and input parameter tables (II), and
- Excel files of evaluation scenarios for three case study islands (II).

The data and files are published on Harvard Dataverse under Creative Commons Zero ("CC0"). For citation, a DOI is provided.

A.3 Interview Guidelines

A.3.1 Experts

Group "experts"

INTRODUCTION

- *Brief* ***introduction of Katrin and Tim***
- **Introduction of research we are working on**
- **SHOW PRESENTATION**
    - The interview takes place in the framework of a research project at Reiner Lemoine Institut, which is a leading research institute in the area of implementing RE worldwide
    - The name of the research project is **„Increasing Climate resilience of island communities in Southeast Asia"**
    - The **overall aim** of the research project is to study the increase in climate resilience of island communities in Southeast Asia by providing reliable access to electricity.
    - The objective of this interview is to identify impacts and appropriate adaptation measures to improve the design of energy systems with regard to impacts of climate change

- I would like to say a few words about the **structure of the interview**.
- The interview will have **three parts**. The **three parts have different kinds of questions** and at the beginning of each part I will explain the specifics in more detail.

- We try to keep the interview duration to one hour. However, the exact duration depends a bit on the length and detail of each answer. That is why we quickly want to crosscheck your **time availability**, for better time keeping. When do you need to leave the interview latest?

- Before we proceed onto the first question, in which I will ask you to introduce yourself, I would like to ask for your **permission to record this interview. The recordings will in no way be made public.** This will allow us a detailed analysis of the outcomes. Do you feel comfortable with this?
- **START RECORDING**
- **Confirm recording** and can you be **quoted**?
- Furthermore, I would like to point out that you may withdraw from this interview at any time.
- Do you have any **questions**? If you are ready, I would like to **start** with the first question?

INTERVIEW QUESTIONS – PART A

For the very first question, I would like to briefly ask you introduce yourself.

[Introduction part A]
In this first part of the interview, we would like to ask you some broadly framed questions to gain fundamental insights into the research subject. You may take time to answer the questions comprehensively.

A.1 What is your view of climate change impacts on energy systems on Southeast Asian islands?

A.2
Do you know of projects that incorporate considerations regarding the risk of climate change into off-grid energy system planning?

> **[if yes:] A.2.1** How do these projects incorporate the risk of climate change into off-grid energy system planning?

RISK ASSESSMENT

A.3 Based on your experience what kind of climate change risk assessment is **currently** applied in the context of off-grid energy system planning?

> **[follow-up:] A.3.1** Do you think this is sufficient?
> **[if no:] A.3.2** From your point of view, what are the reasons for the insufficient risk assessment?

A.4 Based on your experience what kind of climate change risk assessment **should ideally** be applied in the context of off-grid energy system planning?

IMPACT AND ADAPTATION MEASURES

A.5 In your opinion, what kind of measures have the potential to reduce climate change risks of off-grid energy systems? *(if not included in answer, ask technical measures)*

A.6 What are the technical and economic limits to implement these measures?

A.7 In your point of view, what are the effects of climate change on the demand? (load curve)

> **[follow-up:] A.7.1** Are these effects currently considered in energy system planning?
> **[if no:] A.7.2** Should these effects be considered in energy system planning?

A.8 In your point of view, what are the effects of climate change on power generation?

> **[follow-up:] A.8.1** Are these effects currently considered in energy system planning?
> **[if no:] A.8.2** Should these effects be considered in energy system planning?

INTEGRATION OF CLIMATE RESILIENCE IN SYSTEM PLANNING

A.9 Based on your experience, what are ways to measure and evaluate climate resilience of energy systems?

A.10 Do you think it is possible to formulate an economic value for climate resilience?
[example]
insurances: cost for insuring the energy system

A.11 In your view, how do we establish and mainstream the integration of climate resilience considerations in energy system planning?

Closed-Ended Questions – Part B

We have now arrived at part B of the interview, in which we would like to gain deeper insights into selected aspects of the research subject. In order to gain a holistic understanding of the subject at hand we will ask a series of specific question considering different components of the energy system.

Adjusted Component Prices

In this section we would like you to estimate the additional investment cost required to ensure climate resilience of each individual component. Under the precondition that a certain risk category is relevant in a region, please rank the change in initial investment cost required for each of the following components according the given options.

B.3 How would you estimate the additional investment cost for:

B.3.1 solar generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.2 hydro generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.2 wind generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.3 diesel generator

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.5 grid

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.6 power house

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.7 inverter

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.8 batteries

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

For the following section we would like to ask you for an estimation

B.3.8 How would you estimate the average additional investment cost for a decentral system setup as opposed to a central system set up?

B.3.9 How would you estimate the additional investment cost for the integration of emergency point infrastructure?

B.3.10 Are there any additional investment costs that are not covered by the components listed before?

[If yes:] Please describe in detail.

Adjusted Demand/Generation

In the next section we would like you to give estimations on the effect of climate change on the power demand and power generation. Please choose one of the given answer options.

B.4 How would you estimate the change in the base load due to climate change effects within the next 30 years?

No Change ☐ | Decrease ☐ | Increase ☐ ⇨ up to 5% ☐ | up to 10% ☐ | up to 15% ☐ | up to 20% ☐ | >20% ☐

B.5 How would you estimate the change in peak load due to climate change effects within the next 30 years?

No Change ☐ | Decrease ☐ | Increase ☐ ⇨ up to 5% ☐ | up to 10% ☐ | up to 15% ☐ | up to 20% ☐ | >20% ☐

B.6 How would you estimate the change in efficiency of the energy system due to climate change effects within the next 30 years?

No Change ☐ | Decrease ☐ | Increase ☐ ⇨ up to 5% ☐ | up to 10% ☐ | up to 15% ☐ | up to 20% ☐ | >20% ☐

B.7 How do you think the required days of autonomy of the energy system will change over the next 30 years?

No Change ☐ | Decrease ☐ | Increase ☐ ⇨ up to 5% ☐ | up to 10% ☐ | up to 15% ☐ | up to 20% ☐ | >20% ☐

INTERVIEW QUESTIONS – PART C (Comparison)

We have reached the last section of the interview. In this section we would like you to rank four statements. ***For any of the questions it also fine to not give an answer at all****.*

C.1 From your point of view, how important is access to reliable electricity supply for increased resilience for the island communities?

no answer ☐ | Very important ☐ || important ☐ || moderately important ☐ || slightly important ☐ || not important ☐

C.2 From your point of view, how strong are the impacts of climate change on energy systems on Southeast Asian islands? [only ask if details were given in B.7]

no answer ☐ | Very strong impact ☐ || strong impact ☐ || moderate impact ☐ || slightly impact ☐ || no impact ☐

C.3 To which degree are climate change impacts currently integrated in energy system planning?

no answer ☐ | Very high degree ☐ || high degree ☐ || moderately degree ☐ || slightly degree ☐ || no degree ☐

A.3.2 Technology provider

Group “project developer/ utilities (energy cooperatives)/ technology provider”

INTRODUCTION

- *Brief* ***introduction of Katrin and Tim***
- **Introduction of research we are working on**
- **SHOW PRESENTATION**
  - The interview takes place in the framework of a research project at Reiner Lemoine Institut, which is a leading research institute in the area of implementing RE worldwide
  - The name of the research project is **„Increasing Climate resilience of island communities in Southeast Asia“**
  - The **overall aim** of the research project is to study the increase in climate resilience of island communities in Southeast Asia by providing reliable access to electricity.
  - The objective of this interview is to identify impacts and appropriate adaptation measures to improve the design of energy systems with regard to impacts of climate change

- I would like to say a few words about the **structure of the interview**.
- The interview will have **three parts**. The **three parts have different kinds of questions** and at the beginning of each part I will explain the specifics in more detail.

- We try to keep the interview duration to one hour. However, the exact duration depends a bit on the length and detail of each answer. That is why we quickly want to crosscheck your **time availability**, for better time keeping. When do you need to leave the interview latest?

- Before we proceed onto the first question, in which I will ask you to introduce yourself, I would like to ask for your **permission to record this interview. The recordings will in no way be made public.** This will allow us a detailed analysis of the outcomes. Do you feel comfortable with this?
- **START RECORDING**
- **Confirm recording** and can you be **quoted**?
- Furthermore, I would like to point out that you may withdraw from this interview at any time.

Do you have any **questions**? If you are ready, I would like to **start** with the first question?

INTERVIEW QUESTIONS - PART A

For the very first question, I would like to briefly ask you introduce yourself.

[Introduction part A]

In this first part of the interview, we would like to ask you some broadly framed questions to gain fundamental insights into the research subject. You may take time to answer the questions comprehensively.

A.1 From your point of view, what are the main challenges in energy system planning, which are a result of climate change?

A.2 Do you have experience with projects in which damages of energy system components or economic losses in general could directly be linked to climate change?

- **[If yes:] A.2.1** Please give an overview.

A.3 Are you currently including climate change in energy system planning?

- **[If yes:] A.3.1** Please give an overview.
  - **[follow-up A.3.1.1]** Do you think this is sufficient?
  - **[If no:] A.3.1.2]** In your opinion, what are the barriers of sufficiently including climate change in energy system planning?
- **[If no:] A.3.2** In your opinion, why is climate change currently not included in energy system planning at your company?

A.4 In your opinion, what kind of measures have the potential to reduce climate change risks on off-grid energy systems?

- **[if not included in answer, ask technical measures]**

A.5 What are the technical and economic limits to implement these measures?

A.6 From your point of view, what are possible effects of climate change on the power demand? / change in operation of technical devices

- **[specification]**
  - What change in the operation of technical devices do you expect?
- **[if not included in answer, ask about base load]**
- **[if not included in answer, ask about peak load]**

A.7 From your point of view, what are possible effects of climate change on power generation?

INTERVIEW QUESTIONS - PART B

We have now arrived at part B of the interview, in which we would like to gain deeper insights into selected aspects of the research subject. In order to gain a holistic understanding of the subject at hand we will ask a series of specific question considering different components of the energy system.

[introduction]
Based on what you have reported earlier, I would like to go into more detail about the environmental impacts on the energy system on the island.

B.1 Do you have experience with or information on climate change related damages of the energy system

☐ Yes ☐ No

↓ (Yes) ⇨ (No) **B.2**

B.1.1 Do you have experience with damages effecting **solar power generation**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.2 Do you have experience with damages effecting **hydro power generation**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.3 Do you have experience with damages effecting **wind power generation**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

Follow up questions F.1 – F.7
F.1 In what way was the component damaged?
F.2 What was the cause of the damage?
F.3 Where you able to repair the damage?
  If yes: F.3.1 What was the cost of the repair?
F.4 Was a replacement required?
  If yes: F.4.1 What was the cost of the replacement?
F.5 Did you change the system design as a consequence?
  If yes: F.5.1 What was the cost of the system adjustment?
F.6 What was the financial loss as a result of the damage?
F.7 How long did it take until the system was back to normal operation?

B.1.4 Do you have experience with damages effecting **the diesel generator**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.5 Do you have experience with damages effecting the **battery storage**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.6 Do you have experience with damages effecting the **grid**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.7 Do you have experience with damages effecting the **inverter**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

B.1.8 Do you have experience with damages effecting the **power house**?

☐ Yes ☐ No Yes ⟹ F.1 – F.7

Follow up questions F.1 – F.7

F.1 In what way was the component damaged?
F.2 What was the cause of the damage?
F.3 Where you able to repair the damage?
  If yes: F.3.1 What was the cost of the repair?
F.4 Was a replacement required?
  If yes: F.4.1 What was the cost of the replacement?
F.5 Did you change the system design as a consequence?
  If yes: F.5.1 What was the cost of the system adjustment?
F.6 What was the financial loss as a result of the damage?
F.7 How long did it take until the system was back to normal operation?

Adaptation Measures

Based on what you have described in the previous section of the interview, we would like to dive deeper into possible adaptation measures regarding climate change.

B.2 Do you have experience with or information on adaptation measures to increase the energy systems' climate resilience within your projects?

☐ Yes ☐ No

↓ Yes; No ⇒ **B.3**

B.2.1 Do you have experience with adaptation measures regarding **solar generation**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.2 Do you have experience with adaptation measures regarding **wind generation**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.3 Do you have experience with adaptation measures regarding **diesel generation**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.4 Do you have experience with adaptation measures regarding the **hydro generation**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.5 Do you have experience with adaptation measures regarding the **grid?**

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.6 Do you have experience with adaptation measures regarding the **power house**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.7 Do you have experience with adaptation measures regarding the **inverter**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

B.2.8 Do you have experience with adaptation measures regarding the **batteries**?

☐ Yes ☐ No Yes ⟹ G.1 – G.4

Follow-up questions G.1 – G.4
[make note of all given technical measures to be able to specify]
G.1 Which technical measures exist?
[specify for each measure]
G.2 When should this measure be applied?
G.3 Which challenge does it solve?
G.4 What is the cost of the measure?

Adjusted Component Prices

In this section we would like you to estimate the additional investment cost required to ensure climate resilience of each individual component. Under the precondition that a certain risk category is relevant in a region, please rank the change in initial investment cost required for each of the following components according the given options.

B.3 How would you estimate the additional investment cost for:

B.3.1 solar generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.2 hydro generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.2 wind generation

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.3 diesel generator

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.5 grid

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.6 power house

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.7 inverter

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.8 batteries

	no answer	no increase	up to 10%	up to 20%	up to 30%	up to 40%	>40%
storms	☐	☐	☐	☐	☐	☐	☐
sea level rise	☐	☐	☐	☐	☐	☐	☐
precipitation	☐	☐	☐	☐	☐	☐	☐

B.3.9 How would you estimate the average additional investment cost for a decentral system setup as opposed to a central system set up?

B.3.10 How would you estimate the integration of emergency points emergency point?

B.3.11 Are there any additional investment costs that are not covered by the components listed before?

[If yes:] Please describe in detail.

Demand and Generation

In the next section we would like you to give estimations on the effect of climate change on the power demand and power generation. Please choose one of the given answer options.

B.4 How would you estimate the change in the base load due to climate change effects within the next 30 years?

No Change	Decrease	Increase	⇨	up to 5%	up to 10%	up to 15%	up to 20%	>20%
☐	☐	☐		☐	☐	☐	☐	☐

B.5 How would you estimate the change in peak load due to climate change effects within the next 30 years?

No Change	Decrease	Increase	⇨	up to 5%	up to 10%	up to 15%	up to 20%	>20%
☐	☐	☐		☐	☐	☐	☐	☐

B.6 How would you estimate the change in efficiency of the energy system due to climate change effects within the next 30 years?

No Change	Decrease	Increase	⇨	up to 5%	up to 10%	up to 15%	up to 20%	>20%
☐	☐	☐		☐	☐	☐	☐	☐

B.7 How do you think the required days of autonomy of the energy system will change over the next 30 years?

No Change	Decrease	Increase	⇨	up to 5%	up to 10%	up to 15%	up to 20%	>20%
☐	☐	☐		☐	☐	☐	☐	☐

A.3.3 Island community

Group “island community”

INTRODUCTION

- *Brief* ***introduction of Katrin and Tim***
- **Introduction of research we are working on**
- **SHOW PRESENTATION**
  - The interview takes place in the framework of a research project at Reiner Lemoine Institut, which is a leading research institute in the area of implementing RE worldwide
  - The name of the research project is **„Increasing Climate resilience of island communities in Southeast Asia“**
  - The **overall aim** of the research project is to study the increase in climate resilience of island communities in Southeast Asia by providing reliable access to electricity.
  - The objective of this interview is to identify impacts and appropriate adaptation measures to improve the design of energy systems with regard to impacts of climate change

- I would like to say a few words about the **structure of the interview**.
- The interview will have **three parts**. The **three parts have different kinds of questions** and at the beginning of each part I will explain the specifics in more detail.

- We try to keep the interview duration to one hour. However, the exact duration depends a bit on the length and detail of each answer. That is why we quickly want to crosscheck your **time availability**, for better time keeping. When do you need to leave the interview latest?

- Before we proceed onto the first question, in which I will ask you to introduce yourself, I would like to ask for your **permission to record this interview. The recordings will in no way be made public.** This will allow us a detailed analysis of the outcomes. Do you feel comfortable with this?
- **START RECORDING**
- **Confirm recording** and can you be **quoted**?
- Furthermore, I would like to point out that you may withdraw from this interview at any time.

Do you have any **questions**? If you are ready, I would like to **start** with the first question?

INTERVIEW QUESTIONS - PART A

For the very first question, I would like to briefly ask you introduce yourself.

[Introduction part A]
In this first part of the interview, we would like to ask you some broadly framed questions to gain fundamental insights into the research subject. You may take time to answer the questions comprehensively.

A.1 What environmental impacts do you observe on the island?
[clarification if required]
For example impacts due to…

- Strong winds and storms
- Heavy rain
- Exceptionally high temperatures
- Exceptionally low temperatures
- Sea-Level Rise
- Rising tides
- Dry periods
- Others (please specify)

A.2 What are the main challenges that arise from the environmental impacts that you have described?

A.3 In which way do environmental impacts affect the energy system on the island? Please explain in detail.

A.4 In what way is energy generated on your island?

only RE	diesel and RE	only diesel	SHS
☐	☐	☐	☐

A.5 Roughly how many households used the energy system?
____

INTERVIEW QUESTIONS - PART B

CLIMATE CHANGE IMPACTS

[introduction]
Based on what you have reported, I would like to go into more detail about occurring impacts of the environment.
*The following part of the interview will contain a combination of primary questions and follow-up questions. The **primary questions are yes/no** questions. For each follow-up questions five answers to choose from are given.*

B.1 Do strong storms occur on the island?

Yes	||	No
☐		☐

[if yes: follow-up question B.1.1, if no continue with B.2]
B.1.1 How often do strong storms occur?
Please choose one of the following answers:

more than every 5 years ||	every 3-5 years ||	every 1-2 years ||	every year ||	less than one time a year
☐	☐	☐	☐	☐

[follow-up question]
B.1.2 In the last 10 years, have you noticed a change in the frequency with which storms occur?
Please choose one of the following answers: The frequency, with which storms occur has...

decrease ||	remained roughly the same ||	increased
☐	☐	☐

B.2 Does it happen that parts of the island are flooded?
[clarification if required]
Definition of flooding: covering or submerging of normally dry land with a large amount of water

Yes	||	No
☐		☐

[if yes: follow up question B.2.1, if no continue with B.3]
B.2.1 How often are parts of the island flooded?
Please choose one of the following answers:

more than every 5 years ||	every 3-5 years ||	every 1-2 years ||	every year ||	less than one time a year
☐	☐	☐	☐	☐

[follow-up question]
B.2.2 In the last 10 years, have you noticed a change in the frequency with which floods occur?
Please choose one of the following answers: The frequency, with which floods occur has...

decrease ||	remained roughly the same ||	increased
☐	☐	☐

B.3 Do you experience periods of dry weather on the island, which are causing fresh water scarcity or agricultural challenges?

Yes	||	No
☐		☐

↳ **[if yes: follow-up question B.3.1, if no continue with B.4]**
B.3.1 How often do you face the problem of insufficient clean water?
Please choose one of the following answers:

more than every 5 years	every 3-5 years	every 1-2 years	every year	less than one time a year
☐	☐	☐	☐	☐

[follow-up question]
B.3.2 In the last 10 years, have you noticed a change in the frequency with which periods with dry weather occur
Please choose one of the following answers: The frequency, with which periods of dry weather occur has…

decrease	remained roughly the same	increased
☐	☐	☐

B.4 Based on your experience, is there an increase in extreme temperatures?

Yes	||	No
☐		☐

↳ **[if yes: follow-up question B.4.1, if no continue with B.5]**
B.4.1 How often do you face extreme temperatures?
Please choose one of the following answers:

more than every 5 years	every 3-5 years	every 1-2 years	every year	less than one time a year
☐	☐	☐	☐	☐

B.5 Has the sea level /tide changed (e.g. within the last 10 years)?

Yes	||	No
☐		☐

↳ **[if yes: follow-up question B.5.1, if no continue with B.6]**
B.5.1 Can you give an estimation how much?
____

B.6 Are there times in which it is not possible to leave the island because of the weather conditions?

Yes	||	No
☐		☐

[if yes: follow-up question B.6.1, if no: continue with introduction B]

B.6.1 How often does it happen, that you are not able to leave the island because of weather conditions?

Please choose one of the following answers:

more than every 5 years	every 3-5 years	every 1-2 years	every year	less than one time a year
☐	☐	☐	☐	☐

B.6.2 Do you have the feeling that the frequency of times when it is not possible to leave the island by boat is increasing?

Yes	||	No
☐		☐

CLIMATE CHANGE IMPACTS ON ENERGY SYSTEMS – B

[introduction]

Based on what you have reported earlier, I would like to go into more detail about the environmental impacts on the energy system on the island.

B.7 Do you have experience with or information on climate change related damages of the energy system

Yes	||	No
☐		☐

[If yes:]

B.7.1 Do you have experience with damages effecting **solar power generation**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7 (at the bottom of the page), if no: continue with B.7.2]

B.7.2 Do you have experience with damages effecting **hydro power generation**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7, if no: continue with B.7.3]

B.7.3 Do you have experience with damages effecting **wind power generation**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7 if no: continue with B.7.4]

B.7.4 Do you have experience with damages effecting **the diesel generator**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7 if no: continue with B.7.5]

Follow up questions F.1 – F.7

F.1 In what way was the component damaged?

F.2 What was the cause of the damage?

F.3 Where you able to repair the damage?

  If yes: F.3.1 What was the cost of the repair?

F.4 Was a replacement required?

  If yes: F.4.1 What was the cost of the replacement?

F.5 Did you change the system design as a consequence?

  If yes: F.5.1 What was the cost of the system adjustment?

F.6 What was the financial loss as a result of the damage?

F.7 How long did it take until the system was back to normal operation?

B.7.5 Do you have experience with damages effecting the **battery storage**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7; if no: continue with B.7.6]

B.7.6 Do you have experience with damages effecting the **grid**?

Yes	||	No
☐		☐

[If yes: ask the follow up questions F.1 – F.7; if no: continue with B.7.7]

B.7.7 Do you have experience with damages effecting the **inverter**?

Yes	||	No
☐		☐

[If yes: ask the follow-up questions F.1 – F.7; if no: continue with B.7.8]

B.7.8 Do you have experience with damages effecting the **power house**?

Yes	||	No
☐		☐

[If yes: ask the follow-up questions F.1 – F.7; if no: continue with Part C]

Follow up questions F.1 – F.7
F.1 In what way was the component damaged?
F.2 What was the cause of the damage?
F.3 Where you able to repair the damage?
    If yes: F.3.1 What was the cost of the repair?
F.4 Was a replacement required?
    If yes: F.4.1 What was the cost of the replacement?
F.5 Did you change the system design as a consequence?
    If yes: F.5.1 What was the cost of the system adjustment?
F.6 What was the financial loss as a result of the damage?
F.7 How long did it take until the system was back to normal operation?

A.4 Adaptation Measures

Table A.4: *List of adaptation measures as recommended by interviewees, part I*

Component	Risk Type	Measure
Wind generation	Cyclone	Increase structural strength of mast, blades and turbine
		Select component according to compatibility with high wind speeds (mast, blades, turbine)
		Integrate automated mechanisms for vane position
		Integrate back-up diesel generator to apply vane position if needed
Hydro generation	Flood	Increase structural strength of civil work (dams, walls, tubes)
		Include additional protective elements for construction (dams, walls, etc)
		Apply integrative watershed and land use management
		Adjust design standards (e.g. 100-year flood becomes a 20-year flood)
		Integrate upstream water reservoirs to manage water flows more effectively
Solar generation	Cyclones	Implement tracking systems to adjust angles and directions (out of wind force)
		Implement structural protections
		Increase structural strength of mounting structure
		Adjust angle of installation (select a flat angle to reduce wind forces)
		Select most suitable fixing system: stronger clamps or clamps that facilitate easy deinstallation of panels in case of emergency
	Flood	Raise panels above the ground (e.g. through poles)
	Temperature rise	Implement panel cooling mechanisms (e.g. ventilation, combined generation-farming approaches)

Table A.5: *List of adaptation measures as recommended by interviewees, part II*

Component	**Risk Type**	**Measure**
Inverter	Cyclones	Install inverter in power house
		Improve lightning strike protection
		Apply more robust inverter arrangement: e.g. through string inverters instead of central inverters or self-directed inverters instead of grid-directed inverters)
	Flood	Install inverter in power house
	Temperature rise	Install cooling mechanisms in power house (e.g. ventilation, air-conditioning)
Diesel generator	Cyclones	Install generator in power house
	Flood	Install generator in power house
	All	Install generator in accessible area for quick and easy maintenance and repair
Battery storage	Cyclones	Install storage in power house
	Flood	Install storage in power house
	Temperature rise	Install cooling mechanisms in power house (e.g. ventilation, air-conditioning)
	All	Implement alternative storage technologies
Power house	Cyclones	Increase structural strength (walls, roofs, doors)
	Flood	Raise power house above the ground (e.g. through poles)
	Temperature rise	Install cooling mechanisms in power house (e.g. ventilation, air-conditioning)
	All	Select material (concrete, metal, wood) carefully according to site specific parameters
Grid	Cyclones	Increase structural strength of poles
		Select stronger more resistant cables, connectors and insulators
		Choose underground cable installation
	Temperature rise	Adjust sizing of cables

Table A.6: *List of adaptation measures as recommended by interviewees, part III*

Component	**Risk Type**	**Measure**
All components	Cyclones	Perform regular clearing of trees and vegetation around energy infrastructure
	Temperature rise	Select components according to compatibility with high temperatures
	Sea-level rise	Select components according to high salt corrosion resistance
		Select sites of installation carefully considering future shorelines and flooded areas
Overall system	Flood	Build protective walls, dams, ditches and channels to prevent flooded system components
		Install pumps to evacuate water
	All	Put proper demand side management in place
		Design the system as simple as possible
		Hire well-trained local operators
		Consider increased transportation cost of components, spare parts, fuel etc.
		Consider decentral and modular system setups
		Integrate emergency points and satellite phones
		Compile emergency protocols including different scenarios and prioritisation of energy services
		Put proper spare-part management and inventory in place (provision of most important spare parts in stock)
		Select sites of installation carefully and consider accessibility for maintenance and repair
		Select components with high ingress protection (IR) ratings

Table A.7: *List of adaptation measures as recommended by interviewees, part IV*

Risk Type	**Measure**
Flood	Implement climate change resilient planning of public infrastructure (e.g. roads) Develop and improve hydrological forecasting
All	Integrate improved solar radiation predictions considering climate change to design phase
	Select blackout resilient appliances
	Develop guidelines for improved planning and operation
	Develop financial instrument/mechanism to compensate loss and damages
	Implement nature-based and ecosystem oriented solutions
	Apply community-ownership structures