The role of renewable energy for low-carbon development on small Philippine islands – a mixed methods approach

Doctoral thesis submitted to the

Department of Energy and Environmental Management

Europa-Universität Flensburg

In fulfilment of the degree of Dr. rer. pol. in Economics

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Submitted the 10th of June, 2020.

Executive summary

Islands are particularly threatened by the negative effects of climate change, while often heavily dependent on fossil fuels for their power supply. At the same time, many islands are rich in renewable resources and are considered as ideal niche environments for a rapid implementation of renewable energy. The islands of the Philippines combine these characteristics and serve as the case study for this dissertation. The Philippines is an archipelago of more than 7,000 islands and is one of the most affected countries by climate change induced threats such as rising sea levels and an increasing frequency of extreme weather events. While the largest islands form a centralized grid system, most of the smaller islands are either supplied by fossil fuel-based generators or lack formal electricity supply. The dependence on fossil fuels implies high power generation costs, low energy security, environmental pollution and slower socio-economic development on these small islands. The challenge facing these off-grid islands is to both improve electricity supply through the use of renewable energy technologies and provide access to electricity on non-electrified islands in an affordable, reliable and sustainable way.

This dissertation investigates the role of renewable energy for the improvement and provision of power supply in the off-grid island sector of the Philippines. The first objective is the systematic assessment of the cost-effectiveness of renewable energy for the hybridization of existing fossil fuel powered generation capacity as well as the electrification of islands with no formal electricity supply. The second objective is to identify challenges to the deployment of renewable energy based island grids and analyze the impact of renewable energy implementation on local development outcomes and the Sustainable Development Goals. Finally, the purpose of the dissertation is to present suitable approaches and recommendations for the low-carbon development of the Philippine off-grid sector.

An interdisciplinary mixed methods approach combining energy economics and social sciences is applied to address these objectives. The main focus in the field of energy economics is the simulation and optimization of energy supply options to derive investment requirements for cost-benefit analyses. In addition to extensive data collection in the Philippines, geospatial analyses and cluster analyses are used to derive necessary input data for applied economic analyses of energy systems. Quantitative and qualitative methods from the social sciences complement the overall research approach through field research, the development and implementation of a household questionnaire survey, focus group discussions and expert interviews with relevant stakeholders. The research findings are presented along five published peer-reviewed publications of which each contributes a piece to addressing the overall research hypothesis of this dissertation: *Renewable energy based island grids represent a cost-effective, environmentally sound and socially acceptable development pathway for the electricity supply of Philippine islands.*

The results of the paper can be summarized as the following: First, energy system simulations of solar photovoltaic and lithium-ion battery based hybridization of all existing diesel based island grids reveal an average cost reduction potential of 0.02 USD/kWh at an average RE share of 24%, which would mitigate the combustion of more than 100 million liters of diesel fuel annually. The results show that renewable based hybridization is cost-effective under conservative assumptions and without subsidies. Furthermore, scenario and sensitivity analyses applying input parameters more favorable for renewable energy introduction indicate a much larger potential towards a 50% renewable energy share showing the cost-effectiveness of RE solutions compared to fossil fuels.

Second, the development of a geospatial approach for evaluating the investment costs of interconnection of all island grids by means of submarine power cables shows that investment costs would be more than four times higher than those for decentralized renewable energy island

grid development on the national scale. At the sub-national scale, cost comparison across island groups indicates that 7 out of 30 groups could be more cost-effectively interconnected to the main grid. Three island groups are specifically recommended for more detailed investigation of submarine interconnection based on proximity to the grid and high electricity demand. Such grid optimization efforts could reduce subsidy requirements and lead to more efficient allocation of funds for the development of renewable energy power supply systems on other island grids.

Third, geospatial analysis methods are applied to identify a priority list of not-electrified islands relevant for renewable energy island grid development. In total, 649 islands with a population of 650,000 inhabitants are identified, representig 12.5% of the population lacking access to electricity. A comparison of technologies for 100% renewable energy power supply finds solar photovoltaics in combination with lithium-ion battery storage as the main components while wind power is supplementary due to higher seasonality. Power generation costs are in the range of 0.5 – 0.6 USD/kWh under the applied cost assumptions. Decreasing supply reliability by 1% allows for a 20% reduction in generation costs and the use of excess electricity to power deferrable loads, such as water purification or cold storage, holds further potential for cost reduction.

Fourth, a detailed case study of an existing renewable energy island grid reveals that the introduction of renewable energy increased sustainability (high renewable energy share), affordability (50% tariff reduction) and reliability (24/7 power supply) compared to the status quo of diesel power generation. Further, findings from a household survey, covering 70% of all supplied households, suggests that the majority of households perceive a positive impact on access to information and communication, and provision of health and educational services compared to previous power supply. Although the social acceptance of the project is high it is found that wealthier households are more capable of generating new income through the improved power supply which poses a risk of increasing inequality within island communities.

Fifth, focusing on the same case study presented but applying a different perspective, challenges for an electric cooperative in introducing renewable energy to existing energy systems are investigated through expert interviews, surveys and focus group discussions. The findings reveal slow issuance of subsidies and permits, lack of access to capital, and lack of technical expertise as the main challenges for a wider adoption of renewable energy development through electric cooperatives.

The following recommendations can be derived from these research findings: First, policy makers should first determine which off-grid island groups are suitable for interconnection to the centralized grid. This dissertation provides a preliminary approach for this decision-making process and recommends three specific islands groups where detailed feasibility analysis should be conducted. Second, subsidies saved through off-grid island interconnection should be reinvested into the introduction of renewable energy supply in existing diesel-based island grids. The dissertation highlights the cost-effectiveness of such hybridization and additionally indicates islands with the highest cost saving potential. Third, the extension of service hours should be realized through the implementation of renewable energy on smaller islands. Furthermore, the electrification of not-electrified islands should also be conducted with 100% renewable energy systems to avoid further implementation of expensive diesel generators. This dissertation provides detailed information of the location and characteristics of such islands. Finally, electric cooperatives should be equipped with capabilities to implement the aforementioned systems through providing technical expertise, access to capital and streamlining permission processes.

Zusammenfassung

Inseln sind durch die negativen Auswirkungen des Klimawandels besonders bedroht, während sie für ihre Energieversorgung stark von fossilen Brennstoffen abhängig sind. Gleichzeitig sind viele Inseln reich an erneuerbaren Ressourcen und gelten als ideale Nischenumgebungen für eine umfassende Einführung erneuerbarer Energien. Die Philippinen dienen als Fallstudie dieser Dissertation und sind durch die oben genannten Merkmale charakterisiert. Das Land umfasst mehr als 7.000 Inseln und ist eines der am stärksten von den durch den Klimawandel verursachten Bedrohungen betroffenen Ländern, wie dem Anstieg des Meeresspiegels und einer zunehmenden Häufigkeit extremer Wetterereignisse. Während die größten Inseln durch ein zentrales Stromnetz verbunden sind, werden die meisten kleineren Inseln ausschließlich von Dieselgeneratoren versorgt oder haben keinerlei Stromversorgung. Die Abhängigkeit von fossilen Brennstoffen führt zu hohen Stromerzeugungskosten, einer geringen Energiesicherheit, hoher Umweltverschmutzung und verlangsamt die sozioökonomische Entwicklung des Landes. Die Herausforderung auf diesen Inseln, die den Off-Grid-Sektor des Landes bilden, besteht darin, die Stromversorgung durch den Einsatz erneuerbarer Energien zu verbessern und gleichzeitig einen auf erneuerbaren Energien basierenden Zugang zu Strom auf noch nicht elektrifizierten Inseln auf bezahlbare, zuverlässige und nachhaltige Weise zu ermöglichen.

In dieser Dissertation wird daher die Rolle erneuerbarer Energien für die Verbesserung und Bereitstellung der Stromversorgung im Off-Grid-Sektor der Philippinen untersucht. Das erste Ziel ist die systematische Bewertung der Kosteneffektivität erneuerbarer Energien für die Hybridisierung fossiler Brennstoffe und für die Elektrifizierung abgelegener Inseln. Das zweite Ziel ist die Identifizierung von Herausforderungen bei der Einführung von erneuerbaren Energien auf Inselnetzen, die Analyse der Auswirkungen der Einführung erneuerbarer Energien auf die lokale Entwicklung und die *Sustainable Development Goals*. Schlussendlich ist das übergeordnete Ziel der Dissertation, geeignete Ansätze und Informationen für die Entwicklung erneuerbarer Energien im philippinischen Off-Grid-Sektors zu präsentieren.

Um die Ziele zu erreichen, wendet die Dissertation einen interdisziplinären Methodenansatz an, der Energieökonomie und Sozialwissenschaften kombiniert. Schwerpunkt im Bereich der Energieökonomie ist die Simulation und Optimierung von Energieversorgungsoptionen zur Abschätzung des Investitionsbedarfs für Kosten-Nutzen-Analysen. Neben einer umfangreichen Datenerhebung und Stakeholder-Konsultationen auf den Philippinen tragen geografische Analysen und Clusteranalysen zum energieökonomisch basierten Ansatz bei, der eine Inputdatenerhebung und Charakterisierungsanalyse ermöglicht. Der auf den Sozialwissenschaften basierende Schwerpunkt ergänzt den gesamten Forschungsansatz mit quantitativen und qualitativen Methoden. Dazu gehören Feldforschung auf abgelegenen Inseln, die Entwicklung und Durchführung einer Haushaltsumfrage, Fokusgruppendiskussionen und Experteninterviews.

Die Forschungsergebnisse werden anhand von fünf veröffentlichten Publikationen vorgestellt, von denen jede einen Beitrag zur Beantwortung der allgemeinen Forschungshypothese dieser Dissertation leistet: *Auf erneuerbaren Energien basierende Inselnetze stellen einen kostengünstigen, umweltverträglichen und sozialverträglichen Entwicklungspfad für die Stromversorgung der philippinischen Inseln dar*.

Erstens zeigt die Anwendung der Energiesystemsimulation für eine Solar-Photovoltaik- und Lithium-Ionen-Batterie-basierte Hybridisierung aller bestehenden Diesel-Inselnetze ein durchschnittliches Kostensenkungspotenzial von 0,02 USD/kWh bei einem durchschnittlichen Anteil erneuerbarer Energien von 24%. Dadurch könnte die Verbrennung von mehr als 100 Millionen Dieselkraftstoff pro Jahr vermieden werden. Die Ergebnisse zeigen, dass die auf erneuerbaren Energien basierende Hybridisierung unter konservativen Annahmen und ohne

Subventionen kosteneffizient ist. Darüber hinaus weisen Szenario- und Sensitivitätsanalysen, die günstigere Kosten für erneuerbare Energie annehmen, auf ein viel größeres Potenzial in Richtung eines 50%-Anteils erneuerbarer Energien hin.

Zweitens zeigt die Entwicklung eines geografischen Ansatzes zur Abschätzung der Investitionskosten für die Verbindung aller Inselnetze durch Unterwasserkabel, dass die Investitionskosten mehr als viermal so hoch wären wie die Investitionen für die Entwicklung dezentralisierter, auf erneuerbarer Energien basierender Inselnetze auf nationaler Ebene. Ein vereinfachter Kostenvergleich auf einer höher aufgelösten Ebene zeigt jedoch, dass 7 von 30 Inselgruppen kosteneffizienter an das Hauptnetz angeschlossen werden können. Drei dieser Inselgruppen werden für eine detailliertere Untersuchung einer Anbindung an das Hauptnetz, aufgrund der kurzen Distanz der benötigten Verbindung und des hohen Strombedarfs empfohlen. Dadurch könnten Mittel aus einem Subventionsprogramm für die Stromversorgung abgelegener Gebiete, für die Entwicklung erneuerbarer Energien in anderen Inselnetzen freigegeben werden.

Drittens können durch geografische Analysen 649 nicht-elektrifizierte Inseln identifiziert werden, auf denen eine Implementierung von auf erneuerbaren Energien basierenden Inselnetzten sinnvoll erscheint. Diese umfassen eine Bevölkerung von rund 650.000 Einwohnern, was einem Anteil von 12,5% der Bevölkerung ohne Zugang zu Elektrizität auf den Philippinen entspricht. Eine Simulation von 100% erneuerbaren Systemen für die Elektrifizierung zeigt auf, dass Photovoltaik in Kombination mit Lithium-Ionen-Batteriespeichern die Hauptkomponente dieser Systeme ist, während die Windkraft aufgrund von saisonaler Verfügbarkeit nur ergänzend eingesetzt werden kann. Die Stromerzeugungskosten liegen unter den angewandten Kostenannahmen im Bereich von 0,5 - 0,6 USD/kWh. Eine Verringerung der Versorgungszuverlässigkeit um 1% ermöglicht jedoch eine Senkung der Erzeugungskosten um 20% und die Nutzung von überschüssigem Strom durch flexibel einsetzbare elektrische Lasten, wie Trinkwasseraufbereitungsanlagen oder Kühlhäuser, birgt weiteres Potenzial für Kostensenkungen.

Viertens wird durch eine Fallstudienanalyse, die sich auf ein realisiertes erneuerbares Inselnetz konzentriert, gezeigt, dass die Implementierung erneuerbarer Energien die Nachhaltigkeit (hoher Anteil erneuerbarer Energien), Bezahlbarkeit (50 % Tarifsenkung) und Zuverlässigkeit (24/7-Stromversorgung) im Vergleich zum Status quo der Dieselstromerzeugung erhöht. Darüber hinaus zeigen die Ergebnisse der Haushaltsbefragung, die 70% aller versorgten Haushalte abdeckt, dass die Mehrheit der Haushalte eine positive Auswirkung auf den Zugang zu Information und Kommunikation sowie auf die Bereitstellung von Gesundheits- und Bildungsdienstleistungen wahrnimmt. Obwohl die soziale Akzeptanz des Projekts hoch ist, wird festgestellt, dass wohlhabendere Haushalte durch die verbesserte Stromversorgung eher in der Lage sind, neues Einkommen zu generieren, was die Gefahr einer zunehmenden Ungleichheit innerhalb der Inselgemeinschaften birgt.

Fünftens, basierend auf derselben Fallstudie jedoch mittels anderer Perspektiven, werden die Herausforderungen für eine Stromgenossenschaft bei der Implementierung erneuerbarer Energien durch Experteninterviews, Umfragen und Fokusgruppendiskussionen untersucht. Die Ergebnisse zeigen, dass die langsame Vergabe von Subventionen und Genehmigungen, der mangelnde Zugang zu Kapital und der Mangel an technischem Fachwissen die Hauptherausforderung für eine breitere Einführung der Entwicklung erneuerbarer Energien durch Stromgenossenschaften darstellen.

Schließlich werden auf der Grundlage der Forschungsergebnisse Empfehlungen abgeleitet: Zunächst sollten die politischen Entscheidungsträger Inseln für den Anschluss an die Hauptnetze definieren. Dafür bietet diese Dissertation einen Kostenbewertungsansatz und empfiehlt spezifische Inseln. Subventionen, die durch den Anschluss an das Hauptnetzt eingespart werden, sollten in die Implementierung erneuerbarer Energien auf bestehenden Inselnetzen reinvestiert werden. Die Dissertation hebt die Kosteneffizienz einer solchen Hybridisierung hervor und zeigt zusätzlich Inseln mit dem höchsten Kosteneinsparungspotenzial im Vergleich zur reinen Dieselstromerzeugung auf. Aus dieser Gruppe sollten Inseln mit dem höchsten Strombedarf zuerst in Betracht gezogen werden, um die Minderung der Dieselkraftstoffverbrennung zu maximieren. Eine Verlängerung der Stromversorgungszeiträume sollte durch die Einführung erneuerbarer Energie auf kleineren Inseln realisiert werden, da eine höhere Stromnachfrage das Potential für erneuerbare Energien erhöht. Die Elektrifizierung von nicht versorgten Inseln sollte mit rein erneuerbaren Energiesystemen durchgeführt werden, und diese Dissertation liefert detaillierte Informationen über die Lage und die Eigenschaften dieser Inseln. Wichtig für eine erfolgreiche Umsetzung ist jedoch die Integration von Komponenten, die essentielle Dienstleistungen für abgelegene Gemeinden bereitstellen, wie Trinkwasseraufbereitungsanlagen oder Kühlhäuser, da dadurch die Wirtschaftlichkeit von Elektrifizierungsprojekten verbessert und gleichzeitig zunehmende Ungleichheiten innerhalb der Inselgemeinschaften vermieden werden können. Schließlich sollten Stromgenossenschaften befähigt werden, die vorgestellten Systeme umzusetzen, was durch die Bereitstellung von technischem Fachwissen, Zugang zu Kapital und die Rationalisierung von Genehmigungsverfahren ermöglicht werden kann.

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List of appended publications

No.	Title	Journal	Type/ Impact factor (2020)	Status	Position/ Authors	Score Europa-Universität Flensburg
1	Resilient solar energy island supply to support SDG7 on the Philippines: Techno-economic optimized electrification strategy for small islands	Utilities Policy	Peer-reviewed journal (2.417)	Published	1/2	0.67
2	Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options	Applied Energy	Peer-reviewed journal (8.426)	Published	1/2	0.67
3	Supplying not electrified islands with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines	Energy	Peer-reviewed journal (5.537)	Published	1/1	1
4	Assessing the impact of renewable energy on local development and the Sustainable Development Goals: Insights from a small Philippine island	Technological Forecasting & Social Change	Peer-reviewed journal (3.815)	Published	1/1	1
5	Challenges for implementing renewable energy in a cooperative-driven off-grid system in the Philippines	Environmental Innovation and Societal Transition	Peer-reviewed journal (7.514)	Published	1/4	0.4

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Abbreviations and nomenclature

AC	Alternating Current
ADB	Asian Development Bank
ASEP	Access to Sustainable Energy Program
C	Celsius
CO_2	Carbon Dioxide
DU	Distribution Utility
DC	Direct Current
EC	Electric Cooperative
EPIRA	Electric Power Industry Reform Act
ERC	Energy Regulatory Commission
EU	European Union
EUR	Euro (€)
FGD	Focus Group Discussion
FiT	Feed-in-Tariff
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
GHI	Global Horizontal Irradiation
GWh	Gigawatt Hour
HH	Household
INDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
km	Kilometer
kV	Kilovolt
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
LGU	Local Government Unit
Li-ion	Lithium-ion
MLP	Multi-Level-Perspective
MW	Megawatt
MWh	Megawatt Hour
MWp	Megawatt Peak
NAMRIA	National Mapping and Resource Information Authority of the Philippines
NEA	National Electrification Administration

NPC	National Power Corporation
NPC-SPUG	National Power Corporation – Small Power Utilities Group
NPP	New Power Producer
PRES	Philippine Rural Electrification System Project
PV	Photovoltaics
QGIS	Quantum Geographic Information System
QTP	Qualified Third Party
RE	Renewable Energy
RE Act	Renewable Energy Act
RPS	Renewable Portfolio Standards
RQ	Research question
SAGR	Subsidized approved generation rate
SDG	Sustainable Development Goal
SHS	Solar Home System
SIIG	Small Isolated Island Grid
SPT	Simplified Planning Tool
SPUG	Small Power Utilities Group
TCGR	True Cost of Generation Rate
UCME	Universal Charge for Missionary Electrification
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar ($)

Acknowledgement

This research work would not have been possible without the unconditional support of my supervisors, colleagues and friends for which I am deeply grateful.

First, of all I would like to thank the Reiner Lemoine Foundation for financing my research work with a PhD scholarship. Without this support, the research, in this depth of detail, would not have been possible. Further, I would like to express my sincere gratitude to my two supervisors Prof. Bernd Möller and Prof. Christoph Menke for their important guidance and support during my PhD work and related research. Specially, I would like to thank Dr. Philipp Blechinger for his continuous support, infinite patience and for serving as my key mentor during this great PhD journey.

With the Reiner Lemoine Institut as host institution, I was very fortunate to find myself in a very supportive and encouraging work environment and thank all my colleagues for being such a great team. In particular, I would like to thank Setu Pelz, Dr. Catherina Cader, Clara Jütte and Martha Hoffmann for important support through co-authoring, proof-reading, field work and general advice. Additionally, I was very happy about the support through our managing director Dr. Kathrin Goldammer and I would like to thank my master thesis students Clara Jütte, Christoph Stemmler and Syed Ahsan Bokharee for their great work.

I owe deep gratitude to my friends and colleagues in the Philippines especially Dr. Joey Ocon and Prof. Josephine Dionisio for making my research stay at the University of the Philippines – Diliman a great experience and giving me a deep understanding of this stunning and inspiring country. Dr. Ernesto Terrado and Rene Fajilagutan made the collaboration with the Philippine Department of Energy and the Romblon Electric Cooperative possible, for which I am very grateful. Furthermore, I am very thankful to Joseph Yap IV, Eugene Esparcia, Imee Saladaga, Clarisse Aquino and Billy Esquivel for the great collaboration during fieldwork in the Philippines. Maraming Salamat Po!

Finally, I would like to deeply thank my family and my partner Janika for providing unlimited patience and strength during my PhD research, which was crucial to its success.

About the author

Paul holds an international master's degree in Global Change Management (University for Sustainable Development Eberswalde, Germany) for which he received a scholarship from the German Ministry for Education and Research. He joined the Off-Grid Systems research group of the Reiner Lemoine Institute in 2012 and initially focused on geospatial approaches and simulation tools for assessing the potential for hybridization of diesel-powered energy systems with renewable energy. Paul has headed several research projects, among others feasibility studies for renewable energy on islands. In this context, he has worked with partners from the public and private sector and gained practical work experience in Africa, South Asia and Southeast Asia. Paul joined the Europa-Universität Flensburg for his doctoral research with a PhD scholarship from the Reiner-Lemoine Foundation in February 2017. His PhD research included field work in remote regions of the Philippines and research stays at the University of the Philippines – Diliman and the Arizona State University. At the same time as his PhD research, he implemented four research and cooperation projects, focusing on the use of renewable energy for clean energy supply and providing energy access, funded by the European Union and the German Ministry for Education and Research in the Philippines and other regions of Southeast Asia.

1. Introduction

1.1. The challenge of sustainable energy supply on islands

Addressing climate change and global warming is one of the most urgent and challenging global tasks of this century [1]. Projected consequences of a global temperature increase above the 2° C threshold include a significant sea level rise and higher frequency of extreme weather events [2]. The combustion of fossil resources in the energy sector is a major contributor to global CO_2 emissions [1]. Strategies for the mitigation of these emissions include the use of renewable energy (RE) and the reduction of energy consumption.

In Southeast Asia energy demands have increased by 80% since 2000 and current growth rates are among the highest worldwide [3]. Alarmingly, this demand has been met by doubling the use of fossil fuels for power generation [3]. The decarbonization of energy supply systems in Southeast Asia is therefore a crucial element of broader climate change mitigation strategies to prevent global warming above the 2° C [4]. The region's emerging and rapidly developing countries, such as the Philippines, face a double challenge: On the one hand they must decarbonize the existing power system and introduce more sustainable technologies to meet a rapidly growing energy demand, on the other hand they must provide remote and marginalized communities with sustainable access to energy to improve their living conditions [5].

The archipelagic nature of many Southeast Asian countries leads to a geographically dispersed population living in small communities on remote islands, beyond the reach of centralized electricity supply systems [1]. Implementing decentralized fossil technologies to provide electricity access to such island communities exacerbates climate change [1]. Leapfrogging fossil supply systems with innovative, clean and sustainable technologies is crucial to achieving development targets while minimizing carbon emissions [6]. The United Nations (UN) have formulated 17 Sustainable Development Goals (SDGs) to include social and environmental sustainability in development processes. Among these, SDG7 addresses the energy supply and access deficit, setting a target to provide access to affordable, reliable, sustainable and modern energy for all by 2030 [7]. Achieving SDG7 for the island communities of developing countries such as the Philippines is especially challenging, since this includes both the substitution of existing fossil technologies and introduction of new island grids for providing electricity access.

Island grids worldwide share common characteristics: Low energy security, high energy costs and vulnerability to impacts of climate change [8]. Given the isolation and small size of many islands, the availability and access to local conventional energy resources is limited [9]. As a result, most of the world’s islands are dependent on fuel imports to maintain their economies and infrastructure [10] and spend a large part of their local gross domestic product (GDP) on such imports [9]. Fuel prices are often up to five times above mainland prices due to the additional transport costs and low economies of scale [9].

Although islands account only for a small share of global CO_2 emissions, they are very much threatened by the impacts of climate change [2]. More specifically, islands are most affected by sea level rise, cyclones, increased air and sea temperature and changing precipitation patterns [2]. Fewer resources as well as smaller domestic markets and populations leads to an economic and political dependence on exporting countries or regions [11]. At the same time, many islands have a high local availability of renewable resources [9]. The RE technologies most commonly used on islands to date are biomass, hydropower and increasingly, wind and solar energy [9]. The feasibility of using RE depends on the electricity demand, resource availability and geographical location and needs [9]. In addition, poor grid infrastructure in existing island grids and lack of experiences with RE prevent wider implementation [10].

Detailed research on the feasibility of RE in island grids is important as there is a high potential for improving livelihoods of households, increasing the adaptability of island communities to climate change, mitigating CO_2 emissions and gaining experience for energy system transformation on a larger scale. With more than 50,000 islands and a population of more than 740 million worldwide, sustainable island community power supply is a crucial component of global climate change mitigation and adaption efforts [12]. The Philippines reflect an important and relevant case study country to investigate the appropriateness of renewable energy-based island grids for achieving the SDG7 target given the large number of islands, population, climate vulnerability and dependence on fossil fuels.

1.2. The role of islands in socio-technical transition research

Deep and sustainable changes in the energy related ecosystem of island grids are necessary to achieve a rapid decarbonization of energy systems [13]. Socio-technical transition research examines developments that lead to such fundamental changes in societies and practices [14]. Transitioning from fossil fuel to more sustainable technologies is the prime example of this research field [4]. The Multi-Level-Perspective (MLP) is a frequently applied framework for analyzing socio-technical transitions [15]. The framework consists of three levels at which transitions occur, namely niche, regime and landscape [16]. The niche represents the environment in which innovations occur and evolve, because the framework conditions for such an innovation are in place, e.g. protected environment, economic pressure or political will [17]. The regime reflects the existing system including regulatory frameworks, technical capabilities and common practices. The landscape provides the broader context of niches and regimes. Changes in the landscape are slower compared to the niche and regime. Transitions are results of non-linear processes between the three levels and can be induced by innovations diffusing from the niche level through regime and landscape level. In the context of the MLP, island grids reflect a typical niche level environment [13]. The small size of island systems indicates a controllability that makes islands appear to be an ideal test bed for political, technical, and economic experiments providing quick results and feedback loops [18].

In this context islands, are increasingly gaining interest as research case for energy technology innovation [13]. Here, the dependence on expensive fuel imports in contrast to abundant renewable resources combined with their small size make islands ideal “living laboratories” for demonstrating the feasibility of sustainable energy and smart energy concepts [13]. With these framework conditions islands provide a niche environment where socio-technical innovations (in this case RE) can diffuse faster than in larger systems or on the regime level. The main intention is to gain important learnings and experiences for up-scaling sustainable energy solutions on the main land and in centralized energy systems [19]. Many islands communities already serve as testbeds for experiments with low carbon development. Prominent examples are Samsø, Orkney and Madeira in Europe [20], [21] and Yakushima and Jeju island in Asia [22], [23]. Further research motivation for low carbon development of island communities arises from the particular climate change vulnerability and threatened energy security outlined earlier. The motivation for introducing sustainable energy systems is twofold: On the one hand, sustainable energy systems contribute to the mitigation of climate change by reducing emissions and increasing energy security through the use of local renewable resources; on the other hand improved or increased access to energy adds to the adaptive capacity of island populations to cope with natural disasters [24]. In addition, small island developing states have a strong interest in implementing RE technologies, despite limited CO_2 saving potential, as an argument to urge large industrialized countries to do the same [25]. In conclusion, RE implementation in island grids improves local energy supply and resilience but also provides important learnings for large scale transformation and decentralization of energy systems.

Most of the socio-technical island research is focused on or located in Europe: Studies on the transition of islands energy system towards high RE shares are presented for islands of Greece [26–28], Spain [29], [30], Portugal [31], [32], and Denmark [20] among other European countries. A review of 28 RE island studies finds 15 in Europe as opposed to five in Asia and another five in Oceania [33]. Furthermore, a study investigates the operational models of 10 hybrid island grids but none are located in Southeast Asia [34]. In addition, a specific example of a decision support tool for RE development on islands is presented for North European islands only [8]. In contrast to this little focus on Southeast Asia, studies focusing on the RE potential on islands for case studies [26] or the global scale [27], [28] find a significant potential for RE in the Asia-Pacific region.

In conclusion, detailed and context specific case studies on Southeast Asian islands are still underrepresented in the literature. This is in spite of two most island-rich archipelagos, Indonesia and the Philippines, being situated in Southeast Asia [35]. This research gap underlines the need to investigate transition processes of island grids in the Philippines and their potential impact for wider RE deployment in Southeast Asia and globally.

1.3. The case study country: The Philippines

The Philippines serve as the case study country for this dissertation. The country is located in Southeast Asia and composed of an archipelago of between 7,107 [36] to 7,600 [37] islands with a total land area of 299,000 km² (cf. Figure 1.1). An estimated 2,000 islands are inhabited [38], and only 11 of them account for 94 percent of the total land area and 96 percent of the total population [36]. With a population of 102 million the Philippines are the second most populous country in Southeast Asia with a population density of 336 people/km² [36]. Demographic projections estimate the population to grow to approximately 150 million people by 2050 [39]. The country is divided in three main regions: Luzon, Visayas, and Mindanao [40] (cf. Figure 1.1). More than three quarters of its population live in the two regions of Luzon and Mindanao and about 55 percent live in rural areas [36], while around 40 percent of the urban population live in slums [41].

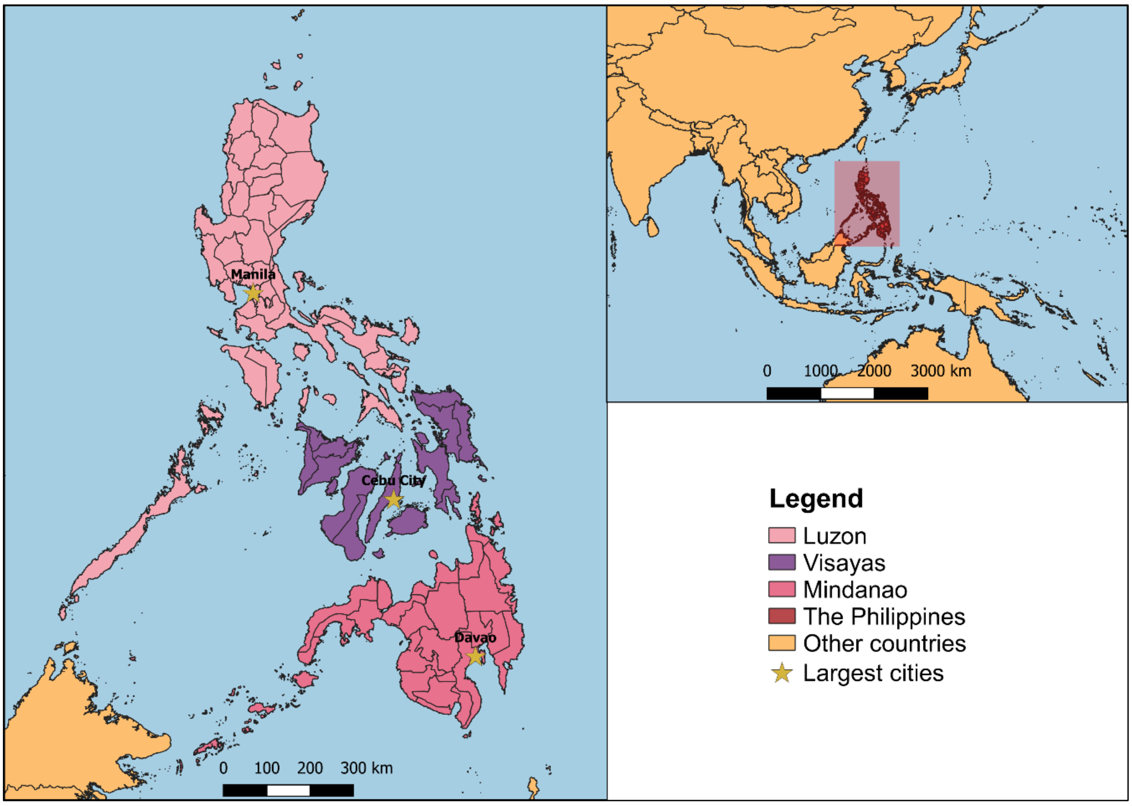

Figure 1.1: Location Luzon, Visayas and Mindanao within the Philippines and within Southeast Asia (own visualization).

The Philippines are rapidly evolving from a developing country into an emerging economy. Over the last decade, the GDP has grown by an average of 5.4 % per year [42]. The service sector is the largest contributor to GDP due to the advantage of a largely English speaking workforce [36]. The agricultural sector is the second largest contributor to the Philippine economy. Although the share is declining, the country is still a major exporter of fruit crops such as coconut, banana and pineapple [43]. Projections by the Asian Development Bank (ADB) expect the country to advance to an upper middle-income status in 2020 [44], implying a steep growth in energy demand. Since 2003 the electricity demand of the Philippines has doubled [45], which contributed significantly to a 50% increase in electricity consumption in Southeast Asia between 2000 and 2013 [46]. For Southeast Asia this rise in electricity demand is projected to triple further by 2050 [46]. However, rapid economic growth is mainly limited to few highly urbanized regions, while many remote islands of the Philippines lag far behind in terms of living standards, human development and economic opportunities [47]. Currently, 21.6 percent of Filipinos are living below the national poverty line [41] mainly due to a combination of low savings rate, high population growth, and extremely low productivity [48].

In addition, the country faces further major challenges such as natural hazards and increased impacts of climate change [49], [50]. Climate vulnerability is considered as one of the main threats for the Philippines as it is ranked among the world's five most affected countries by extreme weather events and natural hazards [37]. Due to its exposed location in the Western Pacific Ocean within the typhoon belt and the Pacific ring of fire, the Philippines are especially vulnerable to natural hazards such as earthquakes, volcanic eruptions, typhoons, flooding, landslides, and sea level rise [36], [37]. A particular genesis zone of typhoons is located east of the Philippines in the Pacific Ocean. Every year more than 20 typhoons hit the country, which equals to 25% of typhoons occurring worldwide [51]. Negative effects of climate change reinforce the country's vulnerability [52]. By 2050, climate-related hazards like super-typhoons, heavier rainfalls alternating with longer and warmer dry seasons are likely to exacerbate risks and further increase poverty. Economic losses are projected to reach up to 50 percent of GDP in the most extreme case by 2100 [53], depending on the implementation of adaptation measures [52].

The Philippines remain dependent on imported fossil fuels such as coal and oil for power generation, despite associated climate change implications and high poverty rates. Such fuel imports are expensive due to the lack of domestic fuel sources, increase CO_2 emissions and leave the country's infrastructure and energy sector sensitive to supply shortages [54]. This hinders socio-economic development and reinforces the country's vulnerability to climate change. Pursuing a low-carbon and resilient energy pathway is of high importance for the sustainable development of the country [55]. The Philippine's Intended Nationally Determined Contribution (INDC) submitted to the United Nations Framework on Climate Change Convention (UNFCCC) in 2015, outlines their motivation to combat climate change and to create resilient and sustainable energy systems, but emphasizes to only be able do so under the premise of economic growth, international cooperation and poverty reduction [56].

The implementation of renewable energy systems can contribute to the outlined objective since renewable energy technologies in island grids are not only contributing to reducing emissions and increasing energy security, but also contribute to improving living conditions and reducing poverty through providing more affordable and more sustainable power supply in marginalized and remote communities as stated in the definition of SDG7 [57].

1.4. The energy sector of the Philippines

Due largely to geographical character of the Philippine archipelago, the national electric power system is fragmented, consisting of two main central grids and many isolated island grids. The two main grids supply the most populous and economically relevant regions. One interconnected grid covers the island groups of Luzon and Visayas and one covers the island group of Mindanao [58]. In addition more than 287 isolated island grids are operated, which are served by an even larger number of power plants [59]. Therefore, the electricity sector can be distinguished into two sectors, a “main-grid island sector” and an “off-grid island sector” (cf. Figure 1.2).

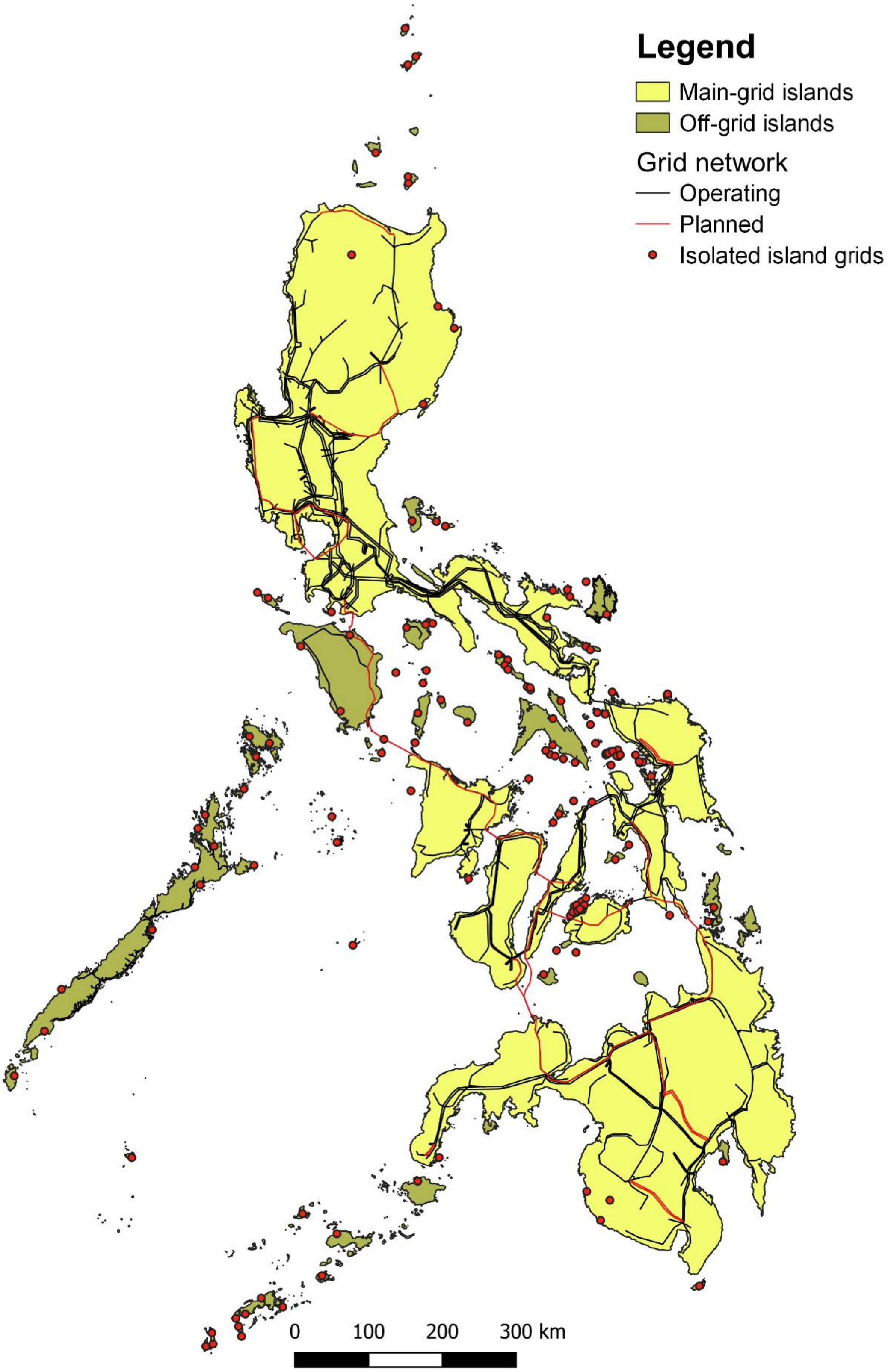

Figure 1.2: Overview on-grid and off-grid islands in the Philippines (own visualization based on [60] **&** [61]**).**

Both sectors are largely dominated by fossil-fuels which challenges the country's energy security given the lack of domestic fossil resources [42]. The two sectors have experienced a decoupled development over the last three decades: The main-grid sector faced a substantial rationalization and privatization program from the 90s onwards to tackle a power supply crisis that costed the national economy up to 1.5% of the annual GDP [62]. Between 1992 and 1998 the country's power generation capacities increased by 70% [63]. The capacity expansion solved the power crisis, but the RE share plummeted from 45% in 1990 to 23% in 2018, as coal became the new baseload fuel [45]. Although generation assets and transmission grid of the former state monopolist the National Power Corporation (NPC) were privatized, power rates are among the highest in Asia and Southeast Asia [64]. In contrast to this rapid development the off-grid sector was left behind. The sector has received only little investments from both private and public actors. Electricity generation is still mainly based on diesel generators and predominantly handled by a subsidiary of the former monopolist called NPC-SPUG (NPC - Small Power Utilities Group). In addition, electricity supply is rationalized to a few hours of the day on most off-grid sector islands and power outages are frequent [65].

Off-grid islands in the Philippines need more RE to improve supply quality, resilience and to achieve SDG7 in the entire country. These islands are in particular exposed to country's challenges such as climate change impacts and natural disasters, while hosting the most poor and vulnerable population [5]. A better understanding of how to serve these island grids with improved RE-based supply systems and the respective socio-economic impacts can not only support sustainable development on these islands, but can also create a blueprint and positive narrative for the entire country and its energy sector. Thus, this dissertation focuses on the potential for developing renewable energy based island grids in the off-grid power sector of the Philippines, which is further described in the following section.

1.4.1. Overview on off-grid island sector

The off-grid sector includes all islands or remote areas which are not connected to the two main grids (cf. Figure 1.2). This covers islands served by isolated grids as well as not electrified or informally electrified islands. According to the most recent official statistics published by the Department of Energy in 2015, the sector has an installed capacity of 400 MW and a demand of around 1,020 GWh per year [59]. More recent data collected by the author and presented in chapter 2 estimates a slightly larger capacity of 449 MW and a consumption of 1,259 GWh. The Department of Energy refers to island grids in the off-grid sector as small isolated island grids (SIIGs) and differentiates the island grids in large areas (no definition based on gross generation), medium areas (gross generation >1 GWh), small A areas (gross generation > 50 MWh), small B areas (gross generation <50 MWh), Philippine Rural Electrification System (PRES) project areas and Qualified Third Party (QTP) projects (cf. Table 1.1). Most of the generation is still government owned through NPC-SPUG while 15 new power producers (NPP) generate electricity for 8 island grids (7 large areas and 1 medium area). The PRES project is restricted to the island of Masbate and was implemented as part of an international cooperation project financed by the French government. The project included the installation of small solar-home-systems (SHS) and diesel generators and is considered as a failure due several organizational flaws and high costs [66]. QTPs are privately operated island grids and include generation and distribution. So far, however, only two QTPs projects have been implemented [59].

Table 1.1: Categorization of off-grid island sector by Department of Energy (adapted from [59]).

Island type	Island grids	Av. service hours	Peak demand (MW)	Gr. generation (GWh)
Large areas	16	24	173	942.6
Medium areas	21	22	23.9	104.4
Small A areas	63	10	9.7	20.6
Small B areas	32	7	0.7	0.9
PRES mini-grids	153	5	1	1.2
QTP mini-grids	2	24	0.8	4.8
Total	287	N/A	209.1	1074.5

Both, installed capacity and electricity generation are based almost entirely on fossil fuels, with a 96% contribution from diesel or heavy oil power plants [59]. Hydropower capacity, mainly installed on the largest "off-grid" island of Mindoro, contributes the remaining four percent. The operation of scattered diesel energy systems involves high costs for diesel fuel, transport and maintenance, resulting in high power generation costs [5]. In addition, many diesel generators have low efficiencies, resulting in even higher generation costs [67].

Although diesel-based electricity generation is considered reliable, this is only true in case of a constant supply of fuel and spare parts. As of December 2019, 36% of all diesel generator units were not operational due to technical problems and were waiting for spare parts or technical support [61]. In order to reduce costs the service hours in diesel-based island grids are often limited to a certain period of the day. Officially reported service hours state an average supply of 12 hours [59]. However, supply durations of 4-8 hours are common on small islands. In addition, diesel power plants pollute the local environment through noise and exhaust emissions. Oil spills pose a significant risk and have a direct impact on livelihoods by contaminating areas used for fishing (example provided in Figure 1.3).

Figure 1.3: Non-operational diesel power barge after the explosion of a generator unit (own picture).

The remaining non electrified areas ("missionary areas") consist of a large number of small islands without electricity supply or informal power supply only. In some areas, local communities or private persons have implemented small "barangay[1]" grids. Such systems

[1] Smallest administrative unit in the Philippines

are makeshift grids, usually supplied by very small diesel or gasoline generators. Customers pay usually per appliance used and costs can be exorbitant, well over 5 EUR/kWh [68]. Electricity fees are directly payed to the owner of the grid (often the wealthiest person in the community) or collected by the local community representatives (barangay counsellors). Such systems are not only very expensive but also very unreliable. Overcharging often leads to the damage of generators (example provided in Figure 1.4).

In conclusion RE are required for the replacement of existing diesel based island grids and in form of new RE-based island grids to provide access to electricity in compliance with the SDG7.

Figure 1.4: Remains of a makeshift barangay grid after damage due to overcharging (own picture).

1.4.2. Regulatory framework of the off-grid island sector

Historically, NPC owned and operated all generation assets and the transmission network as a state-owned utility. As such NPC was as well responsible for supplying remote islands, however limited funds prevented full electrification of the archipelago [69]. With the implementation of the 2001 Electric Power Industry Reform Act (EPIRA) [70] the previously vertically integrated sector was privatized and divided into three parts: generation, transmission and distribution [37]. The intention of the EPIRA law was not only to liberalize the electricity market, but also to stipulate the use of alternative and indigenous resources. In this sense EPIRA did not meet the expectations as the RE share decreased significantly [71]. In addition to that the reform left a highly complex system of responsibilities and actors in the off-grid sector of which the most important are shortly introduced: NPC-SPUG, NPP and QTPs generate electricity and sell to the local distribution utilities (DUs) which consist of more than 120 electric cooperatives (ECs), local government units (LGUs) and other entities [59]. The Department of Energy (DoE) develops policies and strategies, while the Energy Regulatory Commission (ERC) approves tariffs and subsidies and the National Electrification Agency (NEA) oversees the ECs and provides capacity and funding for electrification.

The adoption of the Renewable Energy Act (RE Act) in 2008 [72], was intended to correct this shortcoming and to accelerate the use of RE technologies [5]. Expectations were high given the number of fiscal and non-fiscal incentives to be implemented under it [73]. These included a feed-in-tariff (FiT), a range of tax incentives, a renewable portfolio standard (RPS) for the main-grid and off-grid sector, and a net metering scheme. In addition, both the

EPIRA and RE Act are policies aimed at promoting private sector participation in supplying the off-grid areas alongside the “main-grid” sector. While this has been particularly successful on the main islands of Luzon, Visayas and Mindanao, since there privatization of the generation assets reached 89% in 2014 [74], there has been little change and improvement in the off-grid sector. As of now, two QTP projects were realized [59] and NPP investments focuses on few economically attractive off-grid sector areas. Basically, all private schemes realized have implemented fossil power generation technologies [59]. Still, NPC-SPUG, which was founded as a subsidiary of NPC with the aim of operating existing generation assets until privatization, still operates most of the island grids on 100% diesel fuel.

Since diesel-based electricity generation is expensive, it needs to be cross-subsidized by government funds to keep tariffs affordable for local consumers. This is implemented through the Universal Charge for Missionary Electrification (UCME). The UCME covers the gap between the true cost of generation rate (TCGR) and the subsidized approved generation rate (SAGR) (cf. Figure 1.5). The SAGR is the approved tariff that can be charged to the customers by the DU and which is set individually for each supply region by the ERC based on the local socio-economic conditions. The UCME is derived from a surcharge per kWh consumed from all paying consumers in the main grid systems (Luzon & Visayas and Mindanao).

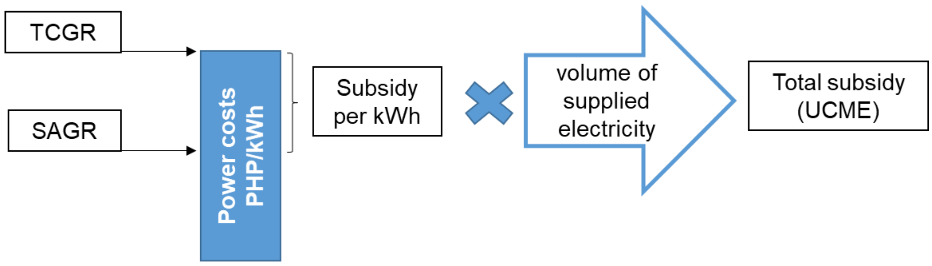

Figure 1.5: Simplified flow diagram of UCME calculation (own visualization).

With the intended expansion of electricity access and the increase in service hours through diesel-powered energy systems, the UCME is likely to continue to grow from 349 million USD in 2017 to more than 550 million USD in 2021 [59] and place an additional burden on national funds [64]. The UCME requirements are very sensitive to fluctuations in fuel costs and quickly rise if crude oil prices increase. The wider impact of an increased subsidy requirement endangers the goal of 24/7 power supply by 2022: Higher subsidy requirements result in lower investments in new electrification. In the worst case, operating hours have to be shortened to save fuel and costs. Strategies to avoid an UCME increase are either to increase the SAGR or decrease the TCGR. Since a large customer base in the off-grid island sector is poor, increasing the SAGR would require first to develop income opportunities. Decreasing the TCGR, instead, could be achieved through implementing RE or connecting island grids to the main grid to reduce power generation costs. Therefore, decision makers need a detailed quantification of costs and benefits of those options to assess the effect on the UCME.

Policy makers have recognized the need for RE use in the off-grid sector and its potential for lowering power generation costs and improving living conditions. Therefore, specific incentives have been implemented to promote the use of RE in the off-grid sector: The renewable portfolio standards for off-grid areas mandate that at least 1% of energy supply needs to be sourced from renewable sources [5]. This percentage shall increase annually but is subject to review from DoE. Furthermore a renewable energy cash incentive is provided in case of RE use in off-grid areas. This would add 50% of the approved SAGR but developers have experienced long delays in the granting of the incentive [75]. Main reasons are the very complex application procedure, which imply high risks and uncertainties for project developers. Recently, the ECs have been encouraged to expand their activities into power generation by Rep. Act. No 10531 [76]. High potential for the introduction of RE arises from the EC lower profit interests, higher interest in local development, more detailed understanding of community's needs, and ownership structure. However, challenges faced by ECs when implementing RE projects have so far not been analyzed.

The section presented several regulatory and policy measures in place for RE development, however those have not yet implemented its full impact. Furthermore, the existing subsidy scheme was outlined which is very dependent on fuel price fluctuations. Renewable energy implementation can reduce power generation costs and increase the energy security. The following section presents a brief literature review of RE use in the off-grid sector.

1.4.3. Literature review of renewable energy development in the off-grid island sector

RE has been increasingly recognized as a potential solution to the supply challenges faced by off-grid island communities. Ultimately the dependence on diesel fuel and necessity to find an alternative to diesel fuel became clear when the country was exposed to the oil crises in the 1970s. Initially, efforts focused on the introduction of small-hydro power and dendro thermal power plants. These were not fully implemented due to the lack of funds, lack of intergovernmental coordination and supply challenges for fuel wood [77]. The use of solar PV in form of SHS and centralized solar battery charging stations was tested in the early 1990s and was found as generally feasible however high investment costs prevented a wider deployment [78]. Hybridization of diesel-based island grids with RE was initially discussed in 1999 [79]. The study concluded that wind turbines were the most cost-efficient retrofit for hybridization based on the cost assumptions of that time. However more recent publications under collaboration of the author also confirmed a high potential for the implementation of solar PV in combination with battery storage applying more recent and accurate cost assumptions [80].

A study, to which the author contributed, characterizes 502 Philippine off-grid islands with respect to their suitability for smart energy systems by applying geospatial and cluster analysis [81]. The study finds a high solar energy potential for all islands with average GHI values between 4.6 and 5.8 kWh/d/m². In contrast, the wind power potential is more extremely distributed with average wind speeds between 1.6 and 6.0 m/s, with very low potential south of the 7th latitude [81]. In terms of socio-economic and physical characterization, the largest group of islands identified consists of islands with low GDP per capita, indicating low and mainly household electricity demand. The study finds solar energy as the most suitable renewable energy source on almost all Philippine islands, although some islands have relatively low potentials (on a national scale) or lack of space constraints [81]. Further studies applying a more generic approach for assessing the RE potential through energy system modelling and cluster analysis find a high potential for solar PV in Philippine off-grid islands [82], [83]

Case studies have focused on a few implemented projects: A sustainability evaluation of an implemented solar PV-lead acid battery based hybrid energy system in Pangan-an island found that the eventual failure of the project and deterioration of the energy systems was a consequence of unaffordable electricity tariffs and the low quality of the applied technology [68]. Weak managerial capacity and insufficient maintenance then led to the ultimate malfunction of the energy system [68], [84]. The evaluation of four donor based RE projects all over the Philippines revealed that all projects failed quickly after donor support stopped due to the lack of technical expertise to maintain the systems [85]. However feasibility studies underline the potential for RE: A techno-economic simulation of a 100% RE system based on solar and battery storage for the island of Gilutongang found LCOE of 0.39 USD/kWh with excess electricity of 39% and a reliability level of 91% [86]. A simulation of a renewable island grid comprised of solar, wind, battery storage and biomass for Carabao island was identified as the most cost-effective scenario, enabling a 72% reduction in GHG emissions [87].

A sustainability assessment was conducted for 21 system configurations for off-grid island supply in the Philippines [88]. Although, 100% RE systems are clearly advantageous over diesel fuel systems with regard to life cycle assessment [89], the environmental impact of RE micro grids, especially with substantial lithium-ion (li-ion) battery storage capacities needs further investigation [90], [91]. Nevertheless, the sustainability assessment identified roof-top PV installations in combination with community-scale wind power and Li-ion batteries as most environmentally sound solution for rural communities in the Philippines [88]. Further sustainability assessments for a prototypical Philippine off-grid community found biomass power systems based on agricultural waste environmentally advantageous over diesel generators [92], the use of integrated energy-water systems was more sustainable than the import of bottled water [93], the application of biogas from manure more environmentally friendly than using diesel generated electricity for cooking [94] and finally presented integrated systems focusing on the energy-water-food nexus for off-grid electrification [95].

The RE policy framework in place is criticized for its design tailored to the needs of the main grid sector and inappropriateness for incentivizing RE island grids in the off-grid sector [5]. Additionally, a study outlines that insufficient institutional capacities and lack of governmental coordination decelerate remote island electrification [96]. A number of recommendations to overcome such policy shortcomings is provided by a study of the International Renewable Energy Agency (IRENA): This includes to streamlining permission processes, revising procurement rules and simplifying the tariff setting for RE projects on off-grid islands [66]. An analysis of donor-based RE projects found that a lack of exchange between national and municipal governments prevented the successful implementation and undermined sustainability of donor funded RE projects in the off-grid sector [85].

The aforementioned studies represent a good overview on technical feasibility for RE-based hybridization in the Philippines. In addition, economic benefits have been studied for selected pilots. However, the bigger picture is missing, such that there remains a gap in understanding the total hybridization potential on remote islands of the Philippines and the impact of the expected supply extension towards 24 hours. Furthermore, new cost data and new technologies that can support current decision making and energy sector planning have yet to be considered. Additionally, interdisciplinary approaches that investigate the socio-economic impact of RE use remain limited. The following section now provides a brief overview about the technological supply options on off-grid islands.

1.5. The technological options for sustainable energy supply on off-grid islands

In general, the same diversity of energy supply options is applied to islands as compared to mainland areas. In fact, the energy systems of very large and densely populated islands (e.g. Luzon as the main island of the Philippines) are comparable to those of continental countries. However, while large islands host most of the world's island population they comprise only a small number of islands [35]. On smaller islands, the difference between average and peak demand tends to be greater, due to the smaller population and mainly residential consumers. This implies a high coincidence factor and requires more flexible capacities [97]. Existing island grids therefore often lack baseload capacities and a transmission grid [98]. Technological options for energy supply on islands are comparable to those in rural electrification settings and consist of stand-alone solutions (solar lanterns, household-based systems), decentralized solutions (diesel-based or renewable energy based-island or village grids) and centralized solutions (grid connection) (cf. Figure 1.6).

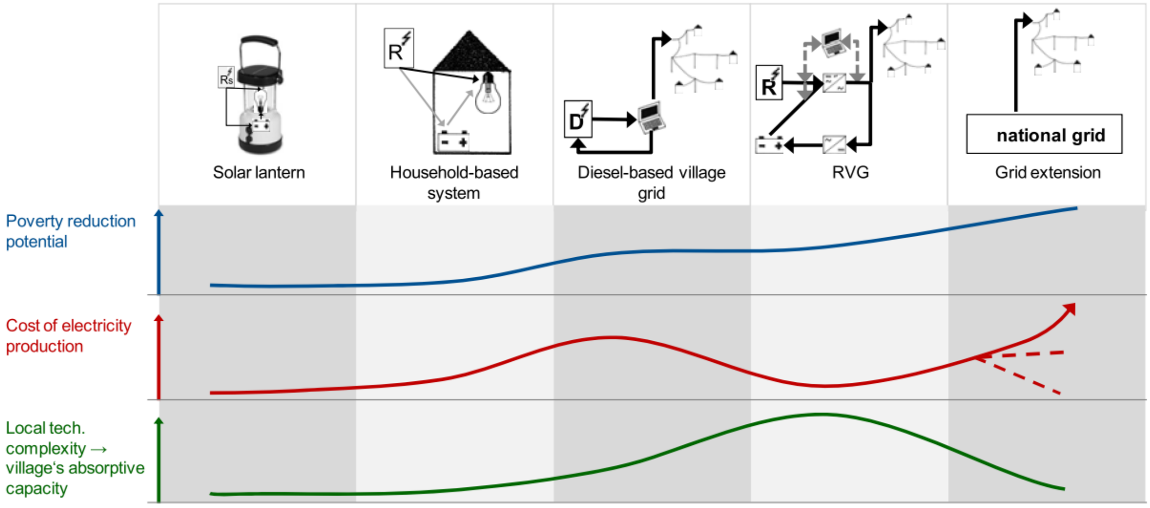

Figure 1.6: Overview on energy access options in relation to poverty reduction potential, cost of electricity production and technical complexity (based on [99]).

1.5.1. Stand-alone solutions

Stand-alone solutions comprise mobile or household-based systems with low power capacities. Such systems can be fossil or renewable based, examples are solar lanterns, solar-home systems and small generators that supply one or few households. The main capability of such systems is to provide power for lighting and phone charging while larger systems can additionally power few electric devices [99]. The advantage of stand-alone solutions is their modularity and transportability, which often makes them the first energy access option providing basic electricity services in many regions of the world [100]. The reliability depends on fuel or renewable resource availability and maintenance of systems which are technically less complex compared to other solutions [99]. The flip side of stand-alone solutions, however, is the low capacity of its systems, which limits power supply to household demands. Larger and productive demands cannot be met, hampering local development [101]. Although investment costs are low on a unit basis, energy costs are high and can exceed 1 EUR/kWh for the example of SHS [102]. Stand-alone systems are already widely applied in islands and have often been implemented by the initiative of the island communities [86]. Small generators, SHS and automotive batteries are the most commonly found stand-alone solutions on Philippine islands [68]. Although stand-alone solutions are an appropriate first step to quickly meet basic electricity demands, they do not provide sufficient power for further development and do not fully comply with the SDG7 target in terms of duration and quality of supply.

1.5.2. Decentralized solutions

Decentralized solutions refer to isolated electric systems. Such systems are often described by the terms micro-grid or mini-grid and are henceforth considered as island grids. No official definition or threshold (e.g. power capacity threshold) is provided for differentiating island grids from main grids, most characteristically island grids usually consist only of one or few generation sources and a distribution grid lacking a transmission grid and baseload power plants [103]. Furthermore, if such systems are comprised of more than one generation technology, they are considered a hybrid island grid.

Two main types of island grids can be differentiated: Fossil fuel based island grids and renewable energy based island grids [34]. For the former, diesel generators are the most commonly applied technology [33]. Diesel generators are a well known and well demonstrated technology and can be operated flexibly [104]. However, generation costs are high and exposed to volatile fuel pricing, and additionally diesel power generation implies global and local environmental damage through emissions [104]. Diesel generators require little investments but high operational and maintenance expenses. These downsides underline the relevance of RE integration in such grids. However, the large majority of island grids in the Philippines currently rely on diesel fuel or heavy fuel oil [59].

Renewable energy based island grids combine one or more RE sources [33]. For RE-based island grids the technical challenges are the harmonization of supply and demand due to the intermittency of renewable energies [103] and the absence of grid stabilizing rotating generators [105]. Beyond power generation technologies, components of such systems typically include energy storage systems in combination with energy management, frequency and voltage control systems [34]. The aforementioned enable load shifting and load levelling as well as frequency stabilization [106]. The capability of providing the aforementioned services depends on the type of energy storage systems which are categorized in mechanical (e.g. pumped hydro), electrical (e.g. capacitors) and electro-chemical storage technologies (e.g. Li-ion batteries) [106]. Li-ion batteries are considered as advantageous over other technologies for application in island grids due to a high specific energy and power density allowing for both providing power for grid stabilization and shifting electricity to time of demand [107]. In addition significant cost reductions are projected for Li-ion storage technologies due to the application of such technologies in the electronics sector and in electric vehicles [90]. In case of a 100% renewable based energy system large generation and storage capacities are required to surpass periods of low RE availability and high demand [34]. RE-based island grids require high initial investments due to component costs and less implementation experience but consume very little operational costs.

Both type of island systems can be combined in a desired continuum of diesel to RE ratios. Diesel-based island grid are very suitable for RE integration since the existing generators in place can serve as backup source and facilitate the quick integration of RE [104]. Here three phases of RE integration are specified: RE introduction, large-scale RE integration and towards 100% RE [21]. The first phase reflects the installation of RE technologies up to a share of 20%. RE is integrated without storage systems to reduce fuel consumption. Grid stability is secured by maintaining the diesel generator output at a minimum level. In the second phase energy storage systems are required since the island grids operate partly on RE only to save more diesel and reach RE shares beyond 20%. For the final phase a combination of generation and storage technologies is required to address the intermittency of sources and secure stable supply [21]. Generally, combining RE and diesel generators leads to more part load operation which reduces the efficiency and lifetime of the diesel generators [11], which questions the capability of integrating existing and sometimes outdated generators in hybrid systems. In addition, RE technologies must be spatially collocated with the energy source, which can be far away from demand centers [11]. Grid lines may therefore need to be extended and grid stability can be affected if stability criteria are not properly integrated [108]. Distribution grids on islands are often in a weak status and may need retrofitting prior to RE implementation [109].

Several renewable based hybrid island grids have been realized in the Philippines, though these remain largely at the pilot project level [68]. Decentralized solutions can be considered as a promising option for islands and are in compliance with the SDG7 goals if they integrate high shares of RE.

1.5.3. Centralized solutions

Connecting islands to larger centralized grids can increase the reliability and affordability of electricity supply, assuming sufficient generation capacity [110]. Grid interconnections increase the efficiency through economies of scale and reduce maintenance costs compared to decentralized solutions [111]. Furthermore, leveraging the grid as a backup power source can facilitate the integration of intermittent RE into island grids and allow for the export of surpluses [112], [113]. Submarine power cables are required to interconnect islands which require much more investment than land power cables due to the necessary insulation and fortification [110]. If possible, land power cables are spanned over short straits or bridges are utilized to achieve cost-efficient interconnections [114]. However most islands are located too far from the shore and are usually connected through submarine power cables at a medium-voltage level (35 - 52 kV) [110]. For longer distances, high voltage direct current (DC) submarine power cables are favored over alternating current cables (AC) due to lower power losses and less required material [115]. Once deployed in the sea, submarine cables are buried in the seabed or armored to avoid damages by other marine activities such as fishing [116]. Submarine power cable connections have been realized worldwide in cable lengths of a few kilometers up to 500 km [117]. In the Philippines several submarine interconnections have been realized and the most important interconnection is the submarine cable link (440 MW/350 kV capacity) coupling the Luzon and Visayas main grids between Luzon and Leyte (21 km) [116]. The planning and realization of submarine power interconnections requires both high capital investments and needs to address uncertainties such as currents, bathymetry and seabed texture [60]. Often low electricity demands on small islands do not economically justify such high effort [111]. Submarine power cable interconnections are an option worth considering for islands, however the compliance with the SDG7 depends on the reliability and energy mix of the main grid.

1.6. The research questions and structure of the thesis

This dissertation studies the role of renewable energy in island grids to improve and provide electricity supply in the off-grid island sector of the Philippines. The primary objective is to systematically assess the cost-effectiveness of different supply options for island grids with a focus on RE-based island grids. The secondary objective is to identify challenges for RE introduction on islands and to assess how RE-based island grids impact local communities and comply with the SDGs. To do so this dissertation contributes with a detailed assessment of the status quo of island grids in the Philippines, the economic potential of RE integration via comparing hybrid systems, grid extension and 100% RE systems, key steps for realization as well as societal impacts and challenges of implementation of such systems. Each research step contributes to the guiding research hypothesis of this dissertation:

Renewable energy based island grids represent a cost-effective, environmentally sound and socially acceptable development pathway for the electricity supply of Philippine islands.

The research hypothesis is addressed through five individual research questions:

i. ***How cost-effective can RE be integrated into existing diesel-based island grids?***
ii. ***How cost-effective are RE island grids compared to grid connection?***
iii. ***How can RE island grids supply the remaining not-electrified islands?***
iv. ***What is the impact of RE island grids on local communities and the SDGs?***
v. ***What are the challenges and risks in implementing RE island grids?***

Each research question is presented in an individual publication and contributes to the guiding research hypothesis of this dissertation (cf. Figure 1.7):

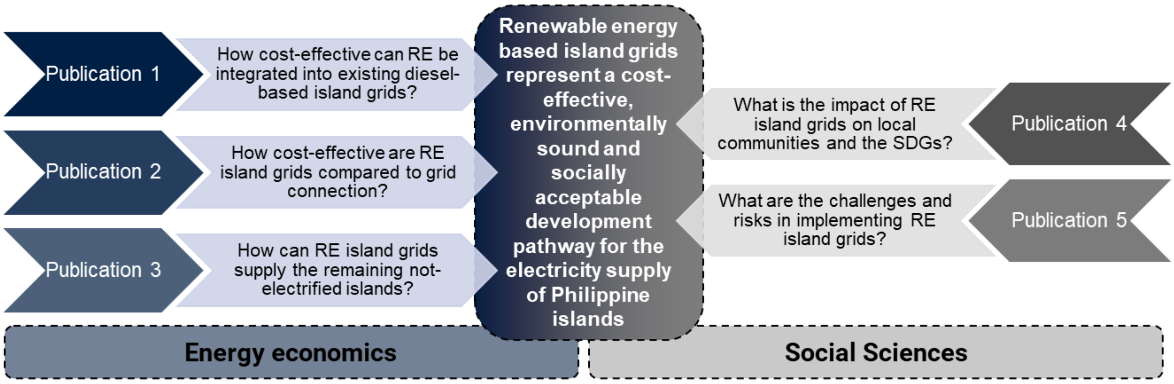

Figure 1.7: Overview about research focus, publication specific research questions and guiding research hypothesis (own visualization).

This thesis applies two distinctive research foci: While the main focus and respective methods can be located within the field of energy economics, a secondary focus is set on investigating the research topic from a social sciences perspective. Researchers emphasize the need for interdisciplinary research approaches to address sustainable energy supply and energy access in an effective way [118]. Therefore, the research foci of this thesis are interweaved through an interdisciplinary approach and employ mixed methods (c.f. Table 1.2).

A commonly applied approach in energy economics is the cost-benefit analysis of investments in the energy sector through the application of energy system simulation tools. Such analyses serve for decision making as energy investments are usually capital intensive, require considerable construction periods and have long operational lifetime [119]. Furthermore, uncertainty about future costs of fuel need to be carefully assessed to avoid lock-in effects [14]. The presented publications in the field of energy economics (publications 1 to 3) contribute to cost-benefit analyses focusing on levelized costs of electricity by introducing different but complementary approaches with the following purposes: To assess the economic feasibility of renewable energy implementation in existing diesel-based island grids, to compare submarine power cable interconnection to RE-based island grid development and by assessing the feasibility of 100% RE island grids to provide electricity access on not electrified islands. Thereby, approaches for evidence-based energy sector planning and decision making for each segment of the Philippine off-grid sector are presented.

Social sciences based energy research is crucial to allow for more diverse perspectives as traditional energy research indiscriminately promotes technology solutions based on techno-economic criteria while leaving other crucial aspects like social acceptance or societal impact out of the discussion [120]. Here, researchers identify three key fields for social science based energy research engagement: Producing actionable knowledge, critically reframing discourses and connecting actors and processes [121]. Gaining novel empirical data through such approaches for exceptional groups such as small, remote and impoverished populations is considered as critically important to design successful sustainable energy interventions [122]. This thesis contributes to this research field by focusing on a remotely located case study with a marginalized population in publication 4 and 5, which represents one of the few implemented RE island grids in the Philippines and contributes novel quantitative and qualitative data through household surveys, expert interviews and focus group discussions.

In summary this dissertation combines five individually published papers covering a mixed methods approach to show pathways towards SDG7 in Philippine island grids alongside associated socio-economic impacts and challenges. The focus, prevalent methods, data applied and technologies considered are listed in Table 1.2.

Table 1.2: Overview about focus perspective, methods applied, data collected and technologies considered of the presented publications.

Publication	Focus	Method	Data	Technology
1	Energy economics	Quantitative: cost analysis	Secondary: Energy sector statistics	RE-based island grid (solar, battery, diesel)
2	Energy economics	Quantitative: cost analysis	Secondary: Energy sector statistics	RE-based island grid (solar, battery, diesel) & central grid connection (submarine power cable)
3	Energy economics	Qualitative: cluster analysis & Quantitative cost analysis	Secondary: Geospatial data and power sector statistics	Entirely RE system (solar, wind, battery)
4	Social sciences	Quantitative: Household impact survey	Primary: >170 household interview	RE-based island grid (solar, battery, diesel)
5	Social sciences	Qualitative: Expert interviews and focus group discussions	Primary: 10 expert interviews and 2 focus group discussions	RE-based island grid (solar, battery, diesel)

The following summarizes the chapters two to seven which present the five scientific publications and presents the research findings in form of a synthesis.

Chapter 2:

Resilient solar energy island supply to support SDG7 on the Philippines: Techno-economic optimized electrification strategy for small islands

This chapter assesses the economic feasibility of RE hybridization of 132 existing diesel based island grids. An energy system simulation tool is applied and the feasibility of solar and battery integration is computed using conservative cost assumptions and stability criteria. Several scenarios reflect the provision of continuous power supply and an anticipated load growth. The findings show that hybridization is cost-effective up to an average renewable energy share of 24% in the studied island grids. Furthermore, the chapter shows that extending service hours and thereby increasing the demand for improving power supply facilitates a higher RE share. Sensitivity analyses of input parameters reveal that diesel fuel costs most significantly affect the hybridization potential and small shifts in economic assumptions in favor of renewable energy generate large increases in the potential for RE integration into island grids.

Chapter 3:

Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options

Chapter 3 introduces a novel approach for evaluating the cost-effectiveness of submarine power cable interconnection of off-grid islands. Geospatial analysis is applied using bathymetric data to optimize the submarine grid extension route. The approach is used to study the cost-effectiveness of submarine grid extension relative to RE island grid development for the 132 diesel based island grids presented in the second chapter. A grid extension requirement of 2,239 km by submarine cable and 1,752 km by land cable is identified to connect all island grids to the main grid. The overall investment for grid connection exceeds the required investment for RE island grid development by factor 4.5 given the high costs for submarine power cable implementation. While submarine power cable investment seems to be too capital intensive on a national scale it can have cost benefits on a more disaggregated scale: Submarine interconnection to Mindoro, Marinduque and

Basilan is promising based on their close proximity to the main grid and the high electricity demand on these islands.

Chapter 4:

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

The fourth chapter turns the focus to the not electrified islands of the Philippines. The objective is to identify the remaining islands in need of power supply and to assess the potential for 100% renewable energy supply of such islands. First, spatial data is analyzed and reveals 649 islands relevant for RE island grid development with a population of 650 thousand reflecting 12.5% of the not electrified population of the Philippines. Second, cluster analysis finds four island "archetypes" reflecting resource availability and population size. Third, an open-source energy system simulation tool is applied to model 100% renewable energy systems based on solar, wind and battery storage. Solar power in combination with battery storage is the essential component of cost-optimal system configurations while wind power capacities are supplementary due to seasonal availability of wind resources. Decreasing the reliability level can reduce power generation costs significantly as both the required capacity and the amount of excess electricity decrease. For a 100% RE-based electrification with a 99% reliability guarantee a capacity of 118 MWp solar power, 212 MWh battery capacity and 10 MWp wind capacity is required. Total investments would sum up to 350 million USD under the applied cost assumption but would only require around 540 USD on a per capita basis.

Chapter 5:

Assessing the impact of renewable energy on local development and the Sustainable Development Goals: Insights from a small Philippine island

Chapter five introduces the social sciences approach and presents a quantitative household survey to assess the impact of the provision of sustainable, reliable and affordable renewable based energy supply on local development and on the SDGs for the case study island of Cobrador. A questionnaire is designed and employed to more than 170 households. The findings of the quantitative survey underline that renewable energy-based islands systems are an appropriate solution to address SDG7 in archipelagos and clearly improves the livelihoods of households through improved health and education services and better access to information and communication. However the household's capability to generate income through the improved energy access largely depends on their level of wealth. The chapter concludes that SDG1 ("No poverty") and SDG10 ("Reduce inequality") are currently insufficiently addressed and recognize a threat of further increasing inequalities in the local communities through providing and improving access to electricity.

Chapter 6:

Challenges for implementing renewable energy in a cooperative-driven off-grid system in the Philippines

The chapter expands on the case study presented in chapter five but introduces a different perspective and a qualitative approach. The study looks into the risks and uncertainties confronted by one electric cooperative when pursuing a low-carbon transition in their franchise area. A mixed-methods approach that combines focus group discussions, expert interviews, and the household survey presented in chapter 5 is used to analyze the uncertainties and risks faced by electric cooperatives when pursuing low-carbon energy development in the Philippines. Finally, the study identified the most serious implementation risks to low-carbon energy transition in the Philippine context, which are slow issuance of subsidies and permits, lack of access to capital and low technical expertise in implementing RE.

Chapter 7:

The final chapter concludes the dissertation by summarizing and discussing the research findings and presenting research limitations and future fields of research.

2. Resilient solar energy island supply to support SDG7 on the Philippines: Techno-economic optimized electrification strategy for small islands

Utilities Policy 54 (2018) 55–77

Contents lists available at ScienceDirect

Utilities Policy

journal homepage: www.elsevier.com/locate/jup

Resilient solar energy island supply to support SDG7 on the Philippines: Techno-economic optimized electrification strategy for small islands

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1. Introduction

The United Nations and the international community have agreed in 2016 on 17 different Sustainable Development Goals (SDGs) to improve living conditions worldwide. Among them the SDG7 aims to ensure access to affordable, reliable, sustainable and modern energy for all (Gupta and Vegelin, 2016). Achieving this goal and its multiple dimensions is a challenge for both developed as well as developing countries. Especially for countries with growing electricity demands alongside electricity access deficits, it becomes very difficult to increase the relative share of renewable energy (RE) in their supply mix at the same time as providing more citizens with access to electricity. For islands and island states, an additional dimension can complement the SDG7: the resilience of energy systems (Ioannidis and Chalvatzis, 2017). For those regions, resilient energy supply systems are of utmost importance as they are more frequently affected by climate change and weather extrema (Michalena and Hills, 2018). Thus, the requirements on resilience of electricity supply systems for islands are specifically high and summarized in the adapted SDG7 (in the following referred to as SDG7 +) description: Provision of affordable, reliable, sustainable and modern energy for all by *resilient* systems. To achieve SDG7 + renewable and decentralized energy technologies provide feasible solutions. Renewables can form hybrid energy systems in combination with battery storage systems and/or diesel power plants (Neves et al., 2014). Such hybrid systems are often the most economical and therefore affordable supply option for islands (Kuang et al., 2016). The reliability is also high due to the use of a diverse technology mix and the use of local natural resources. Sustainability increases with higher shares of renewables in the hybrid system (Erdinc et al., 2015). Modern energy is reflected in the provision of 24/7 power and the resilience is ensured by decentral power supply with an optimized use of local resources reducing dependency from diesel supply and central generation and transmission infrastructure.

However, the global power supply for island systems is mainly dominated by diesel only systems which do not meet the criteria for SDG7 + (Blechinger et al., 2016). Those diesel power plants are often unreliable due to maintenance issues or fuel shortages. In addition, power generation costs are high due to high fuel costs. Finite fossil fuels are combusted in such diesel plants and the supply is often restricted to a few hours of the day leading to a not sustainable operation. Finally, the resilience of diesel power plants is low due to the dependence on fuel as fuel transport chains are especially vulnerable to extreme weather events (Michalena and Hills, 2018). In conclusion, hybridization of such diesel systems should lead to an accelerated achievement of the SDG7 + . For our study, we analyzed the vast islands landscape of the Philippines and their power infrastructure to identify techno-economic transition pathways towards SDG7 + . The Philippines with its more than 7100 islands are a suitable example to illustrate a sustainable transition of electricity supply on islands (Boquet, 2017). Currently, more than 130 diesel power plants are in operation on smaller islands powering independent grids – referred to as small isolated island grids (SIIGs). To understand most efficient transition strategies, we develop the following scenarios reflecting different electricity demands, which are complemented by sensitivity analyses:

- Scenario 0 - Status quo: Current demand
- Scenario 1–24/7 supply: Extension to 24 h supply for all SIIGs
- Scenario 2 – load growth: Addition of 10 years load growth to scenario 1
- Sensitivity analyses: Diesel fuel prices, WACC, battery cost, PV cost,

For all scenarios, we simulate and optimize the power supply for diesel-only and hybrid systems to understand cost structures and further key output parameters. The applied methodology is an island energy system simulation tool developed in Python version 3.6 (Rossum, 1995). In the following, we present the scientific and practical background of this paper, the applied methodology and input parameters, the results of the simulations, optimizations, and sensitivity analyses as well as discussion and conclusion.

2. Overview of Philippine islands' energy situation

The Philippines are quickly evolving from a developing country into an emerging economy. Over the last decade the GDP has increased by

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https://doi.org/10.1016/j.jup.2018.07.005
Received 1 March 2018; Received in revised form 19 July 2018; Accepted 24 July 2018

5.4% per year on an average basis (Mondal et al., 2018). This implies a steep growth in energy demand. Between 2000 and 2013 the energy demand for entire Southeast Asia has risen by 50% and is projected to triple by 2050 (IEA, 2017). However, the rapid economic growth is mainly limited to few highly urbanized regions while many remote islands of the Philippines lag far behind in terms of living standards, human development and economic opportunities (Pernia and Lazatin, 2016). Additionally, the country faces major challenges such as climate change, globalization, inequality and rapid urbanization (Parel, 2014; Leon and Pittock, 2016). Climate vulnerability is considered as one of the main threats for the Philippines as it is ranked among the world's five most affected countries to extreme weather events and natural hazards (Viña et al., 2018). Therefore developing a low-carbon and highly resilient energy infrastructure is of high importance for the further development of the country (Delina and Janetos, 2018). The Intended Nationally Determined Contribution (INDC) of the Government of the Philippines (GoP) communicated to the United Nations Framework on Climate Change Convention (UNFCCC) in 2015 explain the country's motivation to fight global warming and to create resilient and sustainable energy supply systems to lower the vulnerability to the impacts of climate change and natural hazards. Additionally they state the commitment of the country to do so under the prerequisite of economic growth and poverty reduction (RoP, 2015). In conclusion, the Philippines have strongly committed themselves to support the achievement of the previously defined SDG7 +

Compared to other countries special challenges lay in the Philippines' geography: Due to the archipelagic character of the country, the electric power system consists of two major central grids. One interconnected grid covers the main island groups of Luzon and Visayas and one covers the island group of Mindanao (IRENA, 2017a). Besides that, several smaller grids and power plants are operated on the scattered islands to supply electricity in remote regions. Recent studies have focused mainly on the clean energy development in the two major electric power systems mentioned above (Mondal et al., 2018; Viña et al., 2018). Additionally the strategy for a central energy transition to 100% RE by 2050 was presented for the entire country in the framework of a study on South-East Asia (Breyer et al., 2018). Overall, a lack of studies and knowledge regarding the energy transition and electrification of the smaller Philippine islands is notable.

For the GoP it is important to develop clean energy systems in all parts of the country. Especially as developing clean energy technologies in the smaller grids is not only contributing to emission reduction but as well to improving living conditions through improved reliability, affordability and resilience as stated in the definition of SDG7 + . Access to electricity is a key prerequisite for enabling economic and social development. Furthermore, energy access increases resilience to climate change (Perera et al., 2015). The impact of electricity access for development is confirmed by several scientific and practical case studies that have revealed significant positive impacts for example on household income, expenditure, health care, information access and educational outcomes (Gustavsson, 2007; Yadoo and Cruickshank, 2010; Bhattacharyya, 2013).

Recognizing these positive impacts, 100% electrification of all households by 2022 was set as target within the Philippine Energy Plan (PEP). Despite of many projects and initiatives ongoing to improve electricity access the share of electrification was only 89.6% of households in 2016, leaving 2.36 million households without electricity supply (IRENA, 2017b). Challenges to meet the electrification target are the population growth and remoteness of islands and villages. Additionally, electricity supply is often not provided for 24 h. Thus, an additional share of the population suffers from interrupted electricity supply and short service hours. Most locations that are insufficiently electrified are isolated villages and small islands. Since it is mostly not technically or economically feasible to connect these areas to the main grid systems, the GoP provides a considerable amount of subsidies to install and operate off-grid diesel-powered generation facilities in these areas through the National Power Corporation - Small Power Utilities Group (NPC-SPUG) (Roxas and Santiago, 2016).

Operating scattered diesel energy systems comes with high costs for diesel fuel, transportation and maintenance which results in high power generation costs. Further, many diesel generators show low efficiencies leading to even higher generation costs. Additionally diesel power plants harm the local environment by noise and exhaust gas emissions. In order to reduce costs and emissions, the service hours in diesel-based energy systems are often limited to a certain period of the day. For our research sample, in 22% of the SIIGs electricity is available for almost 24 h, in 23% electricity is provided for 18–19 h per day and in the remaining 45% of SIIGs electricity is only provided for 8–9 h per day.

As diesel power generation is expensive, it needs to be cross-subsidized by the GoP to keep the tariffs affordable for the local consumers. This is implemented through the universal charge for missionary electrification (UCME). The UCME covers the gap between true cost of generation rate (TCGR) (0.19–0.57 USD/kWh) and the subsidized approved generation rate (SAGR). The SAGR is the approved tariff which can be charged to the customers by the Electric Cooperatives, the local distribution grid operator, and which is set individually for each supply region (0.07–0.11 USD/kWh). The UCME is derived from a surcharge per kWh consumed from all paying consumers in the main grid systems (Luzon & Visayas, Mindanao). With the intended expansion of electricity access and increased service hours through diesel powered energy systems the UCME is likely to further increase and put additional burden on the national electricity tariff (DoE, 2016a).

One pathway for achieving SDG7 + on small islands is the implementation of RE systems. Such hybridization should be fostered taken into account the following: The motivation for a low carbon energy transition underlined by the countries INDC commitment, the abundance of renewable resources compared to high costs for diesel fuel, the risk of steep UCME subsidy increase and the dependency on fuel imports.

A feasible option for decarbonizing diesel based energy systems is the hybridization with renewable energies such as solar PV, wind power or hydro power combined with energy storage technologies (Cader et al., 2016). Solar PV systems have been acknowledged as suitable alternative energy supply source for the Philippines enhancing local growth (Pernia and Generoso, 2015). The decreasing costs for energy storage technologies, such as lithium-ion batteries (Kittner et al., 2017; Schmidt et al., 2017), and for solar PV (Ilas et al., 2018), as well as the prohibitive high costs for submarine power cable extension to islands (Schell et al., 2017) increase the attractiveness of decentralized hybrid systems.

The global academic community has extensively investigated such integration of clean energy systems on islands. The highest potential for hybridization on smaller islands was identified in the Pacific region mainly in the Philippines and Indonesia (Blechinger et al., 2016). In another research work, a high potential for renewable energy was detected in this region by using cluster analysis (Meschede et al., 2016). The technical feasibility of hybrid systems was demonstrated taking into account the natural conditions of the region (Lau et al., 2010; Hazelton, 2017). Other researchers already explored the options for 100% renewable energy supply in island states like Mauritius (Khoodaruth et al., 2017). Operation and management strategies for islanded micro grids were also extensively studied (Silvestre et al., 2016; Abedini and Abedini, 2017). For the Philippines, the feasibility of renewable energies for rural electrification and the supply of remote islands were discussed as early as in 1992 (Heruela, 1992). More specifically the retrofitting options for diesel based energy systems were

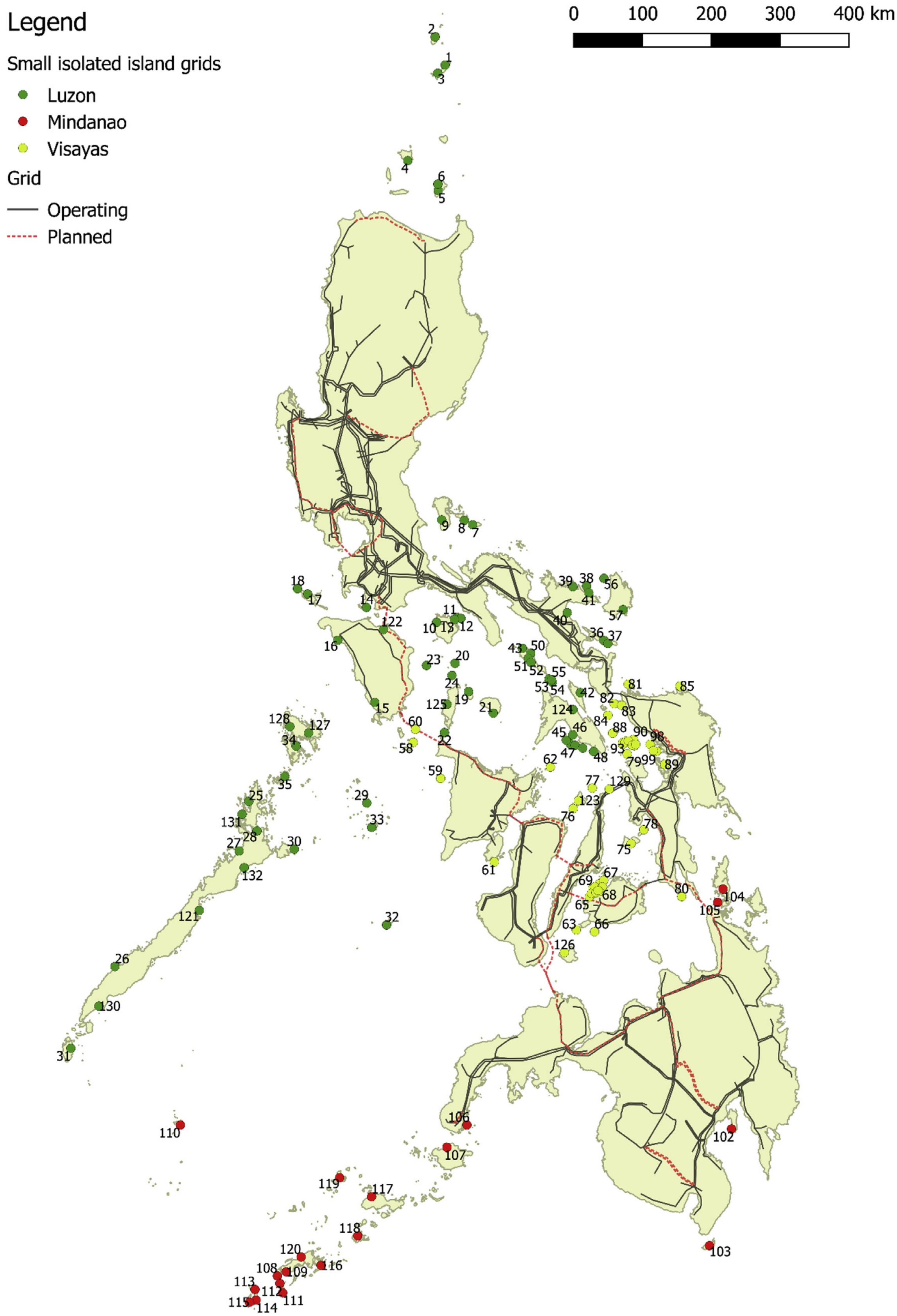

Fig. 1. Overview map of the Philippines showing the considered SIIGs.

Table 1
Key information of identified small isolated island grids per region.

Region	No. of grids	No. power plants	Operating hours	Rated capacity	Diesel fuel price	Peak demand	Demand
	[#]	[#]	[hours]	[MW]	[USD/liter]	[MW]	[GWh/a]
	sum	sum	avg.	sum	avg.	sum	sum
Luzon	67	99	16.5	356.2	0.55	190.7	1022.6
Visayas	46	48	12.8	26.6	0.51	13.1	59.7
Mindanao	19	22	16.2	67.1	0.63	29.8	177.5
National	**132**	**169**	**15.2**	**449.9**	**0.56**	**233.6**	**1259.8**

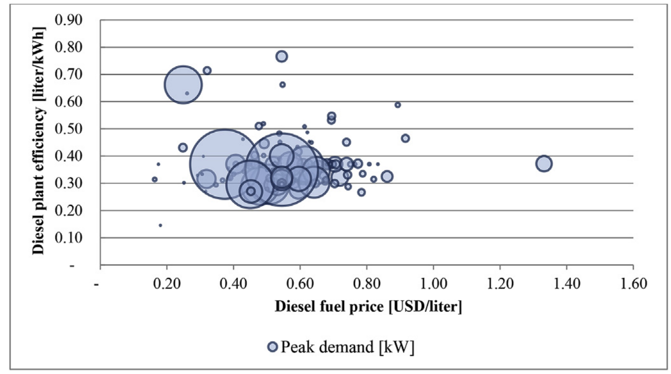

Fig. 2. Peak demand (kW) values illustrated along specific efficiencies (liter/kWh) and diesel fuel prices (USD/liter) for all considered SIIGs.

studied in the late 90s (Barley et al., 1999). More recently, the feasibility of hybridization projects was studied in specific islands or locations of the Philippines e.g. Pangan-an island (Hong and Abe, 2012).

The aforementioned studies represent a good overview on technical feasibility for hybridization on the Philippines. In addition, the economic benefits have been studied for selected pilots. Nevertheless, the big picture is missing, such that there remains a gap in understanding the total hybridization potential on remote islands of the Philippines and the impact of the expected supply extension towards 24 h and of the expected demand growth. Thus, we target this research gap to provide a comprehensive overview on the costs and opportunities to achieve SDG7 + on Philippine island systems.

3. Material and methods

3.1. Data sources and description

For this analysis, 132 SIIGs supplied by diesel power plants in the Philippines were studied (Fig. 1). In each SIIG the customers are supplied through a local isolated distribution grid. Key data was retrieved from the Philippe Department of Energy (DOE) and NPC-SPUG (DoE, 2016a; NPC-SPUG, 2017). These data include mainly location, grid name, region, operator, distributor, power plant capacities, fuel prices, efficiency rate and load demand for each SIIG. The dataset is comprised by the majority of SIIGs and diesel based energy systems in the Philippines, however the authors do not claim full coverage of the entire decentralized diesel power plant portfolio of the Philippines. All identified SIIGs are illustrated in Fig. 1.

The following table provides key information on the considered SIIGs divided into the three main regions of Luzon, Visayas and Mindanao. Values are given as sum (sum) or average (avg.) for the considered SIIGs (Table 1).

The major share of existing diesel power plants (99) and capacity (> 355 MW) is installed in Luzon region. Here the largest installed capacities are located on the main island of the Palawan, Mindoro and Masbate island group. For the regions of Visayas and Mindanao the total installed power capacities are much smaller with 27 MW and 67 MW respectively. For most of the electricity supply in these two regions, the distribution grid is supplied by one diesel power plant only whereas in some of the larger grids in Luzon several plants operate in parallel. Average operating hours per SIIG are around 16 h in the grids of Luzon and Mindanao contrasted to the grids of the Visayas region where especially smaller grids have shorter service hours leading to an average service hour duration of only around 12 h. Diesel fuel prices are on average 0.56 USD/liter, with higher prices in Mindanao of 0.63 USD/liter reflecting the additional transport and handling costs due to the larger distances to the fuel import hubs. The combined peak demand of 190 MW and annual electricity demand of 1022 GWh in Luzon is the highest for the three regions reflecting the larger size and number of grids and longer average operating hours. All energy systems in Mindanao sum up to a peak demand of 30 MW and 177.5 GWh followed by the energy systems of Visayas with 13 MW and 60 GWh.

Looking at the specific SIIGs, the range of LCOE, fuel consumption, and fuel costs is mainly influenced by the very different specific demand, fuel efficiency, and fuel price values. The 38 smallest systems have demand values from 10 to 100 MWh/a; 44 systems have demand values from 100 to 1000 MWh/a; 32 systems have demand values from 1000 to 10,000 MWh/a; 15 systems have demand values from 10,000 to 100,000 MWh/a; and even three systems supply more than 100,000 MWh/a. The three largest systems cover almost 50% of the total demand of all identified SIIGs. The higher the demand values, the higher the total diesel fuel costs per system per year. Diesel efficiency and local fuel prices further influence these costs. Comparing the collected data with regard to diesel prices (USD/liter) and peak demand (MW) reveals that SIIGs with higher demands have often lower specific diesel prices. Correspondingly, diesel fuel efficiencies are better in SIIGs with higher peak demands. It becomes obvious that diesel power generation in some of the smaller SIIGs must be very expensive due to high diesel prices and/or low fuel conversion efficiency (Fig. 2).

3.2. Energy system model

For assessing the techno-economic optimized hybridization potential for each SIIG, an energy system simulation and optimization tool was developed and applied. This tool is able to optimize the system design according to the least cost option in terms of levelized cost of electricity (LCOE). The energy system simulation tool was implemented in the programming language Python (version applied: 3.6) (Rossum, 1995) and validated with HOMER Energy (Lilienthal et al., 2004). Furthermore, previous versions of the tool were already applied in other scientific research studies, e.g. ((Blechinger et al., 2016; Ocon and Bertheau, 2018).

The tool simulates an island energy system in hourly increments for one reference year considering fossil and renewable resources and technical, economic and load data. The considered components are diesel generator, solar photovoltaics (PV), and battery storage serving one electricity demand/load node. Energy flows are simulated along a dispatch strategy, which is illustrated in Fig. 3.

At each hour for the entire reference year, the energy system model applies the dispatch strategy of maximizing the utilization of solar photovoltaic energy generation (solar PV).

First, the model tests if the load of the island can be supplied entirely by solar PV. If positive, it then verifies if the stability requirement (rotating mass), which is set at 40% of the specific hourly demand, is met. With the system always providing at least 40% of the hourly energy demand as reserve from the battery storage or diesel generator, a stable frequency and voltage can be assumed. This constraint is taken from typical control strategies of hybrid control systems (Yang et al., 2018). If excess energy is available due to high solar PV and/or by running the diesel generator for stability reasons, the battery is charged.

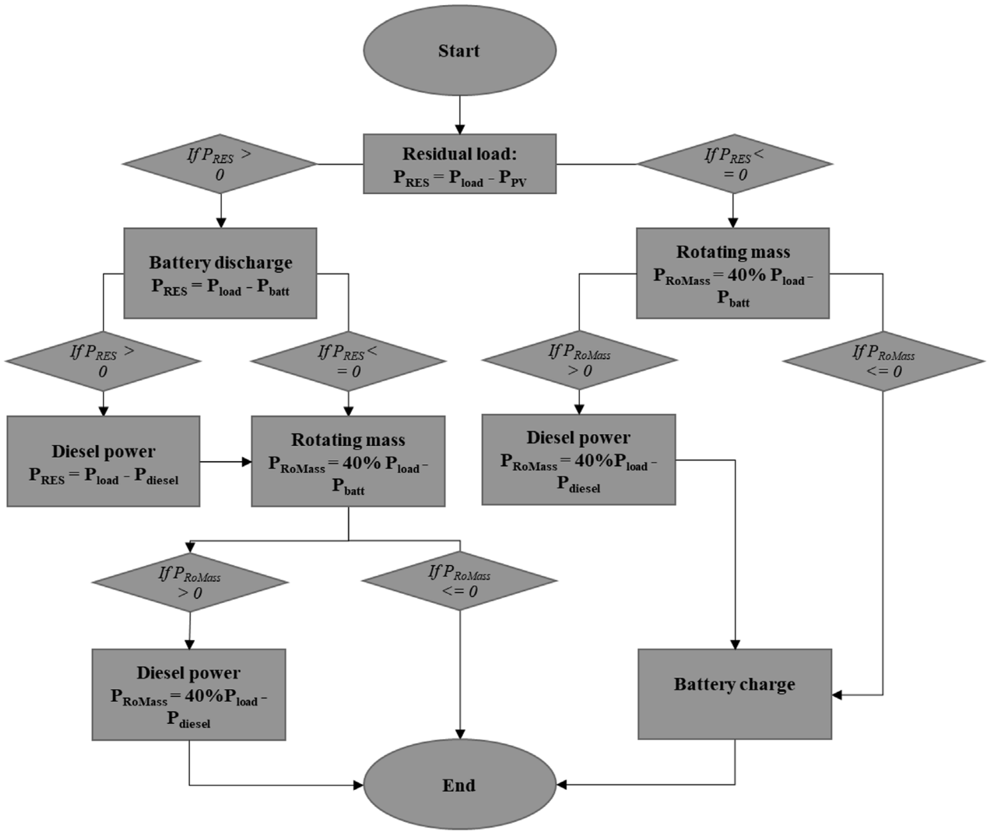

Fig. 3. Dispatch strategy of the applied simulation tool.

If the solar PV generation is insufficient to supply the load, the system discharges the battery depending on the available energy stored in the battery. Once the battery is discharged to its minimum state-of-charge (SOC), the diesel generator is operated. In any case, the battery or the diesel generator must fulfil the stability criterion for each time step.

By varying the sizes of the components in an iterative process, the optimization algorithm minimizes the LCOE under the constraint to meet the demand and stability criterion of every simulated hour of the reference year. Since the diesel capacities are always set to match the SIIGs peak demand, the sizes of PV and battery storage systems are chosen as variable parameters for the optimization. (Tao and Finenko, 2016). The optimization is set to 0.1% accuracy (deviation from global optimum) to increase the calculation speed. Thus, slightly different system configurations might be suggested for similar minimum LCOE values. LCOE are defined as costs per kWh taking into account the annualized initial costs, operational costs per year and fuel costs per year (Equation (1) and Equation (2)). Finally, the simulation reveals the techno-optimized hybrid system configuration for each SIIG based on the local specific resource and load data and the technical and economic assumptions for each component. These simulations are run automated for all SIIGs. This allows a comprehensive study of all SIIGs not limited to specific case studies only.

$$LCOE = \frac{IC * CRF(WACC, N) + Opex + Costs_{fuel} * Fuel}{E_{consumed}} \tag{1}$$

Equation (1): Equation for levelized cost of electricity for power systems.

In Equation (1), *LCOE* stands for levelized cost of electricity. Furthermore, *IC* stands for Initial costs, *CRF* stands for capital recovery factor, *WACC* stands for weighted average cost of capital, *N* stands for project lifetime, *Opex* stands for operational expenditures per year, $Costs_{fuel}$ stands for cost of diesel per liter, *Fuel* stands for consumed diesel per year and $E_{consumed}$ stands for consumed electricity per year.

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \tag{2}$$

Equation (2): Capital recovery factor (CRF)

In Equation (2), *CRF* per technology is calculated according to weighted average cost of capital (*WACC*) and project lifetime (*N*).

The techno-economic renewable potential is defined by the calculated optimized capacities of PV power and battery storage capacity for each SIIG independently. The economic viability is defined by the LCOE reduction of hybrid systems compared to the diesel only systems. For each SIIG, resource and load data are determined by individual data collection as described in the following sections.

3.3. Load data

The electricity demand (load) is one of the most decisive input parameters when assessing the hybridization potential for an energy system. Not only the total daily electricity consumption is important but also at what time of the day this electricity is consumed. This is especially sensitive for the economic feasibility of solar PV as it is an intermittent resource available during sunshine hours only. Thus, special emphasize was put on the collection of accurate and up to date load data in hourly increments for one year.

In our study we applied three different scenarios with different load data: In scenario 0 – “status quo” the current load demand is considered; in scenario 1 – “24/7 supply” the supply service to 24 h for all customers is extended and calculated; and in scenario 2 – “load growth” an increase in energy demand over a ten years period is assumed. Each scenario builds up on the applied load demand and profile of the previous scenario.

- Scenario 0 - Status quo: Current demand

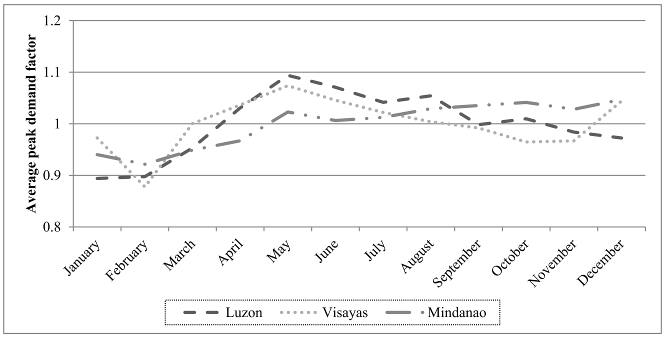

Fig. 4. Variation in monthly demand for the three considered regions.

Scenario 0 assesses the hybridization potential under the current electricity demand. Electricity demand patterns on an hourly basis were mainly collected from the distribution development plans (DDP) of the local electric cooperatives (EC) provided by the Department of Energy (DoE) (DoE, 2016a). It was possible to collect the real load data for the entire year of 2016 or a specific period for 2017 for 126 out of 132 considered SIIGs. Besides hourly demand data on annual scale, daily load profiles were collected and applied.

For the case that annual load profiles in hourly time steps were available (N = 29) they were directly incorporated into the energy system model. If a daily load profile in hourly time steps was available (N = 97), this daily load profile was replicated (x 365) in order to simulate an annual load profile. Subsequently seasonal demand patterns for the three considered regions were incorporated to adapt the monthly consumption values. Thereby, the available annual load data for Luzon (N = 10), Visayas (N = 3) and Mindanao (N = 6) were analyzed and an average monthly load factor was retrieved. Fig. 4 shows the applied seasonality for the three key regions of Luzon, Visayas and Mindanao. Whereas the patterns are similar for Luzon and Visayas with lowest monthly demands in January/February and peak monthly demand in May. The pattern for Mindanao is different with a steady increase over the year and demand peak in December. Overall, the seasonal load variation can be considered as small compared to other non-tropical regions (Blechinger et al., 2016).

A load profile from a SIIG with a power plant capacity in a similar range was assigned to the remaining SIIGs (N = 6) without any existing load information. For each grid, the peak demand was scaled to the dependable power plant capacity, which is available for each of the SIIGs.

- Scenario 1–24/7 supply: Extension to 24 h supply for all SIIGs

For the second scenario, the aim is to study the hybridization potential and overall costs assuming that all SIIGs in the Philippines provide full 24 h electricity supply. This reflects one of the major aims of the GoP to achieve a 100% electrification rate by 2022 and goes along with achieving SDG7 + (DoE, 2016b).

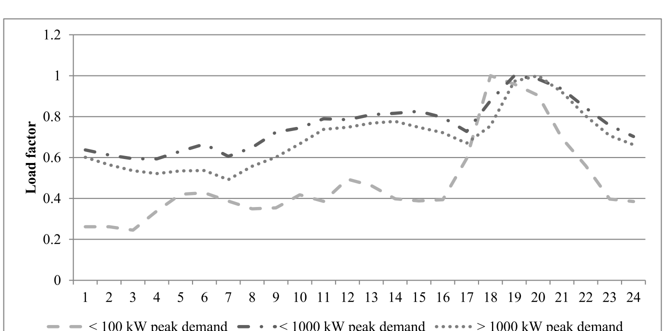

Fig. 5. Average daily load profiles for the three considered demand classes.

Table 2
Applied approach for simulating 24 h load profiles.

Criteria	Action
If demand > 0	The initial value remained
If demand = 0	Load factor from typical class load profile multiplied with the peak demand within the next 48 h from the considered hour. In case of periods were no peak demand was given for a period longer than 48 h the average annual demand was applied as multiplying factor

In our analysis, the load profiles collected for scenario 0 were applied as baseline profiles to simulate 24 h supply. For those SIIGs without 24 h supply the demand gaps were filled with an expected demand. Initially it was necessary to assign a “typical” 24 h load profile for the respective SIIGs scaled according to the daily peak demand. Thus, the data set was split in three classes according to the peak demand: lower than 100 kW, between 100 kW and 1000 kW, and higher than 1000 kW. For each of the respective demand class a typical load profiles were retrieved by averaging existing load profiles. Fig. 5 shows the retrieved typical demand profiles for peak demand < 100 kW, < 1000 kW and > 1000 kW.

All load profiles have their peak demand in the evening hours. From the smaller to larger class profile the ratio of peak vs. average demand decreases. This fits to the overall observation in the Philippines with smaller grids mainly catering residential loads whereas larger grids have a higher base load serving commercial activities during the day.

For incorporating, the 24 h demand data each grid was categorized according to its peak demand. For each category, the generic load profile was applied for each hour of the year based on the criteria listed in Table 2.

By applying these rules, we were able to create 24 h supply profiles for all identified 132 SIIGs with realistic hourly values.

- Scenario 2 – Load growth: Addition of 10 years load growth to scenario 1

For the last scenario, the expected load growth over a period of 10 years was incorporated in order to consider the development of sustainable energy grids that are capable of supplying future demands. From the collected data provided by the DDP, load growth projections were available for 17 SIIGs. Thus, load growth projections available for these 17 SIIGs were analyzed. The load growth factor for the year 2027 with regard to 2017 was retrieved in order to reflect a 10 years projection basis. Finally, the load growth factors for each of the three considered regions were retrieved by averaging the load growth factors for Luzon (N = 10), Visayas (N = 3) and Mindanao (N = 4). The load growth factors retrieved are 2.08 (Luzon), 1.82 (Visayas) and 2.05 (Mindanao). In order to derive the annual load profiles reflecting load growth for each SIIG, each hourly value considered for scenario 1 was multiplied by the load growth factor reflecting its region.

3.4. Renewable resources

Based on the requirements of the energy system model, detailed renewable resource studies were performed to derive local production profiles for PV plants of each of the considered SIIGs. Values for global horizontal irradiation (GHI) were obtained from global datasets in order to assess the specific potential for PV power generation. These datasets are provided by NASA and cover a time period from 1984 to 2005 (Stackhouse et al., 2016). The German Aerospace Center (DLR) further processed the data and derived hourly GHI data by applying a clear sky index approach, taking into account hourly clear sky irradiance data. Results provide GHI time-series in a spatial resolution of areas of 0.5° by 0.5°. For the simulations, the resource area hit by the

Table 3
Overview on technical and economic input values for energy system simulation tool.

Category	Parameter	Unit	Value
PV	CAPEX	USD/kW	1500
	OPEX	USD/kW/year	30
	lifetime	years	20
Battery	CAPEX (Capacity & Power)	USD/kWh	700
	OPEX	USD/kWh/year	10.5
	lifetime	years	10
	maximum C-rate	kW/kWh	1
	maximum depth of discharge	%	80
	charging efficiency	%	90
	discharging efficiency	%	90
	initial state of charge	%	50
Diesel	CAPEX	USD/kW	0
	OPEX (fix)	USD/kW/year	10
	OPEX (var)	USD/kWh	0.02
	Lifetime	years	20
	Rotating mass	%	40
	Efficiency	l/kWh	Individual for each SIIG
	Fuel price	USD/liter	Individual for each SIIG
Economic	Project lifetime	years	20
	Annual Fuel Changings	%	3
	WACC	%	10

centroid of the related SIIG was chosen as local solar resource. The conversion from GHI into PV power generation was based on a model of (Huld et al., 2008) considering crystalline silicon photovoltaic modules. Selected parameters affecting module efficiency are daily average temperature and irradiation, further it was assumed that modules are optimally tilted. A degradation rate of 0.3% per year was applied and an additional reduction of the generated power of 3% was assumed reflecting negative impacts such as clouding and pollution. Combining the aforementioned models leads to an individual PV yield in hourly time steps for each considered energy system. Looking at all identified locations of the SIIGs, the highest average annual PV yield is found for Mindanao with 1535 (kWh/kWp) followed by Luzon (1474 kWh/kWp) and Visayas (1447 kWh/kWp).

3.5. Technical and economic input data

As a final step before applying the above described approach, it was necessary to define the technical and economic input parameters. The different components of the model are characterized by parameters describing their technical and economic characteristics. In typical diesel only supply systems, the diesel fuel costs are the most decisive factor for the power generation costs (Weisser, 2004). Thus, the local diesel price and fuel conversion efficiencies for each SIIG needed to be identified individually, whereas generic input values were applied for all other technical and economic input data, which are presented below. Values are taken from literature references as indicated and validated via discussions with local project developers. A summary of all input parameters is provided in Table 3.

Economic parameters of the PV system are defined by initial costs, operational and maintenance expenditures (OPEX), and lifetime. Technical parameters such as efficiency values were taken into account during the resource assessment. For turn-key PV plants 1500 USD/kWp initial costs were chosen, 2% OPEX, which equals to 30 USD/kWp per year, and lifetime of 20 years (Ilas et al., 2018). We selected lithium-ion battery as energy storage system, considering it as the most appropriate technology for the application on islands, given the expected cost reduction, high efficiency and smaller environmental impact compared to other battery technologies (Vandepaer et al., 2017; Zubi et al., 2018). Initial costs add up to 700 USD per kWh installed capacity; combining the costs for capacity and power at a fixed C-rate of one as a modular unit. OPEX are 10.5 USD/kWh per year and the lifetime is 10 years (Schmidt et al., 2017). Other technical parameters are round-cycle efficiency of 90% and a maximum depth of discharge of 80%.

For all SIIGs, the diesel plants are already in place and therefore no initial costs occur for that technology. Operational costs are based on expenditures such as maintenance or lubricant oils and add up to 0.02 USD per generated kWh. Lifetime of the plants was set to 20 years so no replacements occur during the simulated project lifetime. For system stability, we introduced a stability parameter called rotating mass. A rotating mass share of 40% of the hourly demand was considered. This reflects the operating diesel capacity necessary to provide auxiliary services in case it cannot be provided by the battery.

The diesel fuel efficiency values were retrieved for each SIIG individually and range from 0.26 l/kWh to 0.83 l/kWh (Fig. 2). Additionally, diesel fuel prices were obtained individually for each SIIG ranging from 0.16 USD/liter to 1.33 USD/liter. The high spread of prices is based on different transport costs, economies of scale, but also on the internal accounting system of the sole operator of these plants – NPC-SPUG. The prices do not necessarily reflect market conditions. However, it reflects the benchmark used by the current operator to assess if a potential hybridization project would be beneficial. Therefore, we applied these prices for our hybridization scenarios and added sensitivity analyses showing the influence of undistorted world market based diesel prices on the specific hybridization potential.

Other economic parameters necessary to reflect overall costs of a hybridization project include lifetime and capital costs. For each SIIG a project lifetime of 20 years was applied. The weighted average cost of capital (WACC) was 10% based on an equity share of 40%, equity costs of 15% and loan interest rate of 6.6%. High equity shares represent the high risk perception of the commercial banks regarding small scale hybridization projects.

4. Results and discussion

The results section is structured along the three different demand scenarios: status quo (0), 24 h supply (1), and load growth (2). Additionally, sensitivity analyses are conducted focusing diesel fuel costs, WACC, PV costs and battery costs (Fig. 6). For each scenario, the diesel only and hybrid supply systems are presented showing the respective simulation and optimization results. Results are summarized for the three main regions: Luzon, Visayas, and Mindanao. Values are presented as sum (sum) or weighted average (w-avg.). Average values are weighted along the specific electricity consumption of each SIIG for regional and national LCOE and RE-share.

4.1. Scenario 0 - status quo: current demand

For scenario 0, no changes in the load demand structure are applied. The current demand situation identified via extensive data collection (section 3.3) is the baseline for the simulation and optimization. The following table summarizes the status quo and the related diesel-based power supply (Table 4).

For scenario 0, a total demand of 1.26 TWh with the majority (81%) in Luzon, 14% in Mindanao, and 5% in Visayas is identified. Diesel fuel consumption and total fuel costs per year are also the highest in Luzon. Nevertheless, in Mindanao the share of fuel costs increases to 16%, due to the specifically higher fuel prices per liter compared to share of fuel

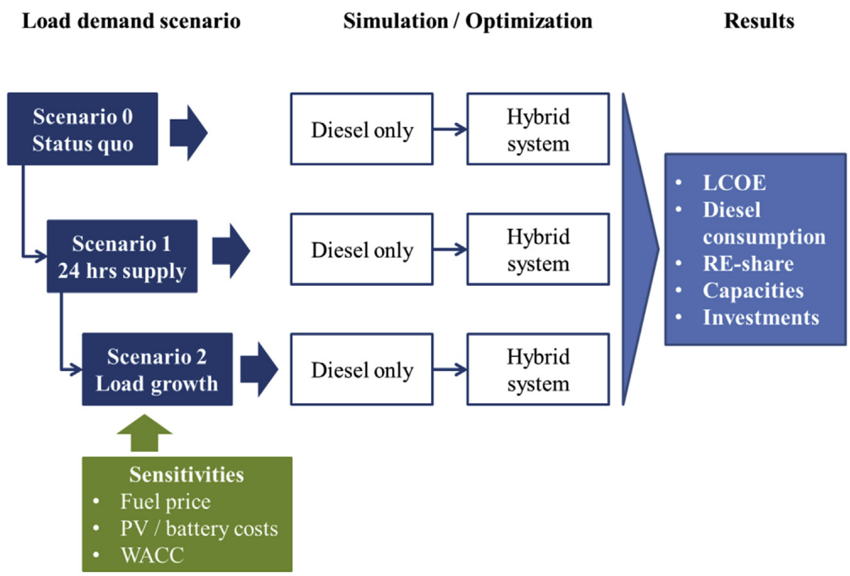

Fig. 6. Scenarios and results - Approach.

Table 4
Results of diesel only simulation - Scenario 0: Status quo.

Region	Demand	Diesel only		
		Fuel cons.	Fuel costs	LCOE
	[MWh/a]	[liter/a]	[USD/a]	[USD/kWh]
	sum	sum	sum	w.-avg.
Luzon	1,022,747	355,793	220,274	0.24
Visayas	59,712	20,824	14,299	0.26
Mindanao	177,479	52,683	43,178	0.26
National	**1,259,937**	**429,300**	**277,751**	**0.24**

consumption of only 12%. Thus, the LCOE are on average higher in Mindanao as well as in Visayas with 0.26 USD/kWh compared to 0.24 USD/kWh in Luzon.

For each of the presented SIIGs an individual optimization was conducted to identify the techno-economic optimized PV and battery capacities. Aggregated results are illustrated in the following table (Table 5).

Analysis of the techno-economic optimization results reveal a potential for hybridization, which would lead to an average renewable energy share of 24% corresponding to a decrease of average LCOE by 0.02 USD/kWh. Thereby, fuel consumption can be decreased by 24% and the total fuel costs by 25%. This results in potential fuel savings of 70 million USD per year, which is achieved by investing approximately 375 million USD into 230 MW PV and 50 MWh battery capacities. The comparison of total savings and investments demonstrates an economic potential for hybridization. Under the current market conditions, a quarter of diesel consumption can be saved without any subsidies for hybridization with solar PV. In order to understand the specific results for each SIIG, the results are visualized in the following figure illustrating the RE-share and PV potential for each SIIG (Fig. 7).

No techno-economic hybridization potential exists under the assumptions of scenario 0 for 74 (56%) out of the 132 SIIGs. This is mainly due to the unfavorable load profiles for solar PV due to the fact that many of these SIIGs provide electricity supply during evening and night hours only. In summary, the average operating hours of only 10 h per day and the load profiles are major barriers for economically viable implementation of solar PV systems in these SIIGs. As these systems are rather small (total demand adds up 90,000 MWh – appr. 7% of all SIIGs) their impact on the total fuel consumption is minor.

In contrast, the 58 SIIGs that show a techno-economic potential for PV and batteries have average operating hours of 21 h per day. These SIIGs represent an average RE-share of 26%. Under the current economic framework, it is worthwhile to focus on those SIIGs which have longer service hours. Implementing solar energy in those systems alone would enable diesel savings of 100 million liter per year. This reflects average savings of 70 million USD per year for the next 20 years assuming a 3% increase of fuel prices per year. For the respective 58 SIIGs, the LCOE would decrease from 0.25 to less than 0.22 USD/kWh on average.

4.2. Scenario 1–24/7 supply: extension to 24 h supply for all SIIGs

In scenario 1, the electricity supply for each underserved SIIG is extended to enable 24 h supply. This is a crucial step to achieve SDG7 +

Table 5
Results of techno-economic optimization - Scenario 0: Status quo.

Region	Demand	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[MWh/a]	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
	sum	sum	sum	sum	sum	sum	w.-avg.	w.-avg.
Luzon	1,022,747	296.1	180.2	36.9	270,297	164,765	0.22	23.6
Visayas	59,712	17.7	10.6	2.6	15,883	10,803	0.24	23.4
Mindanao	177,479	61.5	36.0	10.8	38,046	31,166	0.24	27.8
National	**1,259,937**	375.3	226.7	50.3	324,225	206,735	**0.22**	**24.2**

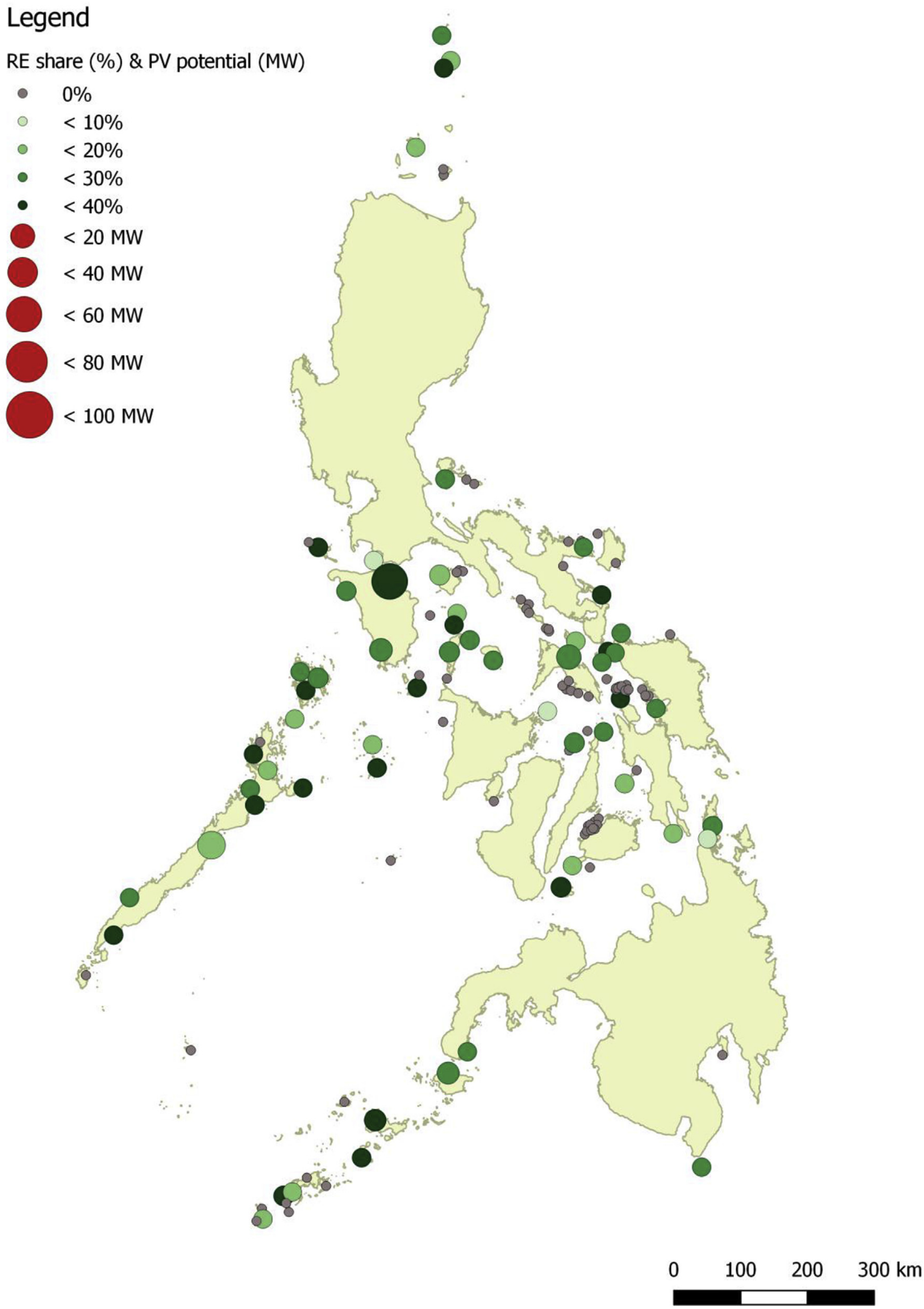

Fig. 7. Overview map showing RE-share (%) and PV potential (MW) for scenario 0.

as it allows each consumer to use electricity during every hour of the day, which is a challenge especially for the smaller systems. While the local impact of extending supply hours from e.g. 9 to 24 h in a specific SIIG and on its consumers is quite high, it remains low in the total consumption and cost numbers. As mainly small-scale systems are affected by the extended service hours the total demand increases only by 2.2% to 1.29 TWh/a. The same increase can be observed in the fuel consumption, where the fuel costs increase slightly by 2.5% due to the higher specific fuel prices of the smaller systems. The LCOE slightly increases as more power is generated in very small SIIGs with lower

Table 6
Results of diesel only simulation - Scenario 1: 24/7 supply.

Region	Demand	Diesel only		
		Fuel cons	Fuel costs	LCOE
	[MWh/a]	[liter/a]	[USD/a]	[USD/kWh]
	sum	sum	sum	w.-avg.
Luzon	1,037,710	360,783	223,775	0.24
Visayas	65,111	22,768	15,866	0.27
Mindanao	184,968	55,055	45,117	0.27
National	**1,287,789**	**438,606**	**284,758**	**0.24**
Change to scenario 0	2.2%	2.2%	2.5%	0.3%

diesel fuel efficiencies and higher fuel prices. Relative changes are higher in the Visayas and Mindanao region as they have a higher share of small scale SIIGs. Aggregated numbers can be found in the following table (Table 6).

Again, an individual optimization of each SIIG was conducted to understand the techno-economic potential of hybridization supplying 24 h electricity. The results are summarized in Table 7.

The most significant change with regard to scenario 0 is that 71 SIIGs shift from zero RE-share to appr. 23%. Only three out of the 132 SIIGs remain without hybridization potential. This is due to the very low specific diesel LCOE of these three SIIGs. On average, an LCOE of 0.22 USD/kWh and a RE-share of approximately 25% is achieved. This reveals a lock-in dilemma for the smaller undersupplied SIIGs: If they do not switch to 24/7 supply the hybridization is also not economically feasible. For all other SIIGs the hybridization potential results in RE-shares of between 10% and 40%. This is in the same range as of the previously identified 58 SIIGs with hybridization potential in scenario 0. These values are illustrated in the following map together with the potential PV capacities. The difference in RE-share is now mainly determined by the specific diesel plant efficiencies, fuel prices and solar irradiation. In addition, the hourly load profile influences the profitability of PV systems. The more demand during the day, the higher the RE-share; this in turn favors larger SIIGs (Fig. 8).

With regard to the total numbers, the changes are more significant than in the weighted average values. Increased investments of 393 million USD (+5%) lead to increased PV capacities of 237 MW (+4.5%) and battery capacities of 55 MWh (+8%). Fuel consumption and fuel costs increase less strongly than the demand, as the hybrid systems cover parts of the demand with renewable energy. The total fuel savings add up to 110 million liter per year and the fuel cost savings add up to 75 million USD per year. In summary, it can be stated that the extension of the supply hours towards 24/7 does not only improve the service quality for the customers but also allows a higher economically viable RE-share. Thus, an extension to 24 h power supply favors also the implementation of sustainable and disaster resilient technologies which both supports the tasks of SDG7+.

4.3. Scenario 2 – load growth: addition of 10 years load growth to scenario 1

Scenario 2 reflects the projected load growth for the different SIIGs. As a project lifetime of 20 years is assumed, we selected year 10 as the reference year. The projection for year 10 is based on the Distribution Development Plans (DDP) compiled by the local electric cooperatives and provided by the Department of Energy of the Philippines as described in the material and methods section.

By reference year 10, the total energy demand is expected to grow by 108% to 2.7 TWh/a. As the load profiles and other input values do not change; rather just the total demand, the fuel consumption and fuel costs also increase by 108%. This means under the assumption of a 24 h diesel based supply and a continuous anticipated load growth, approximately 911 million liters of diesel fuel would be necessary on average per year. This results in total costs of 590 million USD per year on average and the LCOE remain at 0.24 USD/kWh as in scenario 1. The relative regional distribution remains the same as well (Table 8). Such a doubling of energy demand would significantly increase the UCME requirement which is already projected at 240 million USD for 2018 (DoE, 2016a). The load growth does not only affect the total demand per year but also the peak load values. The total peak load adds up to 485 MW in scenario 2, which reflects the peak load at reference year 10. The comparison to the currently available diesel power plant capacities of 450 MW reveals the need for new power plant capacities if the 24 h supply and expected load growth are to be met. For this analysis, the costs of new diesel plant capacities are not considered as we focus on the hybridization technologies only.

For scenario 2 as for the previous scenarios, techno-economic optimization computations were performed to identify the hybridization potential. Results of these optimizations are shown in the following Table 9.

Similar to the simulation of the diesel only systems, the total values – sum – should increase by approximately 108% compared to scenario 1 and the relative values – weighted average –should remain the same. Solar PV and battery capacities alongside fuel consumption and costs increase by 108% while the relative values for LCOE and RE-share remain the same on average. The deviation is a result of the 0.1% accuracy deviation of the optimization algorithm from the global optimum as described in the methodology section. The doubling of energy demand results in average fuel costs of 435 million USD per year, even if 816 million USD are invested into solar PV and battery capacities. Thus, a significant amount of money would continue to be spent on diesel fuels in the future techno-economic optimized hybridization configuration under current economic conditions and relatively high initial and financing costs of the solar PV and battery systems. Reducing initial costs and financing rates would allow more investments into solar PV and battery capacities to lower diesel fuel consumption and costs as well as LCOE while increasing the RE-share. This would further support the sustainability, affordability and resilience of the electricity supply on the SIIGs as it is elaborated in our sensitivity analyses. Fig. 9

Table 7
Results of techno-economic optimization - Scenario 1: 24/7 supply.

Region	Demand	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[MWh/a]	[USD]	[kWp]	[kWh]	[liter/a]	[USD/a]	[USD/kWh]	[%]
	sum	sum	sum	sum	sum	sum	w.-avg.	w.-avg.
Luzon	1,037,710	308.6	186.9	40.4	271,794	165,982	0.22	24.2
Visayas	65,111	20.6	12.3	3.1	16,986	11,685	0.24	25.0
Mindanao	184,968	64.5	37.9	11.0	39,403	32,135	0.24	28.5
National	1,287,789	**393.7**	**237.0**	**54.5**	**328,184**	**209,803**	**0.22**	**24.9**
Change to scenario 0	2.2%	4.9%	4.5%	8.3%	1.2%	1.5%	−0.1%	3.0%

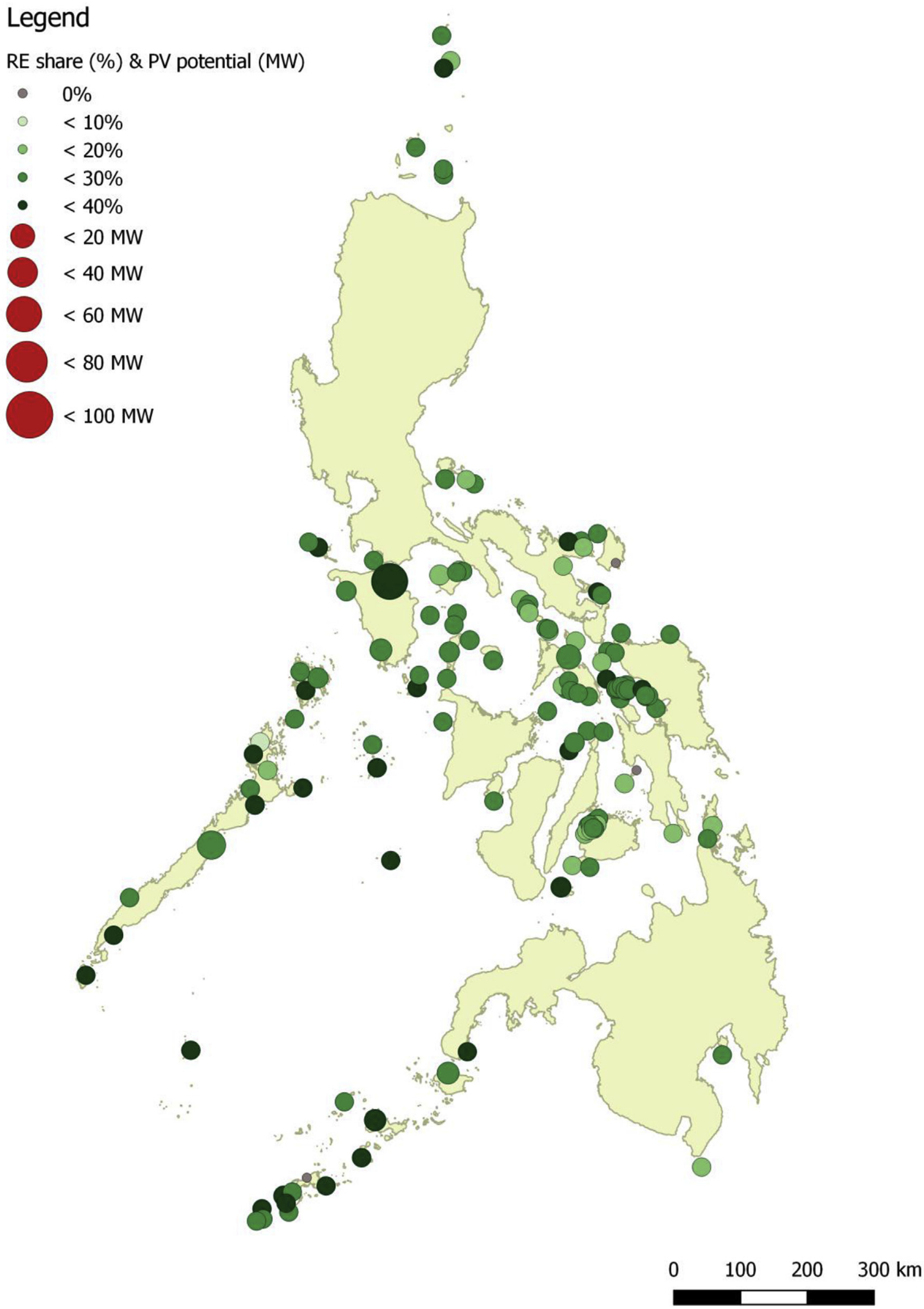

Fig. 8. Overview map showing RE-share (%) and PV potential (MW) for scenario 1.

Table 8
Results of diesel only simulation - Scenario 2: Load growth.

Region	Demand	Diesel only		
		Fuel cons	Fuel costs	LCOE
	[MWh/a]	[liter/a]	[USD/a]	[USD/kWh]
	sum	sum	sum	w.-avg.
Luzon	2,155,291	749,335	464,773	0.24
Visayas	135,233	47,288	32,953	0.27
Mindanao	384,172	114,348	93,708	0.27
National	**2,674,697**	**910,971**	**591,433**	**0.24**
Change to scenario 1	107.7%	107.7%	107.7%	0.00%

highlights the RE-share and solar PV potential for each grid under the assumptions of scenario 2.

4.4. Sensitivity analyses

Sensitivity analyses were applied for assessing the robustness of the above-described results and for studying the sensitivity of the results to key input parameters. Given the heterogeneity in fuel conversion efficiencies (0.26–0.83 l/kWh) and diesel fuel prices (0.16–1.33 USD/liter) for the identified SIIGs, we applied uniform values of 0.35 l/kWh for diesel fuel efficiency and 0.5 USD/liter of diesel fuel prices for all SIIGs as base sensitivity scenario. The reasoning for this harmonization of diesel prices and efficiencies is to introduce a global undistorted scenario which allows a comparison of diesel to hybrid systems in a more transparent way. The specific fuel prices and efficiencies of the previous scenarios are taken from the accounting system of the local operator and reflected the local perspective.

For all sensitivity analyses the energy demand for scenario 2 “load growth” was used resulting in a total annual energy demand of 2.67 GWh for all 132 SIIGs (Table 10). All technical and economic input parameters were determined as described in Table 3, unless otherwise stated in the following sections. Each sensitivity analysis was conducted for changes in diesel prices, WACC, PV costs or battery costs while other parameters remained equal (ceteris paribus).

In our study, the techno-economic feasibility of solar PV – battery – diesel hybrid energy systems was compared to diesel only systems. Thus, diesel fuel prices are one decisive factor for determining the economic feasibility of the hybrid energy systems. The fuel prices for the different SIIGs vary enormously and their composition is not transparent. For coming up with a clearer picture on the influence of the initial diesel fuel price on the optimized configuration a base sensitivity of 0.5 USD/liter was applied. Average diesel spot prices for 2017 were at 0.44 USD/liter (EIA, 2018). Adding fuel and handling costs, 0.5 USD/liter reflects a realistic average value as base price for all SIIGs. The price sensitivity analysis was conducted using 0.25 USD/liter (-50%), 0.75 USD/liter (+50%), 1 USD/liter (+100%) and 1.5 USD/liter (+150%) in order to study the impact of the fuel price development on the economic feasibility of hybrid energy systems. Table 10 reveals the results for the diesel only system with the presented diesel fuel price costs assumptions. As expected, with increasing diesel prices per liter the overall fuel costs increase correspondingly and result in increasing power generation costs (LCOE).

Table 10 presents the results of the sensitivity analyses on diesel fuel prices for the cost-optimized hybrid energy systems. The base scenario applying diesel fuel prices of 0.5 USD/liter and diesel generator efficiencies of 0.35 kWh/l shows similar results as scenario 2 described in section 4.3.

In both scenario 2 and in the sensitivity base case, an LCOE reduction potential of 0.02 USD/kWh is achieved by the implementation of PV and battery systems as revealed in Table 11. Compared to the scenario 2 (Table 9) the higher RE-share of 28% in the base sensitivity scenario is explained by higher investments in PV and battery systems. With diesel fuel prices reduced by 50% no more economic potential for solar PV hybridization can be identified. With increasing diesel fuel prices of 0.75 USD/liter and 1.0 USD/liter the cost-optimized RE-share increases to 34% and 36% respectively. For all three scenarios (base scenario, +50%, +100%) the ratio between PV capacity and battery capacity installed is around 4:1. Hence, the hybrid energy systems are designed for saving diesel fuel during the day with the support of high power batteries for system stability rather than substantially replacing diesel fuel at evening and night hours. This situation changes with diesel fuel prices of 1.5 USD/liter. The investment in solar PV and battery systems more than triples compared to the base scenario and the ratio between solar PV and battery system is in favor of battery systems to allow shifting substantial amount of solar generated power towards the evening hours resulting in a RE-share of more than 50%. Compared to the diesel fuel costs LCOE reduction grows substantially with each diesel price increase step. This is based on the relatively higher LCOE increase of diesel only systems compared to hybrid systems with increasing diesel fuel prices. At diesel prices of 1.50 USD/liter the LCOE savings amount to 0.16 USD/kWh.

The cost of capital in form of WACC is a decisive parameter for the cost effectiveness of solar PV and battery systems. This is due to the cost structure of high initial costs and low operational costs based on the absence of fuel expenditures for these. Thus, financing costs influence the economic performance of these new technologies stronger than those of conventional plants with low investment costs and high fuel expenditures. The results for the financing sensitivity analysis presented in Table 12 highlight that especially higher costs of capital would decrease the potential for solar PV. An increased WACC of 15% halves investments in solar PV with significant impact on the battery potential (decrease by 95% compared to based scenario). Consequently, the RE-share sinks to 17%. Lower costs of capital favor the implementation of solar PV: More solar PV and battery capacities are installed for the cost-optimized hybrid energy system facilitating RE-shares of 33%.

Solar PV investment costs are projected to further decrease after a substantial cost reduction in the last decade (Ilas et al., 2018). The

Table 9
Results of techno-economic optimization - Scenario 2: Load growth.

Region	Demand	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[MWh/a]	[USD]	[kWp]	[kWh]	[liter/a]	[USD/a]	[USD/kWh]	[%]
	sum	sum	sum	sum	sum	sum	w.-avg.	w.-avg.
Luzon	2,155,291	636.2	386.2	81.2	566,160	345,227	0.22	24.0
Visayas	135,233	43.2	25.7	6.7	35,199	24,217	0.24	25.2
Mindanao	384,172	137.3	80.5	23.7	81,291	66,313	0.24	29.0
National	2,674,697	**816.6**	**492.4**	**111.5**	**682,650**	**435,757**	**0.22**	**24.8**
Change to scenario 1	107.7%	107.4%	107.7%	104.7%	108.0%	107.7%	−0.02%	−0.32%

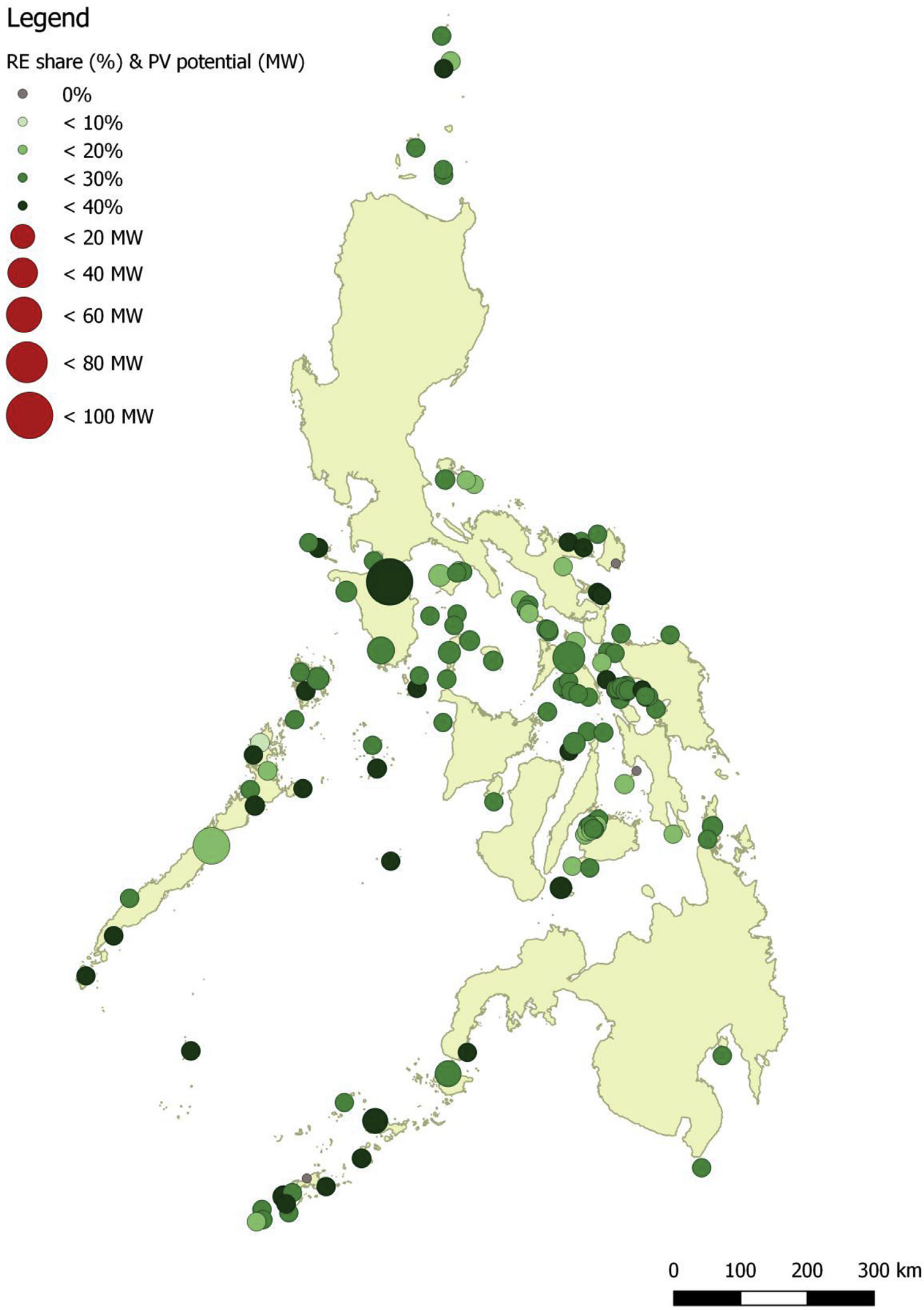

Fig. 9. Overview map showing RE-share (%) and PV potential (MW) for scenario 2.

Table 10
Results of sensitivity analysis for diesel fuel prices - diesel only system.

Sensitivities	Diesel fuel price	Demand	Diesel only system		
			Fuel cons.	Fuel costs	LCOE
	[USD/l]	[MWh/a]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]
		sum	sum	sum	w.-avg.
−50%	0.25	2,674,697	936,144	305,273	0.14
Base scenario	0.5			610,547	0.25
+50%	0.75			915,820	0.36
+100%	1			1,221,094	0.48
+150%	1.5			1,831,641	0.71

effect of lower and higher solar PV investment costs of 750 USD/kW and 2250 USD/kW are similar to the impact of WACC on the cost-optimized results (Table 13). Lower solar PV costs (−50%) allow for RE-shares of 35%. Even higher RE-shares would potentially be achieved with higher battery capacity, which do not increase at the same pace as solar PV capacities when comparing the base scenario and solar PV costs (+50%). Higher solar PV investment costs (+50%) substantially lower the potential for hybrid energy systems since the solar PV capacities shrinks by 45% and battery capacities by 95%. Due to the considered stability requirement, the pure solar PV capacity cannot substitute substantial shares of diesel power generation since diesel power is necessary for stability provision in the absence of battery systems.

For battery investment costs, strong cost reductions are projected so it is worth to test impacts of battery investment costs on the hybridization potential as well (Kittner et al., 2017; Schmidt et al., 2017). The sensitivity analysis provided in Table 14 reveals that changes in battery costs have lower impact on cost-optimized hybrid system configurations, LCOE and RE-share. Lower battery costs (−50%) facilitate a higher battery/solar PV ratio and increase the RE-share to 31%. With higher battery costs (+50%) less PV and battery capacity is installed, however the RE-share decreases less than compared to the above outlined sensitivity scenarios.

The following figures present the results of the sensitivity scenarios for diesel prices, WACC, PV costs and battery costs for a range of −50% and +50% compared to the base scenario for the key output parameters RE-share and LCOE (Fig. 10 & Fig. 11).

Diesel prices are clearly the most influencing parameter for hybridization potential. With diesel fuel prices below 0.25 USD/liter the investment into solar PV is not cost effective under current market conditions. From diesel prices of 0.5 USD/liter onwards solar PV hybridization becomes cost-effective. The potential for solar PV implementation grows steadily with diesel prices of 0.75 and 1 USD/liter and rapidly from costs of 1.0 USD/liter onwards as presented in Table 10. For LCOE the decrease of diesel prices leads to substantially lowered LCOE, as fuel prices are the main determining factor for the economic performance of diesel supplied systems. Increased diesel prices of 0.75 USD/liter lead to a substantial increase in LCOE since the share of diesel power generations is still significant and therefore the costs for fuel rise as well.

Changes in WACC, solar PV costs and battery costs have less impact on RE-share and LCOE. With regard to LCOE, it is important to point out that for all considered sensitivity analyses the cost-optimized hybrid systems have all LCOE reduction potential compared to the pure diesel base scenario with LCOE of 0.25 USD/kWh. Changes in WACC and solar PV costs affect the RE-share almost in the same way. Battery costs impact the RE-share slightly less significantly. With regards to LCOE changes, WACC has higher impact than changes of solar PV and battery investment costs.

For highlighting correlation between the input parameters, a non-favorable RE sensitivity with decreased diesel prices (−50%) and +50% increased WACC, PV costs and battery costs is compared to the base scenario and a favorable RE sensitivity with +50% diesel prices and −50% WACC, PV costs and battery costs (Table 15).

These extreme sensitivities show very different results. The non-favorable sensitivity leads to zero hybridization potential. Under these conditions, no techno-economic driven hybridization would take place on the small Philippine islands. This is contrasted by the favorable RE sensitivity analysis where we can identify RE-shares of more than 50%

Table 11
Results of sensitivity analysis for diesel fuel costs - hybrid energy system.

Sensitivities	Diesel fuel price	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[USD/l]	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
		sum	sum	sum	sum	sum	w.-avg.	w.-avg.
−50%	0.25	48.7	32.5	0.1	918,192.5	299,419.6	0.14	1.9
Base scenario	0.5	942.6	556.6	153.9	670,362.9	437,206.4	0.23	28.4
+50%	0.75	1234.4	726.5	206.6	618,922.3	605,485.7	0.31	33.9
+100%	1	1412.4	836.5	225.2	597,850.9	779,829.0	0.38	36.1
+150%	1.5	3323.7	1320.8	1917.8	419,423.7	820,636.3	0.51	55.2

Table 12
Results of sensitivity analysis for WACC - hybrid energy system.

Sensitivities	WACC	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[%]	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
		sum	sum	sum	sum	sum	w.-avg.	w.-avg.
−50%	5	1185.1	698.2	196.8	626,115.0	408,348.1	0.21	33.1
Base scenario	10	942.6	556.6	153.9	670,362.9	437,206.4	0.23	28.4
+50%	15	485.7	320.7	6.6	776,261.4	506,272.6	0.24	17.1

Table 13
Results of sensitivity analysis for PV investment costs - hybrid energy system.

Sensitivities	PV costs	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[USD/kW]	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
		sum	sum	sum	sum	sum	w.-avg.	w.-avg.
−50%	750	725.9	782.6	198.5	609,867.5	397,751.6	0.23	34.9
Base scenario	1500	942.6	556.6	153.9	670,362.9	437,206.4	0.22	28.4
+50%	2250	678.3	300.6	2.9	784,765.2	511,818.8	0.23	16.2

Table 14
Results of sensitivity analysis on for battery investment costs - hybrid energy system.

Sensitivities	Battery costs	Hybrid						
		Investment	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[USD/kWh]	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
		sum	sum	sum	sum	sum	w.-avg.	w.-avg.
−50%	350	977.6	605.5	198.1	649,020.4	423,286.9	0.22	30.7
Base scenario	750	942.6	556.6	153.9	670,362.9	437,206.4	0.22	28.4
+50%	1050	665.3	417.0	37.9	737,816.6	481,199.2	0.23	21.2

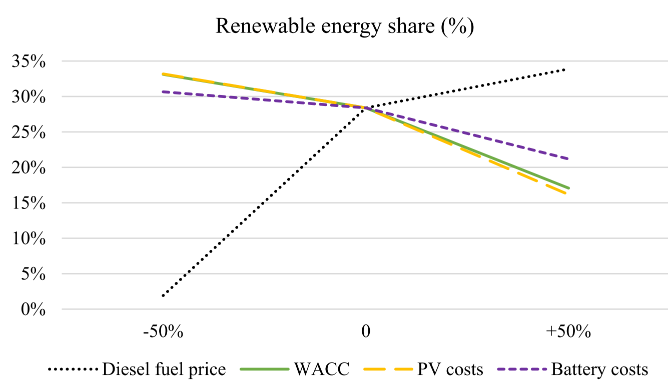

Fig. 10. Impact of selected input parameters on renewable energy share (%).

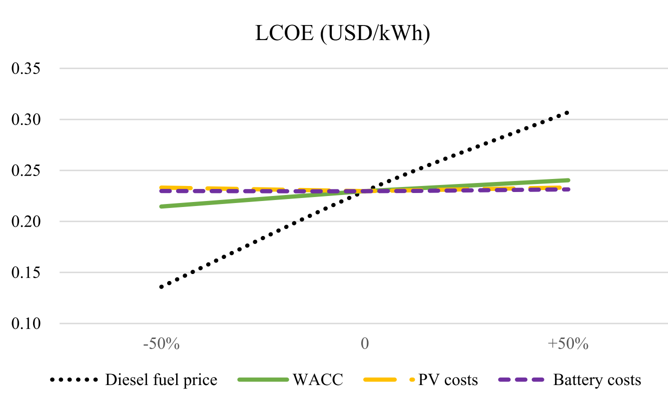

Fig. 11. Impact of selected input parameters on LCOE (USD/kWh).

and relatively low LCOE (Table 16). Similar results were also calculated for the 1.5 USD/liter diesel price sensitivity showing solar PV capacities of 1.3 GW and battery capacities of 1.9 GWh.

Looking at fuel price and technology projections, the favorable solar RE sensitivity seems to be not unlikely. Local fuel prices of 0.75 USD/liter are in place or exceeded in many SIIGs (compare Fig. 2). Also, cost projections of solar PV and batteries show constant decreases, which could result in solar PV costs of 750 USD/kW and battery costs of 350 USD/kWh. Additionally, the GoP could foster such cost development trajectories by setting higher taxes on diesel fuel as currently discussed or providing investment incentives for PV and battery investments. Additionally, financing schemes allowing reducing WACC to 5% would support the implementation of hybridization projects on the small Philippine islands. This would help to rapidly mitigate 50% of diesel fuel consumption and expenditures while increasing the quality towards 24 h supply and following the demand increase projections.

In summary, the sensitivities draw a more positive picture of the techno-economic hybridization potential in Philippine SIIGs. The favorable price and cost developments seem the more realistic sensitivities. Thus, a level playing field between RE and diesel systems combined with the expected global increase on fuel prices show great potential for constantly increased RE-shares without the need of governmental interventions. Hybridization would become a viable business case and could even be introduced as a decentralized approach, for example by providing beneficial net-billing schemes as suggested for Caribbean islands (Blechinger and Breyer, 2012). Considering the mentioned conditions of the favorable RE sensitivity the achievement of SDG7+ on the selected Philippine islands would be significantly accelerated.

Table 15
Assumptions for extreme sensitivities.

Sensitivities	Diesel fuel price	WA CC	PV costs	Battery costs
	[USD/l]	[%]	[USD/kW]	[USD/kWh]
Non-favorable RE	0.25	15	2250	1050
Base scenario	0.5	10	1500	700
Favorable RE	0.75	5	750	350

Table 16
Comparison of RE non-favorable and favorable scenario compared to base scenario.

Sensitivities	Hybrid						
	Invest.	PV cap.	Battery cap.	Fuel cons.	Fuel costs	LCOE	RE-share
	[million USD]	[MWp]	[MWh]	[thousand liter/a]	[thousand USD/a]	[USD/kWh]	[%]
	sum	sum	sm	sum	sum	w.-avg.	w.-avg
Non-favorable RE	0.0	0.0	0.0	936,143.8	305,273.5	0.14	0
Base scenario	942.6	556.6	153.9	670,362.9	437,206.4	0.23	28.4
Favorable RE	1691.6	1411.4	1808.7	421,321.9	412,175.2	0.36	55.0

5. Conclusions

The goal of this paper was to analyze if and how SDG7 +, the provision of affordable, reliable, sustainable and modern energy for all by resilient systems, can be achieved on small isolated island grids of the Philippines. The focus was set on different energy demand scenarios to understand the implications of 24 h supply for all customers and load growth over time. These were extended by different sensitivities to show implications of changed input parameters.

For scenario 0 - status quo, a demand of 1.25 TWh has to be supplied for 132 SIIGs with significant differences in the energy demand per location (ranging from 10,000 kWh/a to more than 50,000 MWh/a). Catering for this energy demand with only diesel power generation leads to the combustion of 430 million liter of diesel annually with implied costs of 277 million USD fuel costs and LCOE of 0.24 USD/kWh. It becomes obvious that diesel power generation is no option in the long term, when taking into account a 24 h supply (scenario 1) and the doubling of this energy demand by 2027 (scenario 2). In order to supply an increased demand of 2.7 TWh/a (scenario 2) with diesel power, 910 million liters of diesel fuel would be required on an annual basis resulting in expenditures for fuel of 591 million USD per year. This will put a strong additional burden on the UCME for each electricity customer in the Philippines. Thus, it will be an immense societal and political challenge to enable this increased quality of supply which would be required if the Philippines want to achieve their energy access target of 100% electrification and increased quality of supply by 2022 (DoE, 2016b).

Hybridization of these diesel systems is one of the preferred measures to reduce the fuel consumption and costs as well as LCOE. As shown for scenario 2 an investment of 816 million USD into 492 MW PV and 111 MWh battery capacities would result in a techno-economic optimized system configuration with a RE-share of 25%. The fuel consumption decreases respectively by 25% and the fuel costs decrease by 156 million USD per year. LCOE decrease from 0.24 to 0.22 USD/kWh. Under the current conditions, this reflects the techno-economically viable solution towards SDG7 +. Load growth and 24 h supply would be covered while the systems affordability, sustainability, and resilience are strengthened via the introduction of PV and battery systems. In conclusion, SDG7 + can only be achieved if the electrification efforts go hand in hand with an energy transition towards hybrid systems. Looking at increasing diesel prices in the future it becomes more and more necessary to start hybridization projects on these islands to keep the electricity supply affordable. Lower technology and financing costs can partly balance increased diesel fuel prices to stabilize the overall LCOE for all SIIGs.

Policy and decision makers can support SDG7 + by setting certain incentives, which may push the RE-share beyond 50%. First of all, the 24 h supply should be targeted as it comes with relatively low overall costs and increases the living quality of the affected consumers significantly. Secondly, 24 h supply is a prerequisite for economically viable hybridization compared to shorter service hours during evening and night. As an additional step, initial costs or WACC can be reduced through tax incentives or special loans which would make the long-term investment into solar PV and battery capacity more attractive. This increases the RE-share, reduces the fuel consumption and costs and moves the Philippines closer towards achieving SDG7 +.

Acknowledgements

The authors gratefully thank the Reiner Lemoine-Foundation for co-financing this research work.

This publication has been produced with the assistance of the European Union. The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union (EU).

This publication partly results from the authors' collaboration with the EU Access to Sustainable Energy Programme (ASEP) Technical Assistance (TA) implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Reiner Lemoine Institut (RLI) gGmbH, and ICF International and funded by the European Union. The authors gratefully acknowledge the support from ASEP and the Department of Energy (DOE) of the Philippines. Any conclusions or recommendations expressed in this article do not necessarily reflect the views of EU ASEP TA or DOE.

Annex 1 (corrected version)

Detailed information of considered diesel based energy systems

Longitude	Latitude	Grid Name	Island group	Specific Region	Province	Island Population	Energy demand (kWh)- Scenario 0	Energy demand (kWh)- Scenario 1	Energy demand (kWh)- Scenario 2
121.967583	20.4392	Batan Is. (Batanes)	Luzon	Cagayan Valley (Region II)	Batanes	12,859	9,827,982	9,827,982	20,412,406
121.835858	20.7823806	Itbayat	Luzon	Cagayan Valley (Region II)	Batanes	3,373	894,449	894,449	1,857,742
121.869108	20.3385556	Sabtang	Luzon	Cagayan Valley (Region II)	Batanes	1,297	824,690	824,690	1,712,855
121.476657	19.2611649	Calayan Is.	Luzon	Cagayan Valley (Region II)	Cagayan	7,527	697,225	1,133,418	2,354,074
121.876572	18.8929194	Balatubat	Luzon	Cagayan Valley (Region II)	Cagayan	5,618	180,789	342,197	710,732
121.871636	18.9701611	Minabel	Luzon	Cagayan Valley (Region II)	Cagayan	5,618	87,290	162,886	338,310
122.327114	14.7002639	Jomalig	Luzon	CALABARZON (Region IV-A)	Quezon	6,864	724,982	1,051,632	2,184,206
122.218414	14.7569583	Patnanungan	Luzon	CALABARZON (Region IV-A)	Quezon	14,002	1,226,443	1,670,504	3,469,583
121.922464	14.7640917	Polillo Is.	Luzon	CALABARZON (Region IV-A)	Quezon	65,550	9,705,265	9,705,265	20,157,526
121.853406	13.4613278	Mainland Marinduque	Luzon	MIMAROPA (Region IV-B)	Marinduque	250,328	49,413,216	49,881,493	103,602,274
122.120728	13.5256222	Maniwaya	Luzon	MIMAROPA (Region IV-B)	Marinduque	1,119	98,160	185,595	385,474
122.173106	13.5120694	Mongpong	Luzon	MIMAROPA (Region IV-B)	Marinduque	880	88,347	168,395	349,751
122.087575	13.4983694	Polo	Luzon	MIMAROPA (Region IV-B)	Marinduque	3,268	44,812	93,797	194,813
120.935931	13.6524861	Tingloy	Luzon	CALABARZON (Region IV-A)	Batangas	20,037	1,985,027	3,242,564	6,734,702
121.045708	12.4403083	Mainland Occidental Mindoro	Luzon	MIMAROPA (Region IV-B)	Occidental Mindoro	1,240,727	84,092,358	84,092,358	174,657,151
120.560722	13.2343889	Mamburao	Luzon	MIMAROPA (Region IV-B)	Occidental Mindoro	1,240,727	26,025,815	26,025,815	54,054,789
120.164894	13.8228139	Lubang Is.	Luzon	MIMAROPA (Region IV-B)	Occidental Mindoro	38,122	4,830,171	4,830,171	10,032,111
120.032511	13.8907333	Cabra	Luzon	MIMAROPA (Region IV-B)	Occidental Mindoro	2,923	91,235	196,758	408,660
122.272608	12.5783667	Romblon Is.	Luzon	MIMAROPA (Region IV-B)	Romblon	38,637	12,871,446	12,871,446	26,733,584
122.096331	12.9386389	Banton	Luzon	MIMAROPA (Region IV-B)	Romblon	7,545	644,631	862,881	1,792,176

Longitude	Latitude	Grid Name	Island group	Specific Region	Province	Island Population	Energy demand (kWh)- Scenario 0	Energy demand (kWh)- Scenario 1	Energy demand (kWh)- Scenario 2
122.5973	12.3043	Sibuyan Is.	Luzon	MIMAROPA (Region IV-B)	Romblon	63,535	9,898,837	9,898,837	20,559,569
121.958186	12.0551278	Carabao Is.	Luzon	MIMAROPA (Region IV-B)	Romblon	10,598	1,542,368	2,162,154	4,490,725
121.722308	12.9122917	Concepcion	Luzon	MIMAROPA (Region IV-B)	Romblon	4,055	772,462	997,818	2,072,437
122.05485	12.7836444	Corcuera	Luzon	MIMAROPA (Region IV-B)	Romblon	12,233	1,439,373	1,979,579	4,111,522
119.394814	11.1717694	El Nido	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	12,068,766	12,455,265	25,869,188
117.64095	9.04216667	Rizal	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	1,535,955	1,589,811	3,301,988
119.268242	10.5354361	San Vicente	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	3,168,428	3,228,734	6,705,978
119.503017	10.7922722	Taytay	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	4,903,906	5,019,700	10,425,757
120.941089	11.1517306	Agutaya Is.	Luzon	MIMAROPA (Region IV-B)	Palawan	6,787	275,673	480,049	997,047
119.9905	10.5575	Araceli	Luzon	MIMAROPA (Region IV-B)	Palawan	22,743	676,074	801,740	1,665,189
117.063506	7.98481389	Balabac Is.	Luzon	MIMAROPA (Region IV-B)	Palawan	14,574	451,581	898,012	1,865,141
121.199406	9.5814	Cagayancillo	Luzon	MIMAROPA (Region IV-B)	Palawan	4,573	253,403	658,201	1,367,062
121.003975	10.8380528	Cuyo Is.	Luzon	MIMAROPA (Region IV-B)	Palawan	22,803	6,451,249	6,472,261	13,442,679
120.014864	11.881475	Culion Is.	Luzon	MIMAROPA (Region IV-B)	Palawan	15,921	2,812,639	2,812,639	5,841,761
119.867206	11.4910778	Linapacan Is.	Luzon	MIMAROPA (Region IV-B)	Palawan	8,539	454,712	735,453	1,527,513
124.043511	13.2300389	Batan Is. (Albay)	Luzon	Bicol Region (Region V)	Albay	19,659	918,554	2,174,362	4,516,082
124.097969	13.1911694	Rapu-Rapu Is.	Luzon	Bicol Region (Region V)	Albay	16,544	1,927,320	2,483,416	5,157,977
123.817908	13.923925	Lahuy Is.	Luzon	Bicol Region (Region V)	Camarines Sur	1,955	136,961	251,377	522,103
123.638939	13.9149389	Quinalasag Is.	Luzon	Bicol Region (Region V)	Camarines Sur	3,786	203,068	518,736	1,077,398
123.565939	13.5844778	Atulayan	Luzon	Bicol Region (Region V)	Camarines Sur	547	13,879	32,037	66,539
123.848517	13.8395972	Haponan	Luzon	Bicol Region (Region V)	Camarines Sur	~500	19,936	19,936	41,406
123.73775	12.5642389	Ticao Is.	Luzon	Bicol Region (Region V)	Masbate	89,627	8,729,014	8,729,014	18,129,884
122.977642	13.1312833	Burias	Luzon	Bicol Region (Region V)	Masbate	89,579	529,949	1,315,687	2,732,640

Longitude	Latitude	Grid Name	Island group	Specific Region	Province	Island Population	Energy demand (kWh)- Scenario 0	Energy demand (kWh)- Scenario 1	Energy demand (kWh)- Scenario 2
123.604944	11.9118444	Chico	Luzon	Bicol Region (Region V)	Masbate	~500	71,950	131,201	272,501
123.552494	11.9585111	Gilotongan	Luzon	Bicol Region (Region V)	Masbate	~500	208,912	382,579	794,604
123.637939	12.0245472	Pena	Luzon	Bicol Region (Region V)	Masbate	~500	81,081	154,634	321,170
123.667603	11.891715	Naro	Luzon	Bicol Region (Region V)	Masbate	1,324	135,135	253,637	526,797
123.911417	11.8124528	Guin-awayan	Luzon	Bicol Region (Region V)	Masbate	~500	71,220	136,600	283,715
123.768742	11.8566444	Nabuctot	Luzon	Bicol Region (Region V)	Masbate	~500	42,878	78,633	163,318
123.088433	13.0658833	Dancalan	Luzon	Bicol Region (Region V)	Masbate	89,579	62,820	122,071	253,537
123.054317	13.0015806	Malaking Ilog	Luzon	Bicol Region (Region V)	Masbate	89,579	52,958	101,994	211,838
123.091333	12.9495889	Mababangbaybay	Luzon	Bicol Region (Region V)	Masbate	89,579	44,923	83,743	173,932
123.326586	12.7384	Osmena	Luzon	Bicol Region (Region V)	Masbate	89,579	60,993	116,158	241,257
123.368022	12.6985333	Penafrancia	Luzon	Bicol Region (Region V)	Masbate	89,579	46,019	101,184	210,156
123.36197	12.7282666	Quezon	Luzon	Bicol Region (Region V)	Masbate	89,579	46,749	87,612	181,968
124.046242	14.0219722	Palumbanes Is.	Luzon	Bicol Region (Region V)	Catanduanes	~500	56,355	99,261	206,162
124.296556	13.6244056	Mainland Catanduanes	Luzon	Bicol Region (Region V)	Catanduanes	259,076	54,152,568	55,240,834	114,733,454
121.547619	11.92855	Caluya Is.	Visayas	Western Visayas (Region VI)	Antique	4,313	2,035,596	2,035,596	4,227,868
121.90755	11.4671	Batbatan Is.	Visayas	Western Visayas (Region VI)	Antique	890	96,811	182,045	378,101
121.576558	12.0976694	Sibolo Is.	Visayas	Western Visayas (Region VI)	Antique	~500	30,505	58,507	121,517
122.609375	10.3918639	Guiwanon Is.	Visayas	Western Visayas (Region VI)	Guimaras	726	49,429	93,374	193,934
123.344744	11.6140333	Gigantes Norte	Visayas	Western Visayas (Region VI)	Iloilo	1,521	1,380,932	1,913,498	3,974,275
123.684419	9.51666667	Balicasag Is.	Visayas	Western Visayas (Region VI)	Bohol	~500	135,901	135,901	282,263
123.988703	10.1127972	Cuaming	Visayas	Western Visayas (Region VI)	Bohol	~500	115,078	227,431	472,366
123.855364	9.94231389	Mantatao	Visayas	Western Visayas (Region VI)	Bohol	~500	34,706	65,349	135,727
123.92345	9.49248889	Pamilacan	Visayas	Western Visayas (Region VI)	Bohol	~500	122,019	165,496	343,730

Longitude	Latitude	Grid Name	Island group	Specific Region	Province	Island Population	Energy demand (kWh)- Scenario 0	Energy demand (kWh)- Scenario 1	Energy demand (kWh)- Scenario 2
124.043653	10.154511	Cabul-an Is.	Visayas	Western Visayas (Region VI)	Bohol	~500	159,282	298,272	619,500
124.023294	10.0702111	Hambongan	Visayas	Western Visayas (Region VI)	Bohol	~500	23,819	45,881	95,293
123.89985	10.0551306	Bagongbanwa	Visayas	Western Visayas (Region VI)	Bohol	~500	54,653	103,708	215,398
123.989014	10.0141083	Batasan	Visayas	Western Visayas (Region VI)	Bohol	~500	35,071	66,140	137,370
123.882306	9.98743333	Bilangbilangan	Visayas	Western Visayas (Region VI)	Bohol	~500	13,627	27,526	57,170
123.927771	10.0717118	Mocaboc	Visayas	Western Visayas (Region VI)	Bohol	~500	24,733	47,012	97,642
123.941321	9.99793891	Pangapasan	Visayas	Western Visayas (Region VI)	Bohol	~500	29,409	55,776	115,845
123.969119	10.0243665	Ubay	Visayas	Western Visayas (Region VI)	Bohol	~500	11,654	22,283	46,280
124.401881	10.62925	Camotes Main Grid	Visayas	Central Visayas (Region VII)	Cebu	86,811	13,988,716	13,988,716	29,054,118
123.643492	11.0793583	Doong Is.	Visayas	Central Visayas (Region VII)	Cebu	1,293	374,385	874,373	1,816,046
123.894544	11.3438028	Guintarcan Is.	Visayas	Central Visayas (Region VII)	Cebu	3,295	188,521	347,156	721,032
124.567942	10.8077833	Pilar	Visayas	Central Visayas (Region VII)	Cebu	13,423	1,467,235	1,617,422	3,359,334
124.349611	11.7807389	Maripipi	Visayas	Eastern Visayas (Region VIII)	Biliran	7,775	848,287	1,121,862	2,330,072
125.064819	9.94746389	Limasawa	Visayas	Eastern Visayas (Region VIII)	Southern Leyte	6,554	849,748	1,111,013	2,307,538
124.364661	12.6731833	Biri Is.	Visayas	Eastern Visayas (Region VIII)	Northern Samar	7,067	1,315,173	1,784,871	3,707,120
124.181203	12.4236611	Capul	Visayas	Eastern Visayas (Region VIII)	Northern Samar	12,690	1,301,291	1,702,616	3,536,279
124.278947	12.4039167	San Antonio	Visayas	Eastern Visayas (Region VIII)	Northern Samar	9,162	1,456,605	1,456,605	3,025,323
124.098361	12.2767806	San Vicente/Destacado Is.	Visayas	Eastern Visayas (Region VIII)	Northern Samar	3,704	284,954	342,734	711,848
125.042331	12.6487861	Batag Is.	Visayas	Eastern Visayas (Region VIII)	Northern Samar	8,910	71,239	142,777	296,544
124.289342	11.9045639	Almagro Is.	Visayas	Eastern Visayas (Region VIII)	Western Samar	8,821	216,638	394,463	819,287
124.448886	11.9251667	Sto. Nino Is.	Visayas	Eastern Visayas (Region VIII)	Western Samar	10,471	57,100	108,404	225,151
124.160578	12.0467056	Tagapul-an Is.	Visayas	Eastern Visayas (Region VIII)	Western Samar	8,952	208,601	622,594	1,293,109
124.840847	11.6459583	Zumarraga	Visayas	Eastern Visayas (Region VIII)	Western Samar	18,467	1,962,896	1,962,896	4,076,873

124.432562	11.9666799	Camandag	Visayas	Eastern Visayas (Region VIII)	Western Samar	3,819	134,075	260,800	541,674
124.291417	11.9254472	Biasong	Visayas	Eastern Visayas (Region VIII)	Western Samar	8,821	47,492	84,284	175,055
124.335594	11.9451167	Costa Rica	Visayas	Eastern Visayas (Region VIII)	Western Samar	8,821	143,573	276,431	574,138
124.319336	11.9236611	Lunang	Visayas	Eastern Visayas (Region VIII)	Western Samar	8,821	84,756	160,382	333,109
124.367639	11.9487611	Kirikite Is.	Visayas	Eastern Visayas (Region VIII)	Western Samar	856	49,684	92,586	192,298
124.442978	11.8853083	Cabungaan	Visayas	Eastern Visayas (Region VIII)	Western Samar	10,471	75,915	134,168	278,662
124.417772	11.8930083	Ilijan	Visayas	Eastern Visayas (Region VIII)	Western Samar	10,471	26,267	55,545	115,365
124.461883	11.9047611	Takut	Visayas	Eastern Visayas (Region VIII)	Western Samar	10,471	165,493	296,306	615,419
124.650561	11.9045	Libucan Dacu Is.	Visayas	Eastern Visayas (Region VIII)	Western Samar	979	223,726	552,564	1,147,658
124.702275	11.80655	Bagongon	Visayas	Eastern Visayas (Region VIII)	Western Samar	~500	52,424	103,115	214,166
124.738931	11.8178417	Buluan	Visayas	Eastern Visayas (Region VIII)	Western Samar	~500	19,743	37,321	77,515
124.69475	11.8243694	Cinco-Rama	Visayas	Eastern Visayas (Region VIII)	Western Samar	735	174,600	319,313	663,202
125.717221	6.93662549	Talicud Is.	Mindanao	Davao Region (Region XI)	Davao del Norte	8,330	1,192,364	1,614,507	3,353,281
125.428503	5.416975	Balut Is.	Mindanao	Davao Region (Region XI)	Davao Occidental	11,485	887,426	1,134,971	2,357,298
125.605339	10.0442395	Dinagat Is.	Mindanao	Caraga (Region XIII)	Dinagat	125,740	22,613,289	22,613,289	46,967,082
125.535678	9.87133056	Hikdop Is.	Mindanao	Caraga (Region XIII)	Surigao del Norte	2,318	439,331	608,188	1,263,187
122.2517	6.98760833	Sacol Is.	Mindanao	Zamboanga Peninsula (Region IX)	Zamboanga del Sur	9,621	384,551	477,111	990,944
121.990783	6.69754167	Mainland Basilan	Mindanao	ARMM	Basilan	504,859	58,882,345	58,882,345	122,296,756
119.7693	5.0221	Bongao	Mindanao	ARMM	Tawi-Tawi	21,578	27,323,950	27,323,950	56,750,974
119.884336	5.075675	Panglima Sugala	Mindanao	ARMM	Tawi-Tawi	175,779	1,327,229	1,589,742	3,301,844
118.498436	6.987075	Mapun	Mindanao	ARMM	Tawi-Tawi	32,459	1,961,101	2,762,755	5,738,154
119.838644	4.80323333	Manuk Mankaw	Mindanao	ARMM	Tawi-Tawi	9,152	164,338	356,648	740,747
119.801933	4.92366667	West Simunul	Mindanao	ARMM	Tawi-Tawi	33,236	1,654,337	2,589,672	5,378,667
119.475667	4.84619444	Sibutu	Mindanao	ARMM	Tawi-Tawi	39,567	772,754	1,534,185	3,186,453
119.490297	4.70736667	Tandubanak	Mindanao	ARMM	Tawi-Tawi	39,567	672,325	1,171,023	2,432,178
119.403236	4.67942778	Sitangkay	Mindanao	ARMM	Tawi-Tawi	33,072	1,645,207	2,203,024	4,575,611

Longitude	Latitude	Grid Name	Island group	Specific Region	Province	Island Population	Energy demand (kWh)- Scenario 0	Energy demand (kWh)- Scenario 1	Energy demand (kWh)- Scenario 2
120.342061	5.16003333	Tandubas	Mindanao	ARMM	Tawi-Tawi	3,965	493,014	1,155,043	2,398,987
121.003147	6.05492778	Jolo Is.	Mindanao	ARMM	Sulu	694,482	52,722,239	53,402,020	110,914,296
120.821397	5.54474167	Siasi	Mindanao	ARMM	Sulu	65,043	3,887,509	4,316,304	8,964,827
120.583506	6.30194014	Pangutaran	Mindanao	ARMM	Sulu	19,029	141,696	317,179	658,771
120.079721	5.26955968	Languyan	Mindanao	ARMM	Tawi-Tawi	175,779	313,922	915,814	1,902,116
118.74684	9.7683884	Palawan Main Grid	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	238,198,236	238,334,306	495,012,768
121.160443	13.3700047	Oriental Mindoro	Luzon	MIMAROPA (Region IV-B)	Oriental Mindoro	1,240,727	248,557,711	249,006,421	517,178,412
123.714243	11.1838269	Mainland Bantayan	Luzon	Central Visayas (Region VII)	Bantayan	135,434	26,859,421	26,859,421	55,786,162
123.640789	12.3493428	Masbate Main Grid	Luzon	Bicol Region (Region V)	Masbate	676,691	111,141,569	112,194,831	233,025,094
121.991892	12.416999	Tablas Is.	Luzon	MIMAROPA (Region IV-B)	Romblon	172,848	28,420,537	28,533,330	59,262,817
123.527479	9.224404	Siquijor	Visayas	Central Visayas (Region VII)	Siquijor	98,123	24,616,989	24,663,398	51,225,092
120.179513	12.050568	Coron	Luzon	MIMAROPA (Region IV-B)	Palawan	58,214	36,317,582	36,317,582	75,430,461
119.934063	12.131825	Busuanga	Luzon	MIMAROPA (Region IV-B)	Palawan	58,214	2,545,221	3,018,317	6,268,949
124.117172	11.330774	Malapascua Is.	Visayas	Central Visayas (Region VII)	Cebu	1,174	4,952,234	4,952,234	10,285,632
117.432239	8.53165	Rio Tuba	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	2,942,257	3,066,622	6,369,275
119.306093	11.007436	Liminangcong	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	847,769	887,730	1,843,787
119.334236	10.319468	Roxas, Palawan	Luzon	MIMAROPA (Region IV-B)	Palawan	781,264	8,243,307	8,622,568	17,908,800

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3. Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options

Applied Energy 251 (2019) 113393

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Electricity sector planning for the Philippine islands: Considering centralized and decentralized supply options

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HIGHLIGHTS

- Submarine cable connection and renewable energy development reduce electricity costs.
- More than 2200 km of submarine cable are required to interconnect all island grids.
- Investment for submarine cable is higher than for renewable energy development.
- Submarine cable connections deliver least-cost electricity supply for larger islands.
- Hybrid renewable energy system are a cost-effective solution for most islands.

ARTICLE INFO

Keywords:
Submarine power cable
Hybrid electricity system
Interconnection
Island power supply
Philippines

ABSTRACT

For archipelagic states such as the Philippines, it is important to evaluate centralized and decentralized approaches to electricity supply to ensure that the many and far-flung islands receive affordable, reliable and sustainable electricity. This study compares the feasibility of (I) submarine cable interconnection and (II) renewable energy based hybrid system development for 132 islands. For (I), we conduct a geospatial analysis and use an algorithm to compute the optimized grid outline, taking into account bathymetric models. For (II) we apply an optimization tool that computes for each island the least-cost power generation option, taking into account diesel generator, solar photovoltaic systems, battery storage, and electricity demand. The results indicate that a grid extension of 2239 km submarine cable and 1752 km land cable would be required to connect all of the islands considered. The overall investment under the given cost assumptions amounts to more than 3 billion USD for submarine cable interconnection and more than 700 million USD for a hybridized system development. Nevertheless, submarine cable interconnection is the most economically feasible option for 35 islands and can reduce power generation costs by up to 0.21 USD/kWh. A sensitivity analysis reveals that submarine cable interconnection remains the cost-effective option for most of the identified islands, even with costs increasing by 90%. This study gives an initial assessment of centralized and decentralized electricity supply strategies, and finds renewable energy based hybrid systems most feasible for the majority of islands, and submarine cable interconnection more promising for a few larger islands.

1. Introduction

More than one billion people globally lack access to clean electricity, which is addressed under the sustainable development goal (SDG) 7: To ensure access to affordable, reliable, sustainable and modern energy for all [1]. Grid extension is the standard approach for providing access to electricity but with the prevalence of sustainable technologies, utilizing local renewable energy (RE) resources [2] in decentralized electricity systems emerges as an alternative option for remote areas [3], which previously were either insufficiently supplied by diesel generators, or not supplied at all [4]. To assess the cost-effectiveness of both decentralized and centralized solutions, least-cost electrification or electricity supply plans are required. Such plans often combine geospatial analysis with electricity system modelling to identify the optimal solution for a certain country or region [5]. Electrification plans have been developed for several territorial countries, such as Ethiopia [6] or Nigeria [7], but not yet for archipelagic countries or island states. Due to their insular character, decentralized

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https://doi.org/10.1016/j.apenergy.2019.113393
Received 28 December 2018; Received in revised form 17 May 2019; Accepted 20 May 2019
0306-2619/

options are often implemented without considering grid extension through submarine cables. This hinders the achievement of SDG 7 on remote islands, which are characterized by a low accessibility due to their inherent insular character [8].

While continental developing regions may benefit from the central grid extension of existing power networks, islands require submarine cable interconnections to achieve a connection to a larger power network. Installing submarine cable interconnections is capital-intensive, but can provide electricity at a low price assuming that the main grid has sufficient generation capacity [9]. Therefore, submarine cable interconnections might stimulate local economic development. Decentralized RE-based hybrid systems on islands present a viable option to increase the renewable energy share and lower generation costs [10], but upfront costs are high and hinder a wider deployment of RE on islands [11]. Nevertheless, this may change in the near future due to the decreasing costs of various technologies, such as solar photovoltaic systems [12], battery storage technologies [13], or innovative finance mechanisms [14].

Assessing and comparing the feasibility of both centralized and decentralized options for electricity supply is important for large archipelagic states such as Indonesia and the Philippines, and also applicable for smaller island states, including the small island developing states (SIDS). Being very vulnerable to extreme weather events and sea level rise [15], both types of countries face specific development challenges and climate change impacts. Low-carbon strategies are essential to mitigating the continuing impact of climate change through electrification and increasing electricity demand [16]. From an electricity access planning perspective, island landscapes are more complex than not archipelagic countries given that assessing centralized and decentralized supply options requires more detailed information (such as that supplied by seabed analysis). With this study, we present an approach for pre-assessing the cost-effectiveness of submarine power cable interconnection and RE-based hybrid electricity system development. We apply our methodology using the case of 132 decentral island electricity systems in the Philippines. The specific purpose of this study is threefold: (a) to identify the required submarine cable and land cable length necessary for island interconnection, (b) to compare the costs of decentralized and centralized electricity system development, (c) to derive a cost assessment for each of these options for each island group.

1.1. The electricity sector in the Philippines

The Philippines are one of the fastest-evolving countries in Southeast Asia. With both economic [17] and demographic growth [18] exceeding the world average, the country is expected to become a upper-middle income country by 2040 [18]. The country's electricity demand is increasing rapidly, contributing to Southeast Asia's enormous hunger for energy which is expected to triple by 2050 [19]. Given that it is also one of the countries most affected by the impacts of climate change [18], it is in the Philippines' inherent interest to increase power generation capacities in an environmentally sustainable manner [17]. In archipelagic states like this one [20], geographical character determines infrastructural development. A huge developmental gap between metropolis and periphery is typical for such countries. Today the bulk of the country's economic wealth is generated in and around the National Capital Region (NCR) of Manila [21], whereas many other parts of the country lag far behind in terms of living standards, education, public health provisions, and economic opportunities. To overcome such disparities, it is imperative that the Philippines develop a secure, sustainable and affordable power supply in all parts of the country.

Currently the main island groups of Luzon, Visayas and Mindanao are connected to two separately operating major electric grids [22], which supply electricity to most of its population and economically prosperous regions. At least another 132 decentralized electricity systems, referred to as small isolated island grids (SIIG), which basically generate electricity through diesel generators [23], are operated on medium- to smaller-sized islands. For these islands, researchers have identified a high potential for the use of RE [24]. Additionally, for a large number (1500–2000) of small and very small islands, power generation is either not officially regulated or not in place [25]. Diesel-based power generation fails to meet the economic and environmental targets of the country for several reasons: (1) Since fuel must be imported, it increases the country's dependency on global oil markets and price fluctuations [23]; (2) Diesel power generation is relatively costly, with average generation costs of 0.39 USD/kWh (compare Section 3.2). For privately-operated diesel generators, the reported costs to the customer can even be as high as 1 USD/kWh [26]. Additionally, electricity tariffs in remote regions are subsidized through the universal charge for missionary electrification (UCME) scheme, thereby increasing the costs of electricity on a national scale [23]. (3) Diesel power generation leads to environmental pollution through the emission of greenhouse gases (GHG) and other pollutants, and the risk of oil spills [18]. For the remote islands, the country faces the same energy security, equity and sustainability trilemma as Viña et al. have described for the country's main islands [18]. To avoid path dependencies and a lock-in dilemma, it is important to carefully assess all possible development options in the electricity sector from a number of different perspectives [27]. In this context, the question arises whether to interconnect the remote islands to the main electric grids, or upgrade the decentralized electricity system with RE. Both options present advantages and disadvantages: Connecting islands through submarine power cables is considered capital-intensive, but would allow for economies of scale. Developing RE-based hybrid systems can lead to an increased electricity autarky but requires higher maintenance efforts. As of today, no systematic assessment and comparison of both approaches has been conducted for the Philippines.

1.2. Submarine power cables and hybrid electricity systems

Submarine cables connect islands close to the shore usually on a medium-voltage level (< 52 kV) [9]. For longer distances high voltage direct current (HVDC) cables are favored over high voltage alternating current cables (HVAC) due to lower power losses and less required material [28]. Once deployed into the sea the cables are buried in the seabed or armored to avoid damages by other marine activities such as fishing [29]. Interconnections by submarine cables are already realized in the Philippines both by AC and DC cables at different voltage levels. The most important interconnection of the country is the high voltage direct current (HVDC) submarine cable link (440 MW/350 kV capacity) connecting the Luzon and Visayas main grids between Luzon and Leyte (21 km) [29]. According to the National Grid Corporation of the Philippines (NGCP), submarine power cable interconnections potentially increase the efficiency of the overall electricity system by lowering operation and maintenance costs through economies of scale and achieving a higher coincidence factor. This factor makes it easier to forecast the demand for electricity for a larger customer group, due to a statistical balancing effect that compensates for fluctuations of the assumed demand. Considering this, electricity demand is easier to assess for larger settlements than for small villages due to a higher volatility of the load [30]. Electricity exports from the main grid to remote islands support economic development on these islands by enabling them to access relatively cost-competitive electricity prices. However, the planning and realization of such projects requires both high upfront capital investments and that uncertainties such as seabed currents be considered [31]. While high and inestimable costs are stated as the main barriers for submarine cable expansion, recently developed probabilistic cost models may increase the accuracy of submarine power cable cost projections [27]. So far, only a few studies on an international scale have analyzed the impact of submarine cable interconnection on electricity sector development, and none of these studies have focused on the Philippines. Ahmed et al. [28] studied the feasibility of HVAC and HVDC submarine interconnection for the ASEAN member states and concluded that HVDC is competitive over HVAC from distances of 160 km onwards. For the case of Greece, studies highlighted that the interconnection of islands would allow for a higher RE share in the electricity mix on the national scale [32] and lower electricity costs on the island scale [33]. Another study, examining the techno-economic feasibility of interconnecting the European and the US electricity sector, concluded that the socio-economic benefits would alleviate the high investment costs [34].

The significant potential that RE holds out for the island context has been intensively discussed in the scientific literature. Kuang et al. [35] provided an overview of the development status of renewable energy on islands, stressing that hybrid electricity systems, based on one or more RE technologies combined with battery storage solutions and/or fossil back-up generators, are one of the most feasible solutions. The global techno-economic potential of such systems, and their significant potential for the Pacific region, was outlined by Blechinger et al. [10]. These findings are supported by Meschede et al. [2], who applied a cluster analysis of islands. Neves et al. [36] presented an overview of case studies of hybrid electricity systems in which different RE and conventional technologies were applied. For the Philippines, a study of the techno-economic potential of transitioning from diesel-based systems to low-carbon electricity systems in order to achieve SDG 7 [24], taking into account site-specific data and recent cost predictions, was conducted by the authors in two publications [24] and [37].

In conclusion, there is a lack of research on least-cost electricity supply or renewable energy planning for the context of small islands and island states in which submarine cable interconnection are compared to RE-based hybrid system development. In this study, we address this knowledge gap by comparing the economic feasibility of submarine interconnection to the central grid with the development of RE-based hybrid systems for 132 decentral island systems in the Philippines. To assess the economic potential of submarine interconnection, we use a geospatial optimization routine to outline provisional submarine cable routes, taking into account digital elevation models and bathymetric maps. Based on the identified required cable length, we derive necessary investment costs. We then analyze the potential for RE-based hybrid system development by applying an electricity system simulation model. Investment costs are projected based on least-cost power generation, considering recent technology cost assumptions. Finally, we compare and discuss both options in terms of the levelized cost of electricity (LCOE), investment costs, and benefits to the development of the overall electricity sector.

2. Methods

The methods chapter provides key information on the studied island grids (Section 2.1), projected electricity demands (Section 2.2), and introduces the approach we use to assess submarine cable interconnection (Section 2.3) and RE-based hybrid system development (Section 2.4).

2.1. Small isolated island grid landscape

In the Philippines, decentralized electricity systems rely mainly on diesel generators for power generation. The objective is to study the feasibility of grid interconnection through submarine power cables for the aforementioned electricity systems and to derive the related investment and power supply costs by applying a geospatial analysis. Subsequently, the feasibility of RE integration in the existing systems is studied as an alternative pathway by applying an electricity system optimization tool. Finally, the viability of both approaches is compared and discussed.

For this study, 132 small isolated island grids are considered. SIIGs are operated by the local electric cooperative (EC) in charge of transmission and distribution. Power generation assets are operated by either the former national power operator NPC-SPUG[1] (86%) or by independent power producers (14%). In early 2018, key data on these SIIGs were collected from the Philippine Department of Energy (DoE) [38] and NPC SPUG [39], covering their location, grid name, region, operator, distributor, power plant capacities, fuel prices, efficiency rate and electricity demand. We assume that the applied dataset covers the most relevant and largest SIIGs in the Philippines. The following table provides key information on the SIIGs we considered within the three main regions of Luzon, Visayas and Mindanao (Table 1).

Table 1 reveals the heterogeneity of the SIIG landscape of the Philippines. Most of the SIIGs (67), and diesel power plants (99), with the highest capacity (> 356 MW), are located in Luzon. The peak demand of 190 MW and annual electricity demand of 1022 GWh are also highest in Luzon, reflecting the larger number of grids and longer average operating hours. Peak and annual demand in the Mindanao region amounts to 30 MW and 177 GWh, followed by those for the Visayas region, with a peak demand of 13 MW and an annual demand of 60 GWh. However, the three largest SIIGs in Luzon (Oriental Mindoro, Palawan main grid, Masbate main grid) comprise 46% of the annual demand for electricity for all SIIGs. Adding the next three largest SIIGs (Occidental Mindoro, Catanduanes, Marinduque) in Luzon to the selection increases the share to 61%. For the regions of Visayas and Mindanao, the total installed power capacities in the SIIGs are much lower (27 MW and 67 MW, respectively). In most of the SIIGs for the two regions, the distribution grid is supplied by only one diesel power plant; by contrast, in the larger grids in Luzon, several plants are supplying the local distribution grids. Average daily operating hours are approximately 16 h in the Luzon and Mindanao grids, as contrasted to the grids of the Visayas region where smaller grids, in particular, have shorter service hours leading to an average service hour duration of only around 12 h per day. Fig. 1 illustrates the SIIGs considered.

2.2. Estimation and projection of electricity demand

To accurately assess the potential of electricity supply options, the impact of electricity demand must be considered for each option. This is especially important for mini-grids [40] and rural electrification in developing countries [41], as electricity demand tends to evolve after electricity access has improved [42]. Furthermore, for the potential of intermittent RE sources such as solar photovoltaics (PV), the temporal distribution of electricity demands can be decisive. To address this we carried out a detailed estimation and projection of electricity demands, based on an approach we applied in a recently published work [24]. Electricity demand patterns were collected on an hourly basis for the majority (126 of 132) of the considered SIIGs from the Philippine DoE [38] and NPC SPUG [39]. This resulted in an annual electricity demand of approximately 1260 GWh (see Table 1). Nevertheless, 87 out of the 132 considered SIIGs supply electricity for less than 24 h per day. Increasing daily service hours to 24 for all consumers is one of the targets of the Philippines government [38], and is in line with its objective to achieve the SDG 7. We have reflected this target by applying 24-hour load profiles for all SIIGs through filling the not supplied service hours according to typical demands. By applying the approach we outlined in a recent publication [24], 24/7 load profiles were derived for each identified 132 SIIG with realistic hourly values, resulting in an increase of 2% to 1287 GWh/a of the total demand for electricity.

2.3. Submarine power cable interconnection – geospatial analysis

Spatial modelling of submarine interconnection to the selected SIIGs assesses the economic feasibility and estimated investment costs of this option. The approach optimizes the overall grid extension path to all

[1] National Power Corporation – Small Power Utilities Group (https://www.spug.ph/).

Table 1
Key information for considered small isolated island grids per region.

Region [name]	No. of grids [#]	No. power plants [#]	Daily operating hours [hours]	Rated capacity [MW]	Fuel price [USD/l]	Peak demand [MW]	Annual demand [GWh/a]
Luzon	67	99	16.5	356.2	0.55	190.7	1022.6
Visayas	46	48	12.8	26.6	0.51	13.1	59.7
Mindanao	19	22	16.2	67.1	0.63	29.8	177.5
Total	132	169		449.9		233.6	1259.8
Average			15.2		0.56		

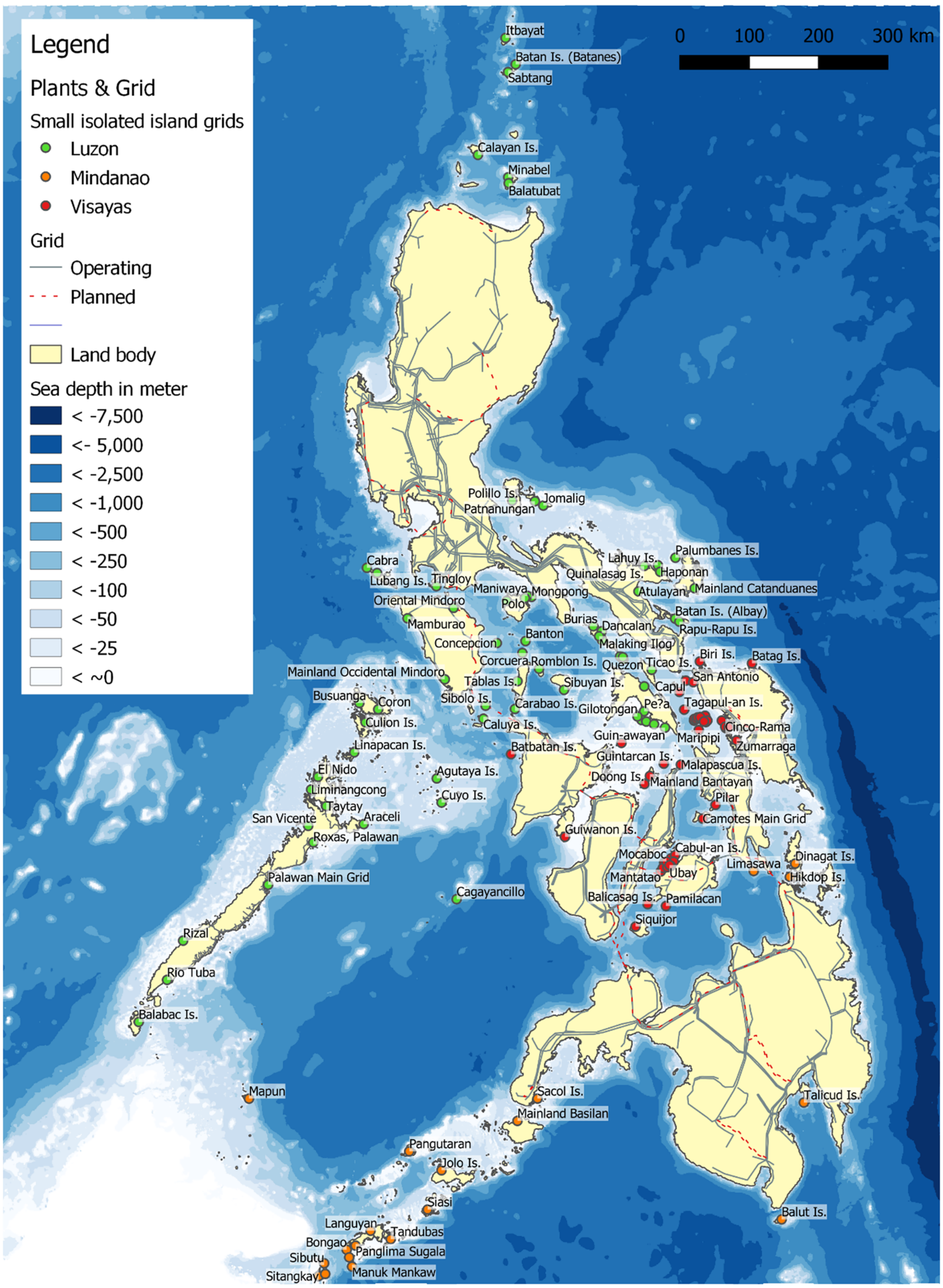

Fig. 1. Location of 132 small isolated island grids and transmission grid in the Philippines.

considered SIIGs under the constraint of following the shortest and flattest possible route instead of only considering the shortest linear distance [43]. The key parameters considered are sea depth and elevation, derived from bathymetric and topographic maps. Hence, the identified grid extension reflects the optimized plan for the interconnection of all SIIGs based on their location-specific characteristics, such as seabed bathymetry and distance to neighboring islands—independently of characteristics such as annual electricity demand. Such a geospatial network planning for insular frameworks requires the following datasets: (1) the location and course of the existing transmission grid as starting point for the grid extension, (2) the location of the SIIGs as the ending point for grid extension, (3) information on sea depth and elevation, to assess the feasibility of spanning the grid over specific routes. Dataset (1) is derived by creating polyline shapefiles of the existing grid and planned grid extension, as published by NGCP [31]. For the subsequent analysis, only the existing grid is considered due to the uncertainty of project realization of the planned grid. Dataset (2) is derived by creating a point shapefile of SIIG locations taken from [38] and [39]. For dataset (3), we applied gridded bathymetric and elevation data for ocean and land in a resolution of one square kilometer covering the Philippine archipelago, provided by the British Oceanographic Center [44]. Fig. 2 visualizes the aforementioned datasets for a sample region and highlights the applied approach.

Based on the described datasets, a decision raster dataset was created by converting terrain information for both ocean and land into slope values based on dataset (3). To allow the optimization algorithm to use the complete existing grid as starting point for grid extension and SIIG locations as ending points, dataset (1) and (2) were added to the decision raster with zero weighted costs. As relative costs increase with higher slopes, the tool optimizes the routes by identifying a route minimizing the bypassing slopes. Additionally, cable routes over land are favored over sea routes. Under these assumptions, an optimum connection pathway to extend the grid to all SIIGs was derived by applying a minimum spanning tree. The minimum spanning tree considers all possible options and connects the locations by minimizing the required connections between all new grid extension lines. Finally, a least-cost grid extension outline was extracted, as highlighted for the sample region in Fig. 2.

The identified grid outline was further processed to differentiate the segments in grid extension through submarine or land cable. The required cable length for each segment was then calculated. Additionally, for all submarine cable segments, the extra cable requirement based on sea depth was derived. This was necessary to accurately estimate investment costs, since submarine power cables need to be buried or fixed in the seabed as illustrated in Fig. 3. For each submarine cable segment, the sea depth was identified in one kilometer-steps and the accumulated depth calculated based on the corresponding elevation difference. To specifically calculate the investment costs for each submarine segment, the accumulated depth was added to the required length.

2.3.1. *Submarine power cable interconnection cost estimation*

Submarine power cable interconnections are major infrastructure projects that require significant planning, labor force, stakeholder dialogues, and investment capital. The assessment of probable costs is crucial for decision makers to advance the planning of such infrastructure projects. It is therefore necessary to assess costs in an early project stage. For submarine power cable projects, cost assessments are very difficult due to the lack of historical data, site-specific conditions, preplanning requirements, and uncertainty of project conditions. An approach based on probabilistic cost prediction for submarine power cables has been introduced [27], but the model is not sufficiently calibrated with data from the focus region. Ultimately, a simplified cost assumption model based on the required submarine and land cable length and voltage level was implemented and applied for this study. The length of the grid extension was derived from the optimum grid extension path, as described above. The voltage level per submarine project was defined based on submarine route length and electricity demand of the islands to be connected, excluding additional electrotechnical characteristics for a simplified approach. Finally, the highest required voltage level based on demand or length was applied. The scheme presented in Table 2 was applied to assign adequate voltage levels to each of the submarine cables.

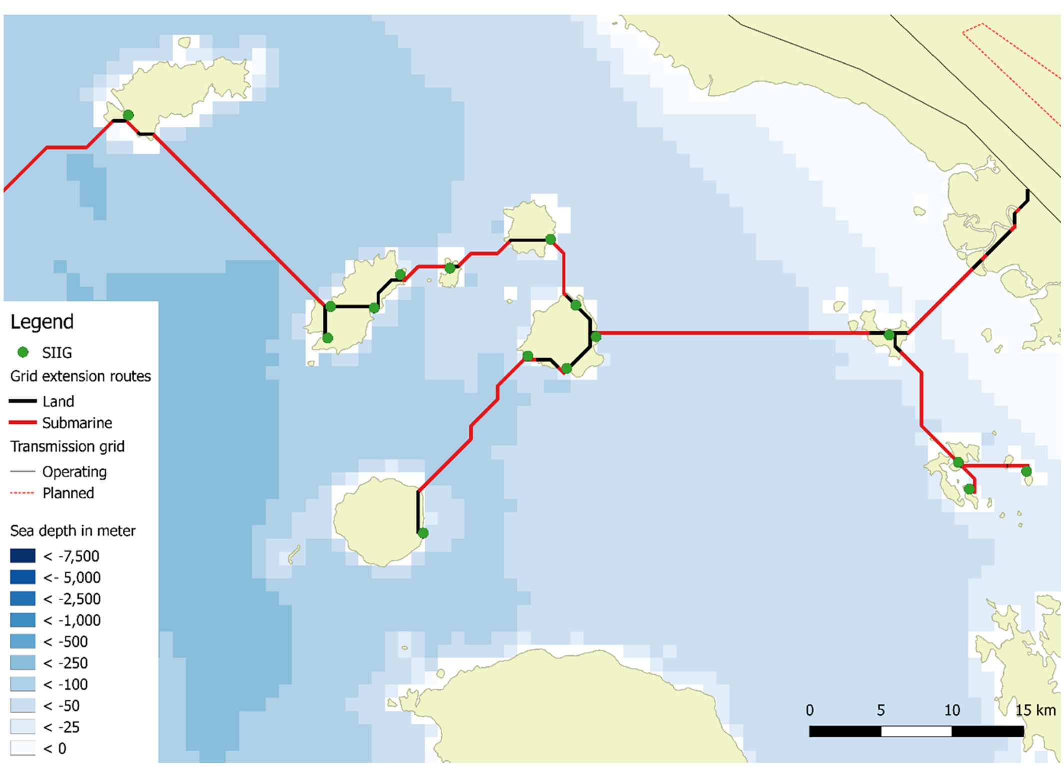

Fig. 2. Example for optimized grid extension via submarine and land cable taking into account local bathymetry and a minimum spanning tree.

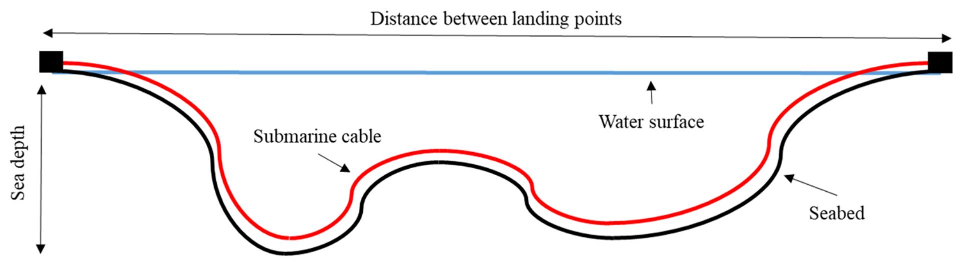

Fig. 3. Sketch of submarine cable route reflecting sea depth.

Table 2
Assigned voltage levels per peak demand and submarine length.

Voltage level (kV)	Peak demand (kW)	Submarine length (km)
13.2	200	< 5
34	1,000	< 10
69	5,000	< 20
138	10,000	< 50
230	> 10,000	> 50

Table 3
Applied cost values for grid extension, taking into account capital expenditures, operational expenditures, interest rates, power generation costs, and lifetime of components.

Category	Parameter	Unit	Value
Submarine power cable	CAPEX (13.2 kV)	USD/km	350,000
	CAPEX (34 kV)	USD/km	500,000
	CAPEX (69 kV)	USD/km	750,000
	CAPEX (138 kV)	USD/km	1,000,000
	CAPEX (230 kV)	USD/km	1,500,000
	OPEX	USD/y	0.005% CAPEX Invest
	Lifetime	yearsYears	40
Land power cable	CAPEX	USD/km	12,000
	OPEX	USD/y	0.05% CAPEX Invest
	Lifetime	years	40
Economic	Project lifetime	years	40
	Interest rate	%	10
	Power generation costs (main grid)	USD/kWh	0.09

Investment costs were calculated by multiplying the identified required cable length by the applied cost value for the respective voltage level for each submarine power cable. For the required land power cable, a fixed cost value of 12,000 USD/km is assumed [45]. Table 3 provides an overview of the applied cost assumptions. These cost assumptions are based on discussions with representatives of the Philippine DoE and the National Electrification Administration (NEA), and reflect costs assumed for submarine cable development in the Philippines. It is certain that costs per kilometer may differ in accordance with technology and voltage level, as well as to the specific project conditions (seabed currents, marine surface, etc.). The power generation costs for the central power supply were not specifically modeled in this paper; instead, we used a generic cost of 0.09 USD/kWh for this variable. Thus, the modeled grid extension pathways should only be implemented if power generation capacity is increased to meet the additional demand.

Finally, the levelized cost of electricity (LCOE) for each of the required infrastructure investments was calculated, as described in Eqs. (1) and (2).

$$LCOE = \frac{IC * CRF(WACC, N) + OPEX}{E_{consumed}} + LCOEgrid \quad (1)$$

Eq. (1): LCOE for submarine power cables. The abbreviations stand for Initial costs (IC), capital recovery factor (CRF), weighted average cost of capital (WACC), project lifetime (N), operation and maintenance expenditures per year (OPEX), and consumed electricity per year ($E_{consumed}$).

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (2)$$

Eq. (2): Capital recovery factor (CRF). CRF is set according to the weighted average cost of capital (WACC) and project lifetime in years (N).

2.4. Renewable energy- based hybrid system development: Electricity system optimization

In this study, the potential for RE-based hybrid electricity systems for each SIIG is analyzed using an electricity system simulation and optimization tool. This approach is based on model used in a recent study by the authors, focusing on the hybridization potential in the Philippines [24]. The applied tool optimizes the system design in terms of lowest LCOE, considering renewable energy (solar PV), fossil fuel resources, and battery storage capacities. The tool is implemented in the Python programming language [46] and was applied in peer-reviewed studies on a global scale [10] and to the Philippine case specifically [37]. It was also validated with HOMER Energy [47]. The approach simulates electricity flows in hourly increments for one reference year, taking into account diesel generator, PV, battery storage, and the electricity demand. The application of components is based on a published dispatch strategy [24], which aims to maximize the use of solar power plant-derived electricity. To ensure the stability of the system, however, at each time-step a stability criterion of 40% of the respective hourly load must be fulfilled by the battery storage or the diesel generator. The feasibility of meeting this criterion while supplying the load entirely by solar power is checked. In the case of insufficient solar power, the system discharges the battery to its allowable lowest state-of-charge (SOC) before activating the diesel generator. The optimization algorithm minimizes the LCOE by using iteration to vary the sizes of the components. PV and battery storage systems are the variable parameters for this study, since the diesel capacities are already in place and are set equal to the SIIG peak demand. The final LCOE takes into account the annualized initial costs; operational costs per year and fuel costs per year and are divided by the overall electricity demand to provide LCOE per kWh (Eq. (3) and Eq. (4)) [14]. The tool feedbacks the configuration of the electricity supply system, leading to minimized LCOE considering the local resources—in this case, solar irradiation.

$$LCOE = \frac{IC * CRF(WACC, N) + OPEX + Costs_{fuel} * Fuel}{E_{consumed}} \quad (3)$$

Eq. (3): Levelized cost of electricity (LCOE) for power systems. The abbreviations stand for Initial costs (IC), capital recovery factor (CRF), weighted average cost of capital (WACC) project lifetime (N), operation and maintenance expenditures per year (OPEX), cost of diesel per liter ($Costs_{fuel}$), consumed diesel per year (Fuel), and consumed electricity

Table 4
Overview of technical and economic input values for electricity system simulation tool.

Category	Parameter	Unit	Value
PV	CAPEX	USD/kW	1400
	OPEX	USD/kW/y	28
	Lifetime	years	20
Battery	CAPEX (Capacity & Power)	USD/kWh	800
	OPEX	USD/kWh/y	8
	Lifetime	years	15
	maximum c-rate	kW/kWh	1
	depth of discharge	%	80
	charging efficiency	%	90
	discharging efficiency	%	90
	initial state of charge	%	50
Diesel	CAPEX	USD/kW	500
	OPEX (fix)	USD/kW/y	20
	OPEX (var)	USD/kWh	0.02
	Lifetime	years	20
	Rotating mass	%	40
	Efficiency	l/kWh	0.35
Economic	Diesel price	USD/l	0.75
	Project lifetime	years	20
	Annual Fuel Changings	%	3
	Interest rate	%	10

per year ($E_{consumed}$).

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (4)$$

Eq. (4): Capital recovery factor (CRF). CRF is set according to the weighted average cost of capital (WACC) and project lifetime in years (N).

2.4.1. Resource, technical and economic input parameter

To assess the local potential for PV power generation, site-specific values for global horizontal irradiation (GHI) were obtained from GHI datasets [48] and converted into PV power generation based on a published conversion model [49]. Combining the aforementioned models lead to an individual PV yield in hourly time steps for each considered electricity system (SIIG). Besides the available renewable resources, it is necessary to define the technical and economic parameters of each component. A summary of all input parameters is given in Table 4.

The system components are basically described by CAPEX, OPEX, lifetime and technical constraints. For solar PV, costs of 1400 USD/kWp were applied [50], OPEX of 28 USD/kWp per year (2% of CAPEX), and a lifetime of 20 years. We consider the use of lithium-ion batteries as an electricity storage system, given its advantageous characteristics over other storage technologies [13]. Initial costs add up to 800 USD/kWh for capacity [51], combining the costs for capacity and power at a fixed c-rate of one as a modular unit. OPEX are 8 USD/kWh per year and the lifetime is 15 years. Other technical parameters are round-cycle efficiency of 90% and a maximum depth of discharge of 80%. No degradation rate is considered, since it is assumed that lithium-ion batteries are operated under stable temperatures (through cooling) and that the maximum depth of discharge is not violated, since temperature and state of charge have been identified as most influential factors for lithium-ion battery ageing and degradation [52]. For all SIIGs diesel generators are already in place. However, since most diesel generators have already operated for years or even decades and are facing the end of their lifetime, it might be necessary to implement new diesel generators—especially as modern diesel generators are more controllable and better harmonized with RE-based hybrid systems. Therefore, initial costs of 500 USD/kW are assumed for diesel generators. Operational costs are based on expenditures for maintenance or lubricant oils and amount to 0.02 USD per generated kWh and 20 USD per kW annually. The lifetime of the new diesel plants was set at 20 years. We introduced a system stability parameter of 40% of the hourly demand (compare Section 2.4). This reflects the operating diesel capacity necessary to provide auxiliary services in case of insufficient supply by the battery storage system. The efficiency value for each SIIG was set at 0.35 l/kWh, reflecting the efficiency of modern diesel generators. The diesel fuel price was set to 0.75 USD/l, assumed as the average diesel cost in the Philippines in 2018. The diesel price growth rate is expected to be 3% annually. For each project, a lifetime of 20 years was applied. The weighted average costs of capital (WACC) are 10%, based on an equity share of 40%, equity costs of 15%, and a loan interest rate of 6.6%.

3. Results

The results chapter outlines our findings with respect to our assessment of submarine cable interconnection (Section 3.1) and hybrid electricity system development (Section 3.2), concluding with a least-cost comparison (Section 3.3) and sensitivity analysis (Section 3.4).

3.1. Submarine cable interconnection

Based on the identified cable routes, interconnecting all considered SIIGs to the main grid of the Philippines requires a 2239 km submarine power cable and a 1752 km land power cable (“overhead” cable). The development of 321 segments of submarine power cable and 412 segments of land power cable is necessary to realize the said grid extension. Based on the considered input parameters the total investment costs add up to approx. 3.2 billion USD for submarine power cables and 21.0 million USD for land power cables. Table 5 gives an overview of the key result values derived by the geospatial analysis.

Since most of the required grid extension for both submarine and land cable would be implemented in the Luzon region, basically due to the larger number of SIIGs there, investment would be predominantly used for projects in that region. However, investment per SIIG is highest in Mindanao due to the lower number of SIIGs, less grid infrastructure in place, and higher remoteness of the islands there. As the geospatial analysis optimizes the submarine cable routes in terms of length and depth, the identified routes follow the shortest path in the shallowest water possible. The longest cable route identified has a length of 168 km and connects the southernmost island of Mapun to Balabac island, south of Palawan (Fig. 4, number 30). Out of all submarine cable routes, only five exceed a length of 80 km, considered as the threshold for AC versus DC power cable deployment [29]. However, the average length of all submarine routes is 7.5 km. The average maximal depth per route of all identified routes is 209 m, whereas the maximal depth exceeds 1673 m for the submarine route passing the Luzon strait towards the northernmost islands of the Batanes group (no. 1 in Fig. 4). Since submarine cables need to be buried or fixed in the seabed to avoid suffering damage from other marine activities (such as fisheries), the depth for passing submarine routes is of importance as well. Therefore, for each route the accumulated depth is calculated to account for additional material requirement. On average, the accumulated depth adds 224 m to the overall cable requirement. For some routes that pass along

Table 5
Overview of the results on submarine power interconnection optimization for the three main regions of the Philippines.

Region	Length (km)		Investment (m. USD)		LCOE
	Submarine	Land	Submarine	Land	USD/kWh
Luzon	1193	1047	1691.8	12.6	0.28
Visayas	450	264	638.7	3.2	0.89
Mindanao	596	441	867.1	5.3	0.61
Total	2239	1752	3197.6	21.0	0.37 (av.)

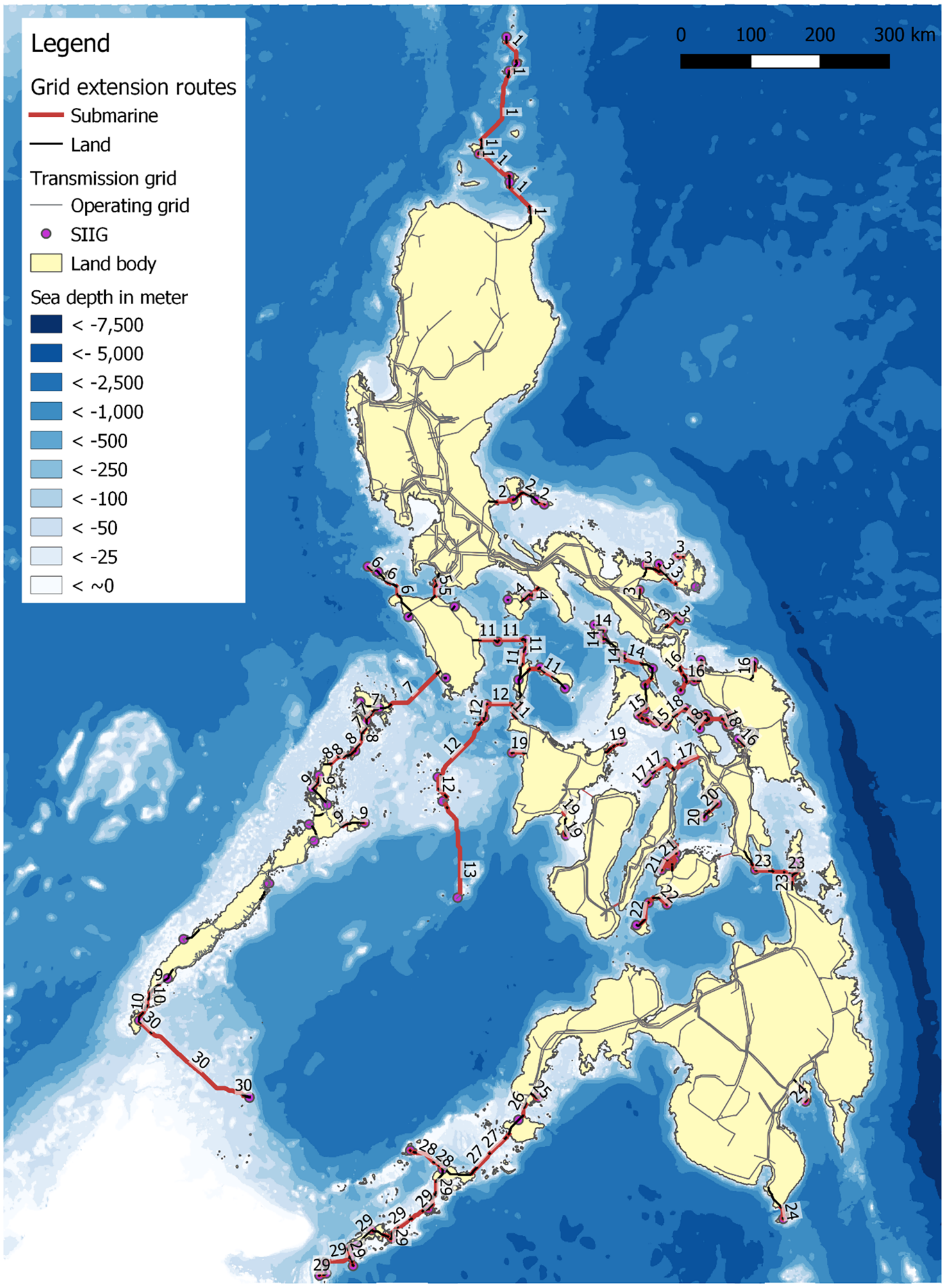

Fig. 4. Optimized submarine and land power cable routes for interconnecting decentralized electricity systems.

deep trenches, however, the accumulated depth is significant; such is the case, for example, for the route passing the Luzon strait towards the Batanes group (no. 1 in Fig. 4), where the added cable requirement is 5.7 km. The land power cables are mainly required to close the gap between the submarine cable landing station and the existing grid. The longest required cable is approximately 47.9 km in length, whereas the average length of all land power cables is 4.8 km. Fig. 4 maps the optimized submarine and land power cable routes for interconnecting decentralized electricity systems.

3.2. Renewable energy – based hybrid systems

The techno-economic modelling of RE-based hybrid electricity systems reveals a significant potential for integrating renewable energy into the existing SIIG. Table 6 provides an overview of key result values identified for the three island regions.

Table 6
Results of techno-economic evaluation of renewable based hybrid electricity systems.

Region	Demand [GWh/a]	Investment m. [USD]	PV cap. [MWp]	Battery cap. [MWh]	LCOE [USD/kWh]	RE-share [%]
Luzon	1011	566.5	291.4	82.5	0.32	30.9
Visayas	92	47.3	23.4	6.7	0.33	27.8
Mindanao	185	94.0	48.9	13.3	0.32	31.4
Total	1288	707.8	363.6	102.5	0.33 (av.)	29.9 (av.)

Under the technical and economic assumptions outlined in Table 4, integrating RE into the existing SIIGs is beneficial, lowering LCOE compared to purely diesel-fueled electricity systems for each of the considered SIIGs. Average pure diesel LCOE are at 0.39 USD/kWh, as

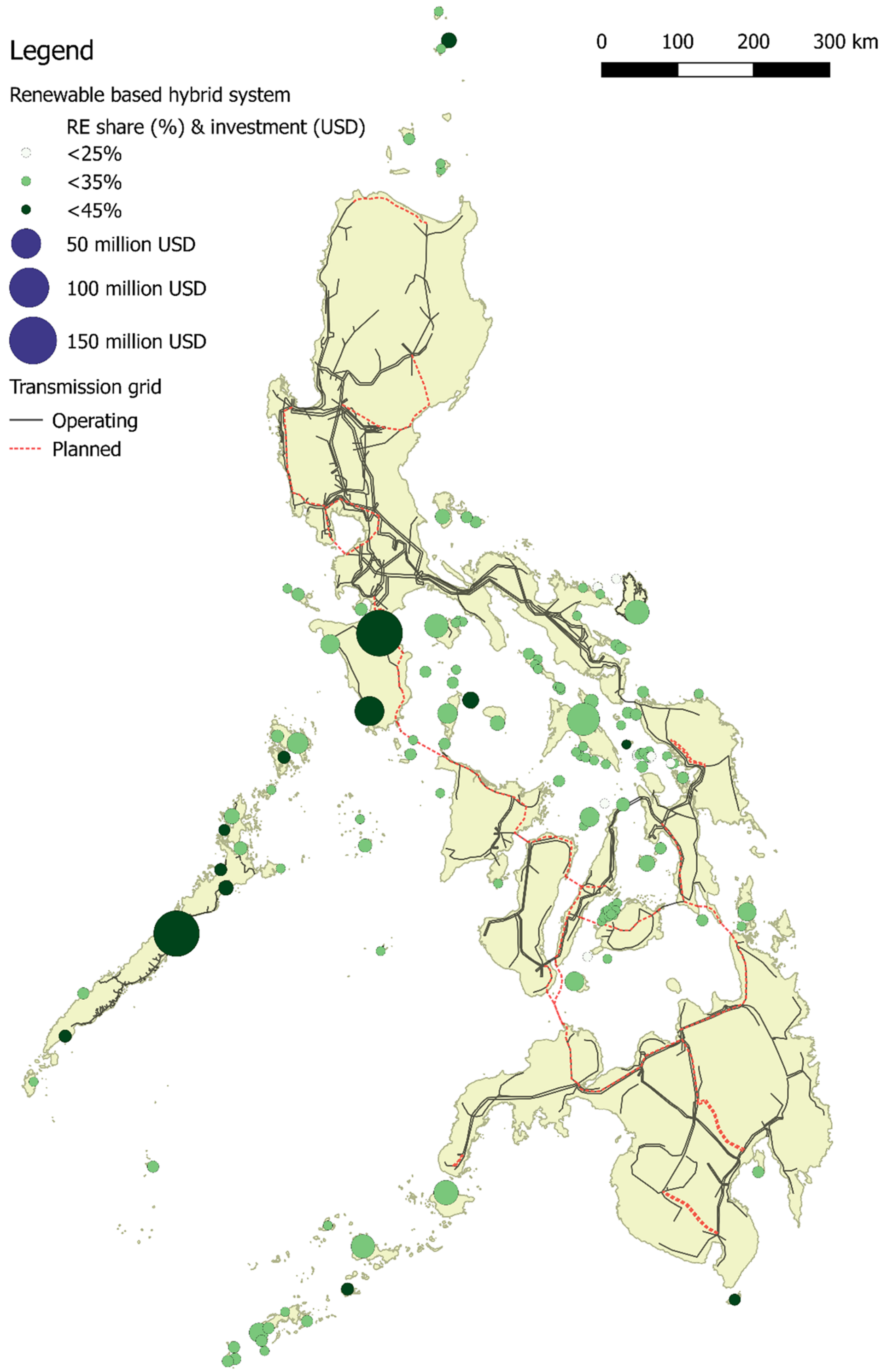

Fig. 5. Overview map showing the overall investment necessary to develop SIIGs to renewable energy based hybrid grids.

compared to hybrid LCOE of 0.33 USD/kWh. LCOE reduction per SIIG is between 4 and 8 USDcent/kWh, with an average reduction of 5 USDcent/kWh. A PV potential of 360 MW, coupled with a battery storage requirement of 100 MWh, must be installed. With such capacities in place, the RE share achieved in the SIIGs would average 30%, allowing for the mitigation of more than 1.3 million liters of diesel fuel and 400 thousand tons of CO_2 emissions annually as compared to pure diesel systems. To implement these systems, an investment of approximately 708 million USD in the existing SIIG power system infrastructure is required. Besides this investment, annual fuel costs of 221 million USD (over the 20-year project period fuel costs are expected to rise to 288 million USD on the annual average based on the expected diesel price) and annual operational expenditures of 32.5 million would accrue.

On a regional scale, its larger number of SIIGs means that Luzon would have the highest PV and battery storage potential and require the greatest investment. Fig. 5 shows the potential RE share and necessary investment for each SIIG. Despite the high number of projects on smaller SIIGs, only a few large SIIGs would take up the most investment requirements. The majority of SIIGs have potential RE shares of between 25% and 35%. Higher RE sharers are simulated for larger SIIGs reflecting the higher daytime electricity demands; allowing for more direct consumption of PV power.

Altering the input parameters defined in Table 4 may significantly impact the overall results presented above. Essentially, dynamic cost developments for electricity storage and diesel fuel may affect the potential for RE-based hybrid systems, as outlined by Ocon and Bertheau [37]. The rapid decrease of electricity storage costs projected by recent studies [51] would allow for a higher share of renewable energy, since a larger battery capacity would replace diesel power generation through the storage of generated solar power. Additionally, the combination of electricity storage technologies for short-term and long-term electricity storage could lead to overall system cost reductions in the future. Lower diesel fuel costs or flatter fuel price growth rate would lead to lower RE shares, as less battery capacity would be installed in the cost optimized hybrid system configuration. However, the more likely increase of diesel costs would result in higher RE shares and a higher economic attractiveness of RE.

The implementation of a cost factor for greenhouse gas emissions (GHG) would significantly reduce the share of diesel generated electricity in the generation mix and thereby potentially increase the overall system costs. Since there are no observable political activities addressing the implementation of such a price on emissions cost, however, it is excluded from the analysis.

3.3. Least-cost comparison: Recommendations for electricity sector development

As final step in least-cost planning, a comparison of the LCOE of submarine cable interconnection with the LCOE of RE-based hybrid systems was conducted. For this, all SIIGs were grouped into 30 island or project groups. Comparing the investment costs of both development options reveals that submarine power cable interconnection with approximately 3.2 billion USD would be substantially more capital intensive than the development of RE-based hybrid systems with approximately 708 million USD. Nevertheless, based on the applied cost assumptions, the average LCOE for submarine cable development in Luzon are lower than those for RE-based hybrid electricity systems (compare Table 5 to Table 6). A more detailed breakdown of disaggregated SIIG level highlights that submarine cable interconnection can be the more cost-effective option for some SIIGs and island groups (compare Table 8).

When comparing the investment costs for both options on the national, regional, or island scale, it is important to consider that the identified investment costs for submarine interconnection do not account for the increased power generation capacities in the main grid, which are probably necessary in order to meet the additional demand. Future research should fill these knowledge gaps. Despite these shortcomings, the approach can indicate where submarine cable interconnection should be favored over RE-based hybrid system development. For analyzing the results on a more detailed level, the SIIGs were partitioned into 30 island groups classified by region and proximity. The island groups, names, and number of comprised SIIG are shown in Table 7 for hybrid electricity systems and in Table 8 for submarine power cables; both are visualized in Figs. 4 and 5.

The last column of Table 8 compares the LCOE for submarine cable interconnection to RE-based hybrid system development and lists the difference. For seven island groups, reflecting 35 SIIGs, submarine interconnection is the more cost-effective option. The highest potential for submarine interconnection is identified for the island of Mindoro (island group 5) with a cost benefit of 0.21 USD/kWh as compared to hybridization. Given its high demand for electricity, high anticipated growth in demand, and short distance from the main grid (20.5 km submarine cable required), our result supports further research into a submarine interconnection, as already discussed by NGCP [31]. The second highest cost benefit is derived for Palawan (island group 9), with 0.10 USD/kWh LCOE for submarine power cables as compared to LCOE of 0.31 USD/kWh for RE-based hybrid electricity systems. Nevertheless, island groups 7 and 8 must be interconnected before Palawan can be connected to the main grid. When adding the investment costs for the aforementioned island groups to the one for Palawan, the LCOE increases to 0.21 USD/kWh, but is still lower than that for RE-based hybrid system development. Additionally, the islands of Busuanga and Culion, which are not viable for connection, could potentially be interconnected in order to connect Palawan to the main grid. However, the technical feasibility of such an interconnection needs to be assessed in detail, especially as one major submarine cable (101 km) passing deep sea would be required for connection between Mindoro and Busuanga. Another potential for interconnection is derived for Masbate (island group 15) via the connection of some smaller islands of island group 18. When considering the investment costs for both island groups (15 and 18), the economic advantage of submarine connection decreases to 0.35 USD/kWh, but would give 23 SIIGs access to the main grid. In the south of the Philippines, connecting the islands of Basilan (island group 26) with a cost-saving potential of 0.19 USD/kWh has a clear cost-reduction potential compared to RE-based hybrid electricity systems. For near Jolo island (island group 27) the potential for RE-based hybrid system development and submarine grid interconnection are nearly identical. However, the interconnection of Jolo is only cost-efficient if Basilan is interconnected. For connecting Marinduque (island group 4) to the main grid, a cost-saving potential of 0.18 USD/kWh is projected. Due to its short submarine cable route (23.9 km) and high electricity demand, this is one of the most attractive submarine connection projects. Finally, the interconnection of several SIIGs in the Bicol region, including Catanduanes (island group 3), with a cost-saving potential of 0.06 USD/kWh, and connecting the Camotes island group (no. 20) with a saving potential of 0.13 USD/kWh, might be feasible for submarine connection. However, in both cases the cost advantages as compared to RE-based hybrid system development are small, and changes in cost parameters may quickly offset the cost advantage.

This detailed breakdown offers some clear recommendations for the remote electricity development sector. First, given the short distances to overcome, the high electricity demand, and the high cost advantages for submarine cable interconnection to Mindoro, Marinduque and Basilan, the feasibility of interconnecting those islands should be individually studied in the near future. Second, the interconnection of Palawan (including Busuanga and Culion) and Masbate (with its several smaller surrounding islands) should be investigated. Once connected to the main grid, the areas could be excluded from the missionary electrification subsidy scheme to decrease the overall UCME burden. For the three suggested priority areas, this would decrease by 37% the annual electricity demand to be subsidized by the UCME. The remaining island groups reflect a high potential for clean energy technology deployment by the installation of RE-based hybrid systems. As outlined earlier, RE-based hybrid systems reduce power generation costs and can therefore help decrease UCME costs as compared to pure diesel power generation. Besides relieving the pressure on national funding, both centralized and decentralized electricity supply options can increase domestic employment opportunities through local construction jobs and the manufacture of necessary parts. This holds true for both RE-based solutions (given the current emergence of a solar power manufacturing industry in the Philippines), and submarine cable interconnection (given that the Philippines are a significant producer of electronics and electrical components).

3.4. Sensitivity analysis of submarine cable costs and electricity demand

The input parameter most difficult to define is the submarine cable cost per kilometer, due to the paucity of published research data or publicly available project data. In order to understand its impact, we conducted a sensitivity analysis on the chosen values to understand their significance for the overall comparison of submarine cable costs

Table 7
Renewable energy – based hybrid electricity systems potential for each island/project group.

No [#]	Project group [name]	SIIIG [#]	Load demand [MWh/a]	Peak demand [kW]	PV size [kW]	Battery size [kWh]	Investment Million [$]	LCOE (Hy.) [$/kWh]	RE share [%]
1	Batanes	6	13,186	2324	4129	1112	7.8	0.31	36%
2	Jomalig	3	12,427	2307	2928	800	5.9	0.33	29%
3	Bicol	8	60,820	11,606	16,145	4898	32.3	0.32	33%
4	Marinduque	4	50,329	9837	13,889	3963	27.5	0.32	33%
5	Mindoro	4	362,367	62,453	108,210	29,963	206.7	0.31	36%
6	Lubang	2	5027	902	1174	334	2.4	0.32	29%
7	Busuanga	3	42,149	8626	10,763	3223	22.0	0.32	33%
8	Culion	1	735	132	196	60	0.4	0.32	33%
9	Palawan	9	274,006	49,728	81,643	23,365	157.9	0.31	37%
10	Balabac	1	898	176	228	69	0.5	0.31	34%
11	Romblon	6	55,144	10,903	15,653	4,258	30.8	0.32	32%
12	Cuyo	5	11,209	2156	2877	818	5.8	0.32	33%
13	Cagayancillo	1	658	133	170	51	0.3	0.31	35%
14	Ticao/Burias	8	10,657	2278	2589	735	5.4	0.33	30%
15	Masbate (main)	7	113,332	22,121	31,317	8962	62.1	0.32	34%
16	Leyte	6	7392	1482	1676	475	3.5	0.33	27%
17	North of Cebu	4	33,033	6737	8427	2458	17.1	0.32	32%
18	Masbate (small is.)	16	4620	1003	1077	310	2.3	0.33	29%
19	Panay	3	2,189	447	543	162	1.1	0.33	30%
20	Camotes	2	15,606	3018	3742	1081	7.6	0.32	31%
21	Bohol	10	959	241	209	63	0.5	0.33	27%
22	Siquijor	3	24,965	5069	6856	1899	13.7	0.32	33%
23	Dinagat	3	24,332	4167	6417	1680	12.4	0.32	31%
24	Mindanao	2	2749	480	745	201	1.4	0.32	33%
25	Sacol	1	477	94	115	37	0.2	0.32	30%
26	Basilan	1	58,882	8680	15,948	4146	30.0	0.31	33%
27	Jolo	1	53,402	9200	14,012	4001	27.4	0.31	34%
28	Pangturan	1	317	76	65	20	0.1	0.33	27%
29	Tawi Tawi	10	43,155	6838	11,155	3116	21.5	0.31	33%
30	Mapun	1	2763	503	673	206	1.4	0.32	32%

for the decentralized options. We increased and decreased the assumed capital expenditure for the submarine cables stepwise from −90% to +90%. Our findings (Table 9) show that the derived least-cost options for the 30 island regions are very robust, specifically for an increase in costs. Another input parameter considered as influential for the potential of submarine cable interconnection is the electricity demand.

Table 8
Submarine power cable interconnection potential for each island/project group.

No [#]	Region [name]	Sub. cab. [km]	Voltage [kV]	Sub. cable invest Million [$]	Land cable [km]	Land cable invest Million [$]	Total invest Million [$]	Generation costs [$/kWh]	LCOE (Su.) [$/kWh]	LCOE Comp. [$/kWh]
1	Batanes	252.0	230	378.0	96.1	1.2	379.2	0.09	3.28	2.97
2	Jomalig	41.7	138	41.7	53.2	0.6	42.3	0.09	0.47	0.14
3	Bicol	59.9	230	89.9	83.5	1.0	90.9	0.09	0.26	−0.06
4	Marinduque	23.9	138	23.9	17.2	0.2	24.1	0.09	0.14	−0.18
5	Mindoro	20.5	230	30.7	37.9	0.5	31.2	0.09	0.10	−0.21
6	Lubang	22.9	138	22.9	79.5	1.0	23.8	0.09	0.62	0.29
7	Busuanga	101.2	230	151.7	92.2	1.1	152.8	0.09	0.49	0.18
8	Culion	47.7	138	47.7	41.0	0.5	48.2	0.09	7.37	7.05
9	Palawan	15.4	230	23.1	158.8	1.9	25.0	0.09	0.10	−0.21
10	Balabac	29.9	138	29.9	39.8	0.5	30.3	0.09	3.84	3.53
11	Romblon	141.5	230	212.2	167.5	2.0	214.2	0.09	0.52	0.20
12	Cuyo	191.1	230	286.7	25.4	0.3	287.0	0.09	2.93	2.62
13	Cagayancillo	137.9	230	206.9	0.7	0.0	206.9	0.09	35.00	34.69
14	Ticao/Burias	30.5	138	30.5	112.0	1.3	31.8	0.09	0.42	0.10
15	Masbate (main)	77.4	230	116.1	42.7	0.5	116.6	0.09	0.20	−0.11
16	Leyte	55.7	230	83.6	76.0	0.9	84.5	0.09	1.36	1.03
17	North of Cebu	78.0	230	116.9	23.1	0.3	117.2	0.09	0.48	0.16
18	Masbate (small is)	111.4	230	167.1	56.1	0.7	167.7	0.09	4.12	3.79
19	Panay	43.8	138	43.8	42.8	0.5	44.3	0.09	2.34	2.01
20	Camotes	18.7	69	14.0	27.7	0.3	14.4	0.09	0.19	−0.13
21	Bohol	73.5	230	110.2	10.0	0.1	110.4	0.09	12.87	12.53
22	Siquijor	68.7	230	103.1	28.0	0.3	103.4	0.09	0.55	0.23
23	Dinagat	72.4	230	108.5	67.7	0.8	109.4	0.09	0.59	0.27
24	Mindanao	25.1	138	25.1	70.8	0.8	25.9	0.09	1.14	0.82
25	Sacol	4.0	13	1.4	8.1	0.1	1.5	0.09	0.44	0.12
26	Basilan	18.6	138	18.6	18.2	0.2	18.8	0.09	0.13	−0.19
27	Jolo	71.7	230	107.6	35.9	0.4	108.0	0.09	0.31	0.00
28	Pangturan	55.3	230	82.9	53.4	0.6	83.6	0.09	29.35	29.03
29	Tawi Tawi	157.3	230	236.0	174.0	2.1	238.1	0.09	0.70	0.39
30	Mapun	191.3	230	287.0	12.6	0.2	287.1	0.09	11.63	11.32

Table 9
Resulting changes in the least-cost electricity supply option after changing the assumed capital costs for submarine cables.

Cost change %	−90%	−50%	−30%	−20%	−10%	0	+10%	+20%	+30%	+50%	+90%
Decentral	10	16	22	22	22	23	23	23	23	24	24
Central	20	14	8	8	8	7	7	7	7	6	6

Table 10
Resulting changes in the least-cost electricity supply option after changing the projected electricity demand.

Demand change %	−75%	−50%	−25%	0%	+25%	+50	+75%
Decentral	26	25	23	23	22	21	18
Central	4	5	7	7	8	9	12

Here, a similar pattern is observed when focusing on the impact of decreasing or increasing electricity demand on the potential for decentral and central electricity supply options (Table 10). In a range of ± 25%, the findings are very robust. More submarine cable interconnections become viable with the more likely scenario of an increasing electricity demand. In the other case, which assumes a lower electricity demand, the decentral solutions (RE-based hybrid systems) are the most economic pathways in most cases.

4. Discussion

This study offers a preliminary assessment of development options for the electricity sector of remote islands in the Philippines. Given its pioneering and novel approach, the study opens up opportunities for further refinement and improvement.

When seeking to optimize submarine cable routes, it is important to consider further marine activities and threats in future works. Shipping channels and areas of intense fishing activity can damage submarine power cables and thus pose a high threat to these materials [53]. The potential impact of submarine power cables on marine life (e.g. on crabs [54] and other coral fauna [55]) must also be taken into account. In the Philippines, seabed currents and unexploded warfare material can threaten the feasibility of submarine cable interconnection, as described by the grid operator [31].

With this study, we have successfully adapted an approach, originally developed for electrification planning with overhead lines [43], for the case of island interconnection with submarine power cables. The identified optimized submarine cable routes are based on bathymetric maps and the estimated investment costs are based on cost values collected through expert interviews. Nevertheless, the costs of submarine power cable projects are difficult to assess in detail, given that costs are sensitive to a variety of parameters. Among other factors, type of seabed (rocky/sandy), use of AC or DC technology, and voltage level have a significant impact on costs [27]. To obtain a more detailed cost benefit analysis, future research work must assess input parameter in more detail. Furthermore, electro-technical aspects need to be studied in more detail. Here, only an assumption on the most suitable voltage level for required electricity generation was possible. A detailed electricity flow model can shed light on the electro-technical feasibility of supply options discussed in the present study, which focused on route estimation and identifying optimal connection pathways.

With regard to assessing the potential for RE-based hybrid electricity systems, the assumed cost parameters clearly influence the LCOE and investment costs and thus affect the applied results. Another study revealed that diesel and battery storage costs have the highest impact on LCOE and investment costs [37] of all cost factors. Future research needs to address sensitivity analyses that focuses on cost assumptions for technologies, and should consider the cost of transporting material to remote islands in the Philippines. The uncertainty surrounding how electricity demand will develop in the future is another factor that significantly affects the derived potential for renewable energy integration [41].

Despite these limitations, we obtained valuable results for electricity sector planning in the Philippines. The main submarine interconnection lines proposed are similar to the grid expansion plans of NGCP. Still, for each new interconnection project it is necessary to conduct a least-cost comparison with a RE-based hybrid system to avoid investments into submarine cables when the RE-based hybrid system would be the more cost-effective option. Currently, submarine cable deployment is also being analyzed by local electric cooperatives, who are responsible for supplying their franchise areas with electricity. Findings from those studies as well as lessons-learnt of implemented submarine cable interconnection projects can be used to validate the cost findings for submarine interconnection.

5. Conclusion

The main objective of this study is to compare the viability of submarine power cable interconnection and RE-based hybrid system development for 132 small isolated island grids in the Philippines that currently rely on diesel power generation. The results discussed above provide key information about electricity sector planning that will help decision makers develop and implement the most suitable electricity supply option for island contexts.

By optimizing the spatial grid extension outline for the interconnection of all SIIGs, we identify a grid extension potential of 2239 km by submarine cable and 1752 km by land cable. The overall investment for the given cost assumptions amounts to more than 3.2 billion USD for grid infrastructure alone, not considering the power generation capacity required to meet the demand on the newly connected islands. For hybridizing the considered systems, the overall investment for the given cost assumptions amounts to 708 million USD. Such an investment would allow for the implementation of 363 MW of PV and 102 MWh of battery storage capacity, leading to an average RE share of 30%.

On the island scale, we reveal that submarine interconnection of the Catanduanes, Marinduque, Mindoro, Palawan, Masbate, Camotes, and Basilan island groups is the least-cost option and should be further studied for its potential implementation in the near future. Priority should be given to submarine power cable connection to Mindoro, Marinduque and Basilan, based on their close proximity to the main grid and the high electricity demand on these islands. However, additional power generation capacities are needed in the main grid to meet the additional annual electricity demand of 935 GWh/a (for all islands with potential for submarine interconnection) or 471 GWh/a (for three recommended submarine interconnections). Nevertheless, connecting the recommended islands would allow for a graduation from the UCME subsidy scheme and reduce the amount of national funding needed to subsidize future electricity tariffs. A portion of the money saved could be invested in RE-based hybrid system development on islands where submarine connection is not viable.

Going beyond submarine cable interconnection the development of RE-based hybrid systems hold out enormous potential for cleaner energy supply and reducing expenses for the subsidy schemes in place. This underlines that improving the enabling framework for RE-based hybrid system development can lead to more sustainable, affordable and reliable electricity supply while submarine power cable interconnection might be a viable option for islands with high electricity demands and high growth potential. Our findings and the developed methodology may be of interest to countries with a topography, insular character, and increasing demand for electricity similar to the Philippines.

Acknowledgement

P. Bertheau is grateful to the PhD Scholarship of the Reiner Lemoine Foundation. This work is also supported by the Research Project entitled, “Ener-PHIL – Research Cooperation supporting the Energiewende on the Philippine Islands” funded by the BMBF. The authors are grateful to staff of the Philippine Department of Energy and National Electrification Administration for the data provisioned and advice.

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

Energy 202 (2020) 117670

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

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ARTICLE INFO

Article history:
Received 20 December 2019
Received in revised form
21 March 2020
Accepted 18 April 2020
Available online 22 April 2020

Keywords:
Philippines
SDG7
Hybrid energy system
Geospatial analysis
Cluster analysis
Energy system modelling

ABSTRACT

Access to clean energy is required for facilitating sustainable development in remote areas. In the Philippines many small islands are not supplied with electricity although it is aimed to achieve universal electrification by 2022. Here, renewable energy holds a large potential given the abundant resource availability and high costs for fossil fuel. However, a lack of key information for electrification planning prevents the wider deployment of renewable energy.

Therefore, this paper presents a combined approach applying geospatial analysis, cluster analysis and energy system modelling: First, we identify not electrified islands. Second, we utilize cluster analysis for pattern recognition. Third, we perform energy system simulations of 100% renewable energy systems combined of solar power, wind power and battery storage.

Thereby, we find 649 not electrified islands relevant for our analysis with a population of 650,000. These islands are grouped in four clusters according to population and renewable resource availability. For each cluster we found that cost-optimized 100% renewable energy systems are based on solar and battery capacities with supplementary wind capacities. Generation costs and system designs are most sensitive to variation in battery and capital costs. Allowing short-term supply shortages can significantly decrease costs through smaller capacitiy requirements.

1. Introduction

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

Strategic energy access planning is required to advance towards SDG7 and utilize resources most efficiently [6]. Advanced software tools are needed to allow for energy access planning [6] and several examples of such tools have been developed and presented in the scientific literature [6,7]. The presented tools allow for deriving key information for energy access planning, among other the electrification type (grid connection, mini-grid, stand-alone), system design, power generation costs and dispatch of off-grid systems, distribution grid network design and additional upstream generation requirements [6]. Results of such tools allow for different depth-of detail [6]: Prefeasibility studies indicate optimal electrification solutions for areas and customers clustered in raster cells of different sizes (e.g. km^2). Examples have been presented for Sub-Saharan Africa [8,9], Nigeria [10], Ethiopia [11] and Kenya [12]. Intermediate analysis tools add a further level of detail since individual villages or populated places are taken into account, grid network designs are retrieved and further technological constraints are considered. Such tools have been applied to Nigeria [13,14] and Ghana [15] among other. Finally, tools considering detailed generation networks and designs provide the maximum level of detail by including detailed village grid layouts and introducing a large variety of technological constraints for power system design. Ciller

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https://doi.org/10.1016/j.energy.2020.117670
0360-5442/

and Lumbreras (2020) [6] identify only one existing tool providing such detail but do not present peer-reviewed articles. Geospatial software has been applied as essential and integrated part of many of the aforementioned tools or was utilized for gathering data (e.g. population distribution, renewable resources). This includes several tools applied for Africa on the prefeasibility level [7,16,17]. Furthermore, geospatial analysis was used for case studies in Timor Leste [18] and Nigeria [14] on the intermediate analysis level. The presented tools and case studies focus mainly on Sub-Saharan Africa given the large need for energy access interventions there. However, thereby the tools neglect other regions in need of energy access interventions like Southeast Asia and disregard the local specific conditions e.g. the large number of islands. A combined approach of geospatial analysis and energy system modelling was applied on a global scale to study the feasibility of RE integration into island grids [19] and for a classification regarding the RE potential on islands [20] but not specifically for the strategic planning of providing energy access. In the Philippines, the case study country of this paper, similar combined approaches were utilized to quantify the potential for upgrading diesel based island systems with RE [21] and to project costs for submarine cable connection [22]. However both studies consider pre-electrified islands. Overall these findings highlight that electrification planning tools are rarely designed and applied to regions outside Africa which reflects a research gap. Furthermore, a review study formulates research needs for the improvement of electrification planning tools including adding multi-criteria optimization, including more detailed year by year planning, adding further power generation technologies, improving grid network design and addressing uncertainties of input parameters [6]. Our study contributes to the research field with a detailed assessment of the not electrified island landscape of an understudied country, the Philippines, and a simulation of 100% RE based electrification pathways. Thereby, we address the identified research gap by focusing on a region outside Africa and address some of the research needs for improving electrification planning tools outlined earlier. We present a novel and combined approach based on geospatial data and energy system modelling which is replicable to case studies with similar boundary conditions. The approach can be assigned to the intermediate level as defined by Ref. [6] as single islands are considered and system designs are simulated based on a set of technical constraints. Finally, we develop and present an integrated geospatial and energy system analysis tool which is fundamental for effective electrification planning and facilitates to derive key information for large geographic areas [11]. We base our approach on similar studies presented for landlocked countries as presented in Ref. [8,10–12,18] and contribute with a methodological adaptation to the insular context of the Philippines.

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

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

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

A) Where are not electrified populated islands located?
B) What are specific population and renewable resource characteristics of the not electrified islands and how can the islands be grouped for energy access planning?
C) What are the techno-economically optimal supply options for certain island groups considering an 100% renewable combination of solar power, wind power and battery storage?

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

2. Material and methods

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

2.1. Geospatial analysis

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

2.1.1. Identification of not electrified islands

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

2.1.2. Assessment of population and renewable resource availability

Following the identification of not electrified islands we quantify the inhabitants per islands as key information for electrification planning. We assess the population of not electrified islands by using population raster datasets. We apply the High Resolution Settlement Layer (HRSL) dataset [36,46]. This dataset is based on population census and satellite imagery for the year 2015 and provides a specific population value for each raster cell (extent of 30 to 30 m). For the quantification of inhabitants per island we summarize the raster cell values for the extent of each island polygon using geospatial software “raster-statistics-for-polygons” function. Beside the population per island we assess the renewable resource availability for solar and wind power. For solar power we apply global horizontal irradiation (GHI) datasets providing mean kWh/m^2/year for the period of 2007–2018 [47]. For wind power we apply datasets for wind speed in m/s at 50 m hub height for the period of 2008–2017 [48]. Both datasets are provided on a pixel scale of ~250 m. We derive the mean value of all raster cells covering a specific island using geospatial software “raster-statistics-for-polygon” function.

2.2. Cluster analysis

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

2.2.1. Partitioning clustering using PAM

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

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

2.3. Energy system simulation

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

2.3.1. Simulation model

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

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

The identification of the cost-optimal system configuration is based on the minimization of the annual electricity supply costs (Equation (1)).

Applied formula for calculation of annual electricity supply costs.

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

Equation 1

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

Applied formula for the calculation of the CRF per technology.

$$CRF(WACC, N) = \frac{WACC*(1+WACC)^N}{(1+WACC)^N - 1} \qquad \text{Equation 2}$$

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

Applied formula for calculation of the LCOE.

$$LCOE = \frac{\min\ \ Annual\ \ supply\ \ costs}{E_{supplied}} \qquad \text{Equation 3}$$

In equation (3), the levelized cost of electricity (LCOE) are calculated based on minimal annual supply costs (Equation (1)), divided by the supplied electricity ($E_{supplied}$) per year.

Dispatch function for energy system modelling.

$$E_{PV}(t) + E_{Wind}(t) + E_{Batt,out}(t) \cdot \eta_{out} + E_{short}(t) - E_{inv}(t) - E_{Batt,in} - E_{ex}(t) = E_D(t) \qquad \text{Equation 4}$$

Equation (4), describes the dispatch of assets which have to be utilized in such way to balance the electricity bus. In the equation E_i stands for energy flow from asset i [kWh], $E_{Batt,out}$ for battery discharge after discharge losses [kWh], $E_{Batt,in}$ for battery charge before charge losses [kWh], η for conversion efficiency, E_{short} for curtailed energy flow to balance out supply shortage [kWh], E_{ex} for energy flow dumbed to balance out excess generation [kWh], E_D for energy demand (kWh).

We apply a temporal resolution of one year in hourly time steps. Thereby we take into account seasonal variation in resource availability and electricity demand (see subsection 2.3.2).

2.3.2. Input parameter

Renewable resource data (solar and wind), electricity demand and technical/economic parameter per component are required for the simulation of the case studies.

Renewable resource data is derived from the renewables. ninja project [81] which provides open access to hourly solar and wind resource data. For each case study island the island's centroid serve as location for the resource data download. The data provides hourly power output for solar and wind power plants for the reference year of 2014. Solar and wind resource data is based on weather datasets and satellite observations [82–84] and power outputs are calculated by a conversion model for solar power outputs [85] and a conversion model for wind power outputs [86]. For deriving hourly solar power outputs we apply a system loss of 10%, tilt angle of 10° and azimuth angle of 180° [87,88]. For calculating hourly wind power outputs we apply a hub height of 30 m for the XANT M21 turbine model given its suitability for micro grids.

Detailed forecasting of electricity demands is of high importance for appropriate electrification planning [89]. The temporal resolution of electricity demands is equally important to the overall electricity consumption due to the intermittence of renewable resources. Researchers have introduced models for projecting electricity demands based on statistics and/or household surveys to face the uncertainty of electricity demands in not electrified areas [14,71,90–92]. As extensive household surveys are out of scope of this study we apply reported electricity demands and load profiles from the scientific literature. Lozano et al. [71] conducted a household survey for a small Philippine island to estimate electricity demands for a techno-economic assessment of a hybrid energy system and finds an electricity demand of 0.43 kWh/day per island resident. Similar values of 0.34 kWh/day are found for a comparable RE based hybrid system in the Philippines [93,94]. We apply the value of 0.43 kWh/day per island resident for estimating overall electricity demands since the reported case study reflects a small Philippine island. The daily electricity demand per case study is calculated based on the specific island population. The resulting energy demand per island is then distributed over load profiles reported for small island communities in the Philippines [21,71] and a seasonal variation for the three main regions of the Philippines is incorporated as provided in Ref. [21].

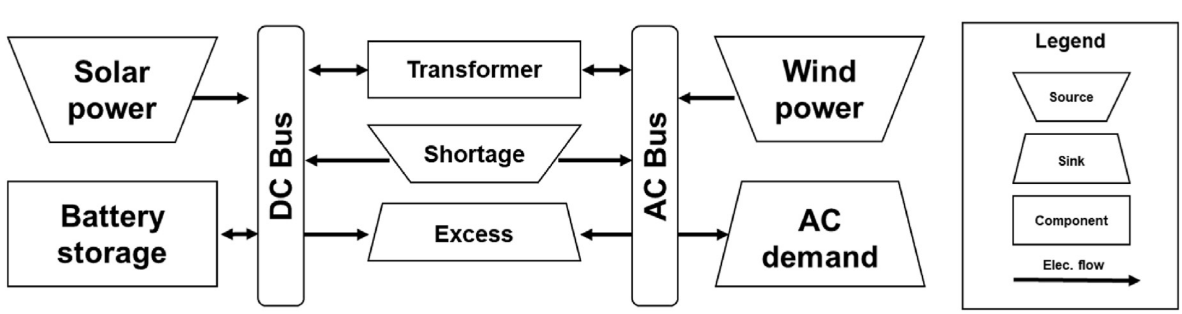

Fig. 1. *Sketch of energy system model, own illustration based on* [74,75].

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

2.3.3. Energy system model validation and sensitivity analysis

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

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

3. Results

3.1. Geospatial analysis

We identify 171 islands with connection to the electricity grid or power plants based on the geospatial approach outlined in subsection 2.1.1 and exclude these islands from further investigation. For the remaining more than 17,600 polygons reflecting land masses we assess the population as described in subsection 2.1.2. Thereby we identify 1,920 islands as populated (population > 0) with an overall population of more than 734 thousand. This population reflects approx. 14% of the not electrified population of the Philippines taking into account recent estimations [25]. A more detailed overview on number of islands and overall population is provided for different population classes in Fig. 2.

A large number of more than 1,200 islands (population classes <10 to <100) have a very small population which summarize up to 23 thousand. The population classes of <500 to <5,000 comprise the bulk of the not electrified population on a smaller number of islands. Especially, focusing electrification efforts on islands between <1,000 and < 5,000 can lead to considerable progress in providing energy access given the relatively high overall population. A significant share of the population lives on only 21 islands larger 5,000 inhabitants. More than 59% of the identified islands have a population lower than 50 (n = 1,146). We exclude these islands prior to the cluster analysis, since we consider SHS as more appropriate for the electrification of islands with very small populations and the focus of this study on 100% RE micro grid development. Through excluding the aforementioned islands the number of overall islands decreases to 774. However, the overall population only decreases by 2.4% to 716– thousand. For the remaining 774 islands the mean GHI and mean wind speed per year

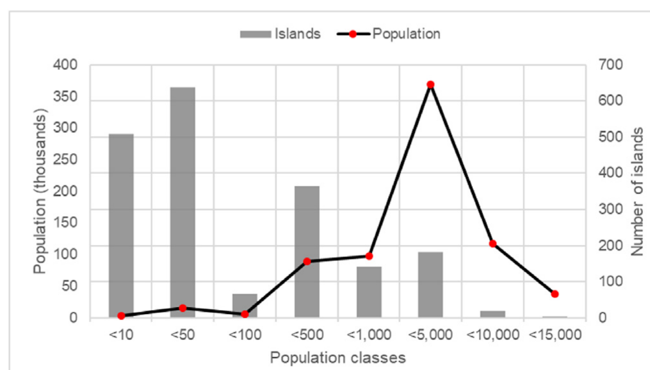

Fig. 2. Overview on overall population and number of islands for not electrified Philippine islands.

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

Parameter	Unit	Value	Source	Parameter	Unit	Value	Source
PV CAPEX	USD/kW	1500	adapted from [97]	Wind CAPEX	USD/kW	2500	adapted from [97]
PV OPEX	USD/kW/y	15		Wind OPEX	USD/kW/y	62.5	
Lifetime	years	20		Lifetime	years	20	
Battery capacity CAPEX	USD/kWh	250	[21,100]	Max. depth of discharge (DoD)	%	80	[21,100]
Battery power CAPEX	USD/kW	450		Charging efficiency	%	97	
Battery OPEX fix.	USD/kWh/y	5		Discharging efficiency	%	97	
C-rate (kW/kWh)	Ratio	1		Lifetime	years	10	
WACC	%	8	[71]	Project lifetime	years	20	

are calculated as outlined in section 2.1.2. No values can be derived for 125 islands due to data gaps. Finally, a dataset comprised of complete population and renewable resource information for 649 islands and a population of 650 thousand is consigned to the cluster analysis.

3.2. Cluster analysis

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

Table 2 provides information on number of islands and overall population per cluster group as well as population statistics and renewable resource data for the medoids islands. Cluster 1 groups the most islands (227) with a higher overall population (142 thousand). In contrast to that cluster 2 comprises only 76 islands but a much larger overall population of 314 thousand. Cluster 3 and 4 are characterized by comparable values in terms of number of islands (186 and160) and overall population (96 thousand).

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

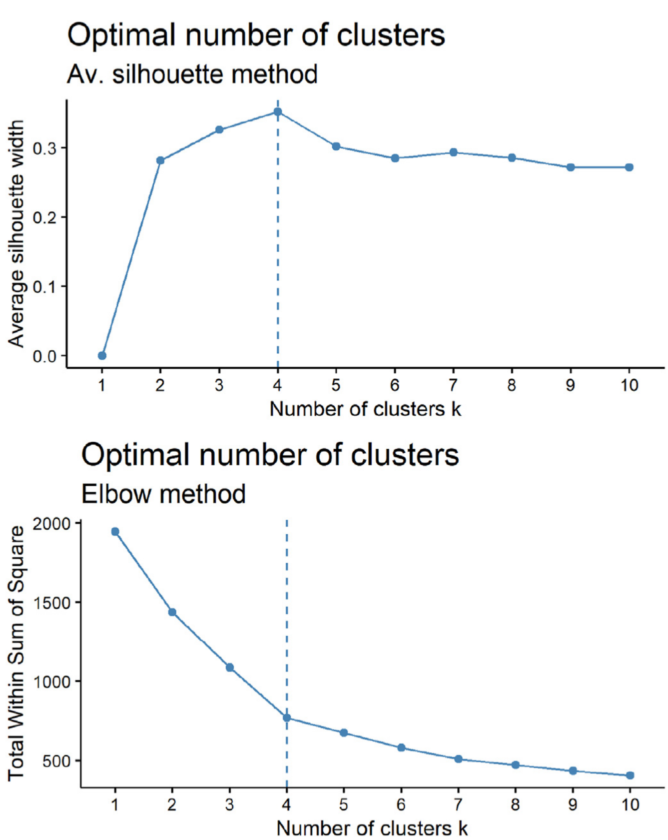

Fig. 3. Results of average silhouette width (left) and cluster sum of square (right) for cluster solution between 1 10.

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

3.3. Energy system simulation

3.3.1. Validation of energy system tool

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

3.3.2. Input parameter

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

The electricity demands applied for assessing 100% RE energy

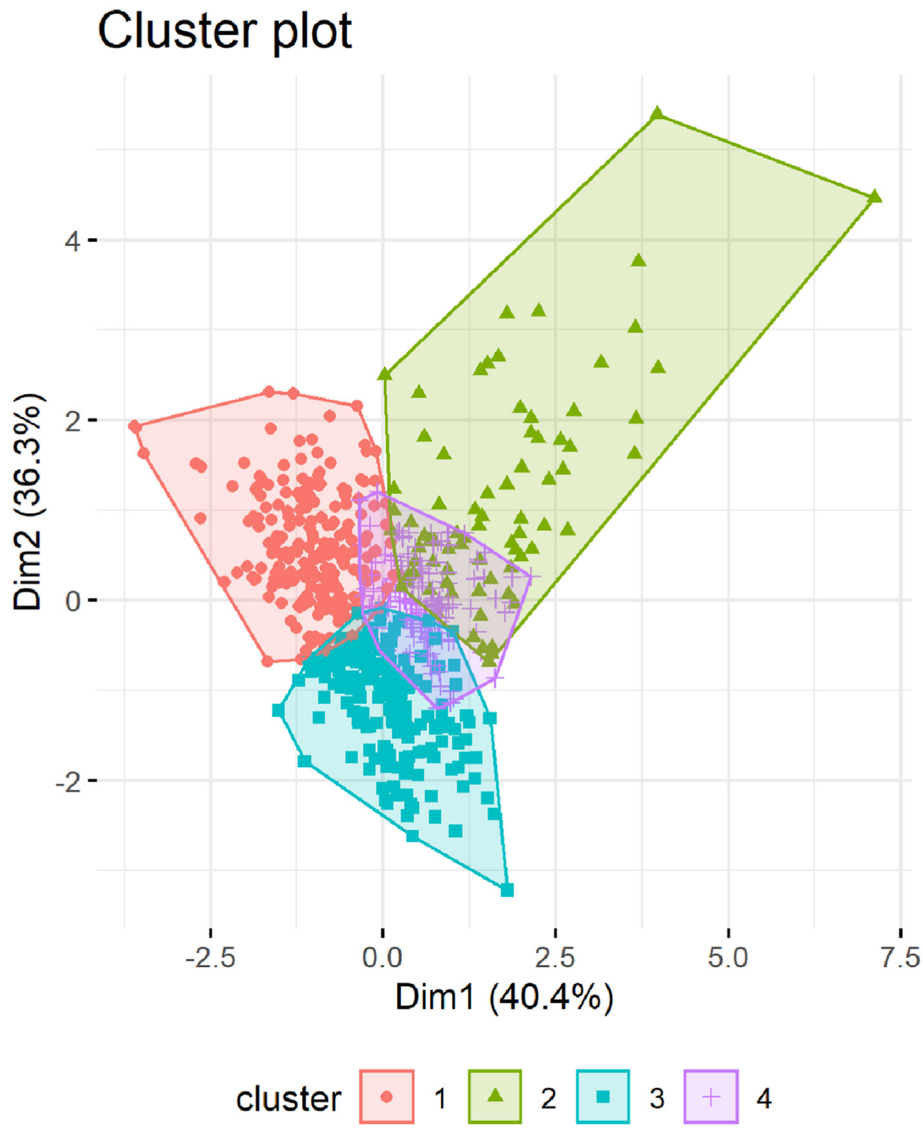

Fig. 4. Cluster plot showing four cluster solution.

Table 2
Key characteristics of the three proposed cluster groups.

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

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

3.3.3. Simulation results

For each case study island we apply the scenarios and sensitivity analyses outlined in subsection 2.3.3 with the input parameters presented in subsection 2.3.2. Table 4 provides the energy system simulation results for each case study island. We find LCOE in a range of 0.53–0.61 USD/kWh. This would allow for interruption-free and entirely renewable power supply on the islands and

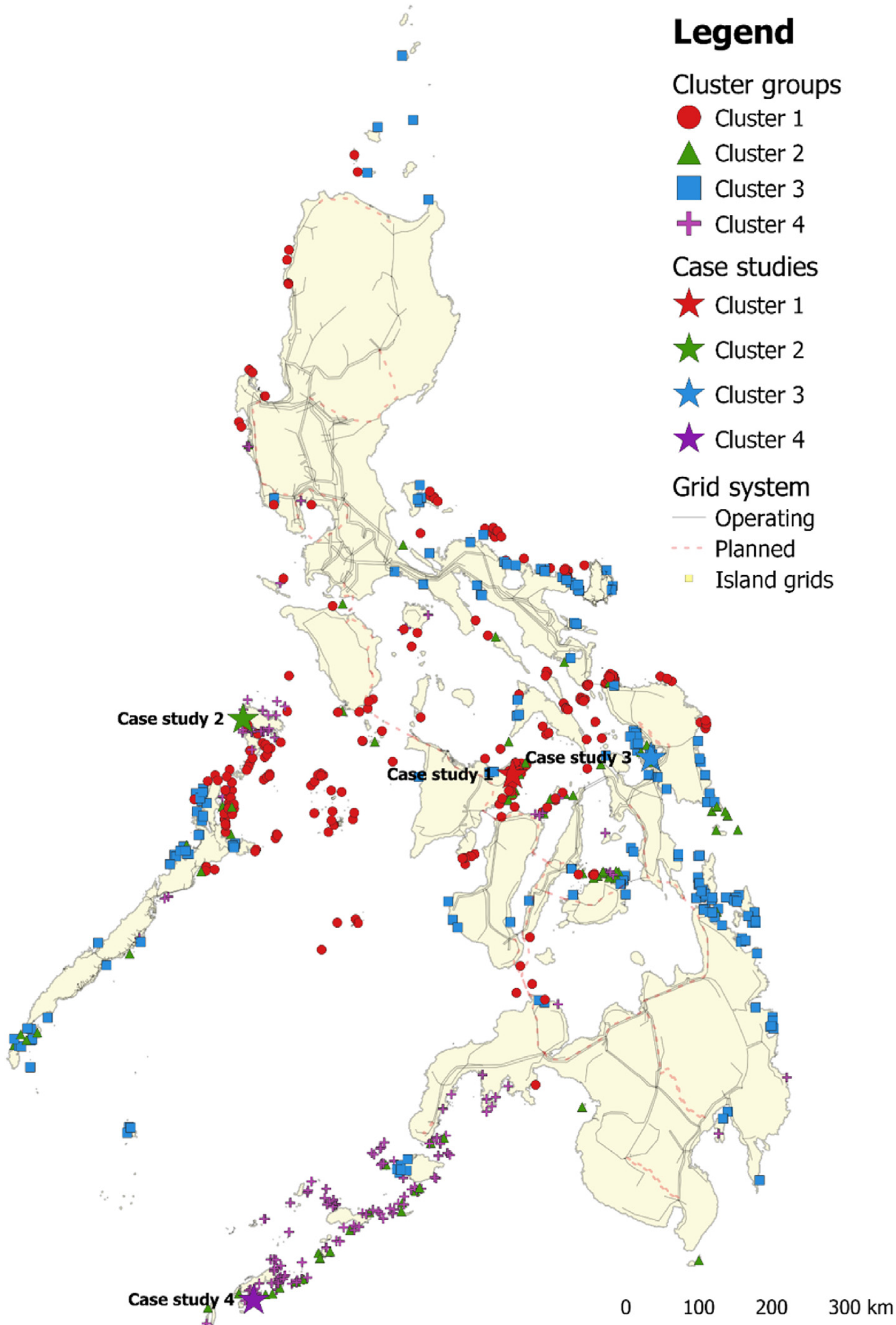

Fig. 5. Overview map showing island per cluster group, case study islands, and grid infrastructure.

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

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

would comply with the SDG7 targets. The reliability of the 100% RE systems comes at a considerable price: Since the energy system components are dimensioned to supply the demand even in the worst-case-scenario of the year (low RE resources and high demand) the power capacities are oversized compared to the typical daily electricity demand. Consequently, a considerable share of the generated electricity is dumped (range of 55%–61%). However, the costs are still below retail costs charged for environmentally harmful diesel power reported in the scientific literature [71,102]. In terms of the technology share we find solar power in combination with battery storage as the essential components of the cost-optimal system configurations. Solar power capacities to be

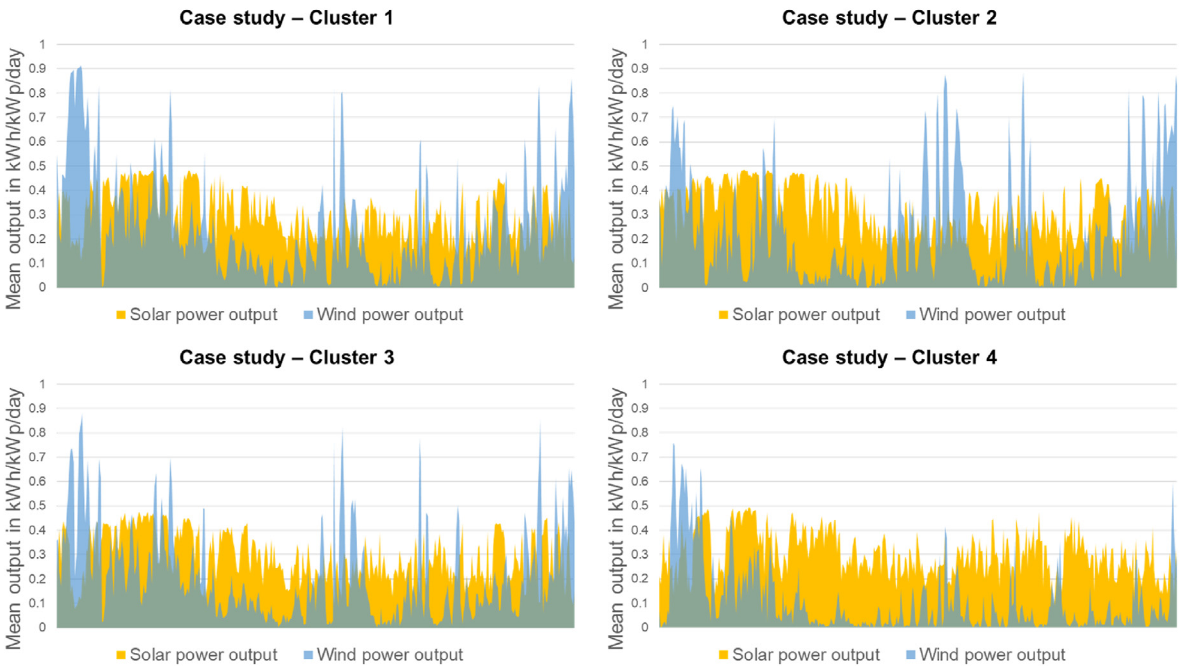

Fig. 6. Solar and wind mean power output in kWh/kWp per day for the four applied case study islands.

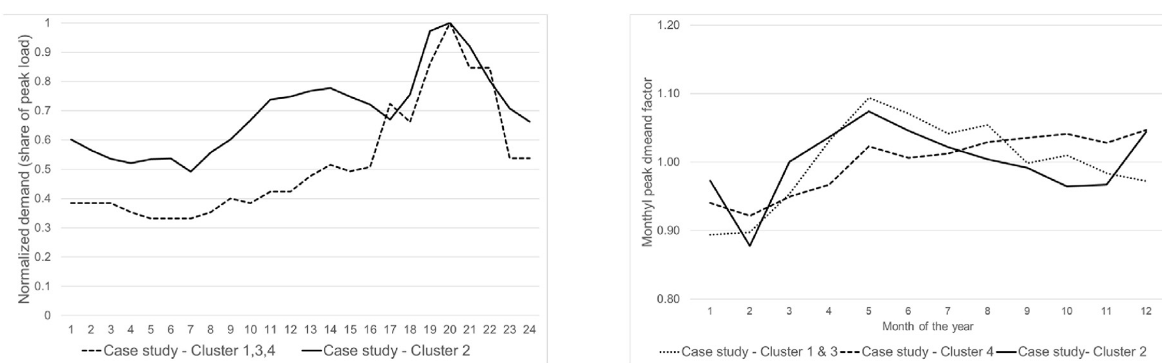

Fig. 7. *Normalized electricity demand (left) applied for case study islands based on* [21,71] *and monthly variation in peak demands applied for each case study island based on* [21].

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

Case study	LCOE (USD/ kWh)	Annual supply costs (USD)	Peak demand (kW)	Annual demand (kWh)	Solar capacity (kW)	Wind capacity (kW)	Battery capacity (kWh/ kW)	Reliability (% of demand)	RE share (%)	Solar power yield (kWh)	Wind power yield (kWh)	Excess electricity (% of total)
Cluster1	0.60	44,493	17.6	73,842	149.3	3.0	169.1	100	100	193,489	6653	61.8%
Cluster2	0.53	286,884	95.7	542,105	850.5	48.7	1177.7	100	100	1,172,706	98,923	56.1%
Cluster3	0.56	45,186	18.8	80,201	125.5	11.3	187.7	100	100	162,540	21,872	55.2%
Cluster4	0.61	45,983	17.3	75,282	124.9	18.2	175.9	100	100	165,685	17,665	57.7%

installed are in a range of 6–8 above the peak demand and battery capacities are in a range of 0.79–0.85 of the daily energy demand. Wind power capacities are a part of the cost-optimized solution although capacities are small compared to the other technologies. However, the effect of such small capacities on power generation costs in a 100% RE system can be significant and offsets up to 0.2 USD/kWh compared to solar-battery systems. The economic advantage of wind power is the replacement of substantial battery storage capacities and thereby the reduction of power generation costs. A disadvantage of wind power lays in the seasonality of wind resources (as presented in subsection 3.3.2) which limits wind power to a supplementary power source. The concurrence of solar and wind power capacities is a decisive factor for the system design and results in lower wind power capacities for case study 1 (higher concurrence) than expected compared to case study 4 (lower concurrence) although higher wind resources are available.

Sensitivity analyses reveal the effect of cost variation on LCOE and installed capacities: A variation in Solar CAPEX of −80% to +100% shows a significant impact on LCOE with a spread of −0.18 to +0.22 USD/kWh since solar power is the essential part of 100%

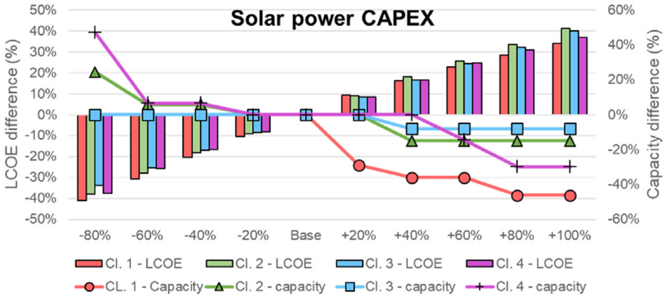

Fig. 8. Sensitivity analysis for Solar CAPEX.

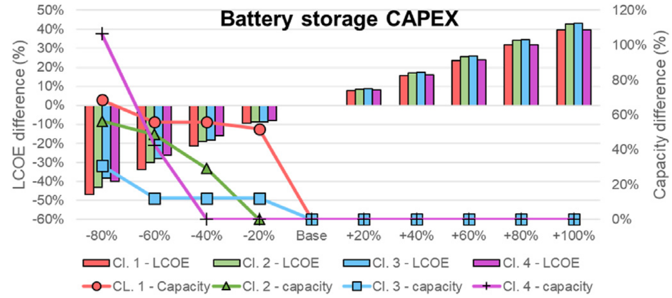

Fig. 10. Sensitivity analysis for Battery CAPEX.

RE systems (Fig. 8). With increasing CAPEX the solar capacities decrease while battery capacities significantly grow. Lower solar CAPEX have a lower effect on system capacities and solar capacities increase only for case study 2 and 4 replacing wind power capacities. Variation in Wind CAPEX affects the LCOE in a smaller range of ± 0.05 USD/kWh as wind capacities have a supplementary role and solar capacities generate the bulk of required electricity. Wind power capacities change little with CAPEX variation apart from the 80% reduction scenario which affects a large growth of wind capacities replacing a part of solar capacities in case study 1 and 2 (Fig. 9). A large LCOE spread between −0.28 and +0.24 USD/kWh is found for the battery CAPEX sensitivity analysis (Fig. 10). Hence, battery CAPEX is the most influential parameter on LCOE as large capacities are required in a 100% RE system to shift generated electricity to the time of demand. Additionally periods of low renewable resource availability need to be bypassed with large capacities. Rising battery CAPEX have no effect on the installed capacities. Lower battery CAPEX show similar results as for increasing solar CAPEX: Larger battery capacities are part of the cost-optimized system while solar capacities decrease. Fig. 11 shows the effect of different WACC to the LCOE, which is affecting each case study in a similar way. The difference in costs range is large with −0.19 to +0.30 USD/kWh. The effect on capacities is very low and only change the system design for case study 1 above a WACC of 14.4% (lower solar capacity − larger battery capacity).

We apply sensitivity analysis for reliability levels in a range of 100%−90% to study the impact on LCOE and installed capacities (Fig. 12). The lowest reliability level of 90% allow for LCOE reduction between 0.17 and 0.22 USD/kWh. The cost reduction is realized as much lower capacities need to be installed in a range of −33% to −45%. The sensitivity analysis further reveals that a reduction of the reliability level by 0.5% has the largest impact with an average LCOE reduction of 16%. Reducing the reliability level further by 0.5% to a 99% reliability level allows for an additional average LCOE reduction of 3.4%. With further steps the LCOE reduction potential increases in a slower pace. This finding indicates that the optimal solution between reducing costs and maintaining high supply reliability levels can be achieved by applying a 99% reliability level.

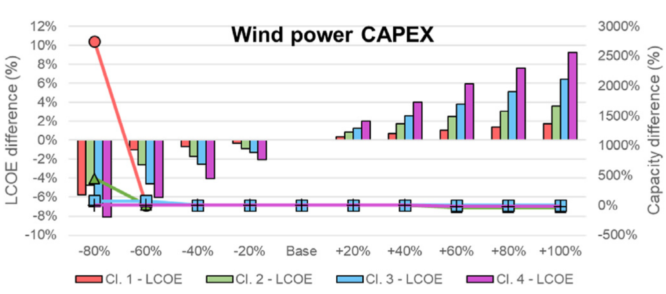

Fig. 9. Sensitivity analysis for Wind CAPEX.

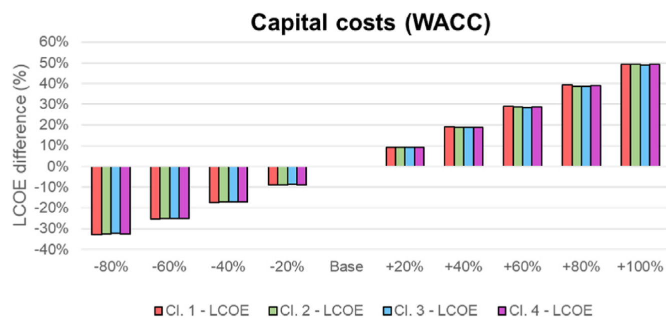

Fig. 11. Sensitivity analysis for capital costs.

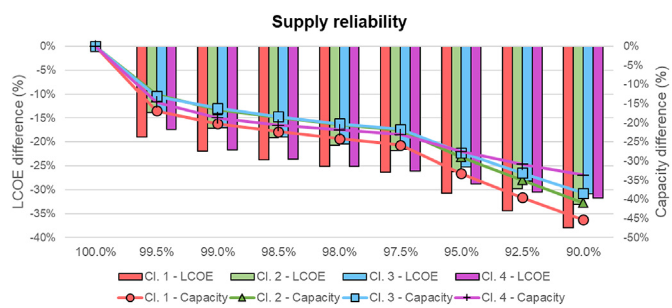

Fig. 12. Sensitivity analysis for reliability in terms of annual supplied electricity.

For a 99% reliability level we find power generation costs in a range of 0.43−0.47 USD/kWh which are significantly lower than for the 100% reliability level and are closer to the cost range for utility scale diesel power generation costs taking into account diesel fuel growth projections [21,103]. The technology composition is affected by reducing reliability levels: When applying a reliability level of 99% the PV capacities are reduced in a range of 25%−45%, whereas battery capacities are reduced only by 3%−10%. Wind power capacities have more diverse patterns as capacities are reduced by 8% and 12% for case study 2 and 3. Whereas for the more extreme case study 1 (high wind resources) the capacities increase by factor 3 and case study 4 (low wind resources) the capacities shrink by 75%. By allowing a 99% reliability level the seasonality of wind resources is not as disadvantageous anymore in cluster 1 and affects the split between solar and wind capacities. Whereas lower wind capacities are required to overcome the short periods of the year with low solar resource availability for case study 4. Practically, a reliability level of 99% would lead to power curtailment in 205, 203, 211 and 163 hours of the year for case study 1−4 respectively. However, for an average share of 26% of that period the curtailment is lower than

30% of the hourly demand so that critical loads could potentially still be supplied. Hence, we consider the 99% reliability level as acceptable for this study as it would still improve the status quo of few service hours on many islands [21,28,71,102]. The share of excess electricity is reduced to 39%–42% which increases the economic feasibility. Nevertheless, the share of excess electricity remains high and future research should focus on how to utilize excess electricity e.g. for water purification or water desalination.

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

4. Discussion

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

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

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

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

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

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

- First, a number of the considered islands may be already supplied with electricity through small community networks or household solutions. Official statistics about such systems covering the entire country would improve the database for this approach. Potentially, the analysis of recent and high-resolution

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

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

night light satellite imagery could facilitate to gain a more accurate overview on not electrified islands.
- Second, cluster analysis depends on complete datasets and adding or removing relevant missing values potentially affects the cluster split and assignment. Filling the missing values with accurate data could improve the research findings.
- Third, for the energy system modelling approach we limit the technology selection to solar and wind power in combination with battery storage. Taking into account further low-carbon technologies (e.g. biomass) could enhance the findings and improve the implications for policy makers. Especially, the integration of less intermittent and more schedulable renewable generation technologies such as biogas from agricultural residues [118] could reveal further development options.

5. Conclusion

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

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

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

I am acknowledging the funding of my PhD research through the Reiner Lemoine Foundation. The author thank the Reiner Lemoine-Foundation for co-financing this research work. Additionally, the author also thanks Philipp Blechinger, Martha Hoffmann, Karoline Gerbatsch and Setu Pelz for methodological support and proofreading.

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5. Assessing the impact of renewable energy on local development and the Sustainable Development Goals: Insights from a small Philippine island

Technological Forecasting & Social Change 153 (2020) 119919

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Assessing the impact of renewable energy on local development and the Sustainable Development Goals: Insights from a small Philippine island

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ARTICLE INFO

Keywords:
Energy access
Energy-Poverty Nexus
Sustainable Development Goals, Socio-economic impact
Philippines

ABSTRACT

Access to sustainable energy is crucial for achieving the Sustainable Development Goals. A particular challenge for countries like the Philippines, is to provide sustainable energy on its far-flung islands. Renewable energy technologies hold substantial potential for improving sustainability and reliability while decreasing costs. We present a socio-economic impact survey for a case study island: Cobrador represents a typical small Philippine island with a population of approximately 1,000. The implementation of solar power and batteries led to increased service hours, affordability and environmental soundness. We applied a household questionnaire focusing on electricity usage patterns and targeted 170 randomly selected households representing 70% of the population. Our data show a clear positive impact of the intervention on access to education, information, health services, and perceived safety, whereas we found a weaker impact on income generation. Overall, we reveal a beneficial impact on different aspects of the household's daily routine. However, we also identify significant differences in the electricity usage pattern of below-average and above-average income households, specifically with the latter more frequently using electricity for income generation. Future sustainable energy interventions need to be aligned with programs incentivizing poor household's electricity use for enabling all households to equally profit from sustainable energy.

1. Introduction

The global community has agreed on 17 Sustainable Development Goals (SDGs) to address various global development challenges and inequalities. The SDGs provide a framework to include social and environmental sustainability in development processes (Stevens and Kanie, 2016). Innovative, clean and sustainable technologies are crucial instruments for advancing towards these SDGs (Moyer and Bohl, 2019). Supportive technology policy is therefore of paramount importance to stimulate the development and diffusion of those technologies (Liu et al., 2019). An important example is the use of renewable energy (RE) technologies for achieving SDG #7: "Ensure access to affordable, reliable, sustainable and modern energy for all" (United Nations, 2015). Thus, many supranational institutions and national governments promote RE for the energy transition and rural electrification to provide and improve energy access and to address increasing energy demands in a sustainable manner (Almeshqab and Ustun, 2019).

Energy access and electrification can provide opportunities for new businesses, extended study and working hours, better health and education infrastructure and new opportunities for community building activities (Karekezi and McDade, 2013). However, context-dependencies prevent generalizable conclusions about these interlinkages that ultimately depend on locally specific factors. Insights from case studies reveal that the capability to benefit from access to electricity strongly depends on the socio-economic and socio-cultural context (Kumar, 2018). It is hence necessary to assess the impact of modern and improved energy access at the local level to derive recommendations for policy makers and technology policy interventions (McCollum et al., 2018). The research direction is therefore bottom-up, using case studies to derive local and regional recommendations instead of taking a global approach and breaking it down to the country level.

Such case studies need an interdisciplinary approach combining energy research with social sciences based approaches (Sovacool, 2014; Sovacool et al., 2015). This could be the analysis of an energy supply system by including the electricity user perspective via qualitative interviews, quantitative surveys and case studies, especially in less studied regions like remote areas of developing countries (Sovacool, 2012; Bhattacharyya and Palit, 2014). Lessons learnt of such studies can serve as crucial insights for addressing the need for access to energy in a more adequate and sustainable way in the future. In conclusion, supporting

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https://doi.org/10.1016/j.techfore.2020.119919
Received 31 March 2019; Received in revised form 5 October 2019; Accepted 15 January 2020

technology policy for SDGs needs context and regional specific research to improve evidence-based decision making and energy sector planning.

In our paper, we address this need by investigating the impact of providing more affordable, reliable and sustainable access to energy on consumption patterns, appliance uptake and overall socio-economic development. We selected the local community of Cobrador Island in the Philippines as case study. Choosing a typical small island in this region allows to extend recommendations not only for the Philippine context but also for Southeast Asia. Many remote islands in this region suffer from unreliable power supply and in the Philippines, still 2.36 million households (HHs) lack access to electricity (IRENA, 2017a). The purpose of our study is to highlight the effects of sustainable energy supply on the local community and to address the following research aspects to derive recommendations for policy makers:

a) How can SDG#7 be achieved on remote islands and what are specific consumption patterns and appliance usages to be considered?
b) How is the achievement of SDG#7 addressing crosscutting SDG targets such as access to information, access to education, access to health services, income generation and other?
c) How can the achievement of SDG#7 contribute to poverty alleviation and addressing inequalities?

To find solutions to these questions we have developed and applied a quantitative questionnaire and surveyed a significant share of households on the case study island. We use descriptive statistics to explore the data and analyze relevant aspects in more detail. Findings were compared to historical data of electricity consumption patterns on the island and to results of other case studies. The specific measure that addressed SDG#7 on the case study island was the hybridization of a diesel generator with solar PV and battery storage to provide clean and reliable electricity on a 24/7 base. The geographical, demographic, socio-economic, infrastructural and institutional framework conditions of our case study reflect a situation comparable to a large number of islands in the Philippines and Southeast Asia. Therefore, this case study analysis can serve for deriving implications for wider RE deployment in the region.

2. Background

The background section introduces the context of this study. First, we examine the interlinkages between energy access, SDGs and RE. Second, we highlight the energy access situation in the Philippines. Finally, we introduce the background of the selected case study.

2.1. Global context: energy access and the sustainable development goals

The lack of access to electricity hampers human development in many regards (Bhattacharyya, 2013). For example, a lack of modern lighting in households is considered to limit the ability to pursue not only productive activities after nightfall, but also educational and recreational activities. Likewise, business development and the provision of public services like health care and education are difficult (Bonan, 2017). Fig. 1 provides an overview on possible linkages between SDG#7 and other SDGs.

The possible linkages of SDG #7 to the other SDGs have been studied to a large extend already (Le Blanc, 2015; Alloisio et al., 2017; McCollum et al., 2018). A strong interconnection is often found concluding that access to modern energy services enables the implementation of a series of other SDGs, hence significantly contributes to sustainable development in general. Access to modern energy forms is fundamental to human development and to support the alleviation of poverty (SDG #1) according to Akter (2017) as well as Casillas and Kammen (2010). Energy access is also critical to enhance agricultural yields and productivity, which can increase food security (SDG #2) (Acheampong, 2017). In terms of increased health and well-being (SDG #3), access to modern energy services can reduce diseases caused by the emissions of traditional biomass for cooking and of kerosene lamps (Amegah, 2016). Especially women are highly affected by indoor air pollution (Das et al., 2017). The use of refrigerators facilitates cooling of medicine, especially of vaccines. Moreover, it allows for the cooling of food, which on the one hand results in better hygiene and on the other hand in new economic opportunities by selling preserved food or ice (Palit and Chaurey, 2011). Access to modern lighting enables for studying after nightfall, and modern information and communication technologies in schools can raise the quality of education and information access, which contributes to SDG #4 (Collste et al., 2017). A strong impact of improved electricity access on women's safety and girls' school enrollment is found and it can empower women by improving their income-earning, e.g. through time-saving from household chores (SDG #5) (Akter, 2017). Time savings for women can also be used for productive activities and education. SDG #7 can hence have a strong positive impact on the SDGs #5 (Gender equality), #8 (Economic growth) and #10 (Reduced inequalities) (Burney et al., 2017). Moreover, decentralized renewable energy systems such as solar home systems (SHS) or village-scale solar systems can enable more participatory and inclusive processes for managing energy supply on the community-level (Kunze and Becker, 2015). Depending on the policies in place it can also help to reduce inequalities between poorer and wealthier households (SDG #10) (Casillas and Kammen, 2010). On a local as well as global scale SDG #7 is an enabling factor for the implementation of SDG #13 on climate change mitigation and adaptation (Cherian, 2015; Riahi et al., 2016; Alloisio et al., 2017; Gambhir A et al., 2017). Ensuring access to clean and modern cooking and heating energy can also lead to less disturbance of the local biodiversity and the ecosystems caused by firewood collection and thereby contribute to SDG #15 (Life on Land) (Pagdee, 2017).

Whereas the positive impact of modern energy services on a variety of other fields might be evident, and many governments have acknowledged the importance of action in this field, many still struggle to deploy RE technologies, especially in remote areas. In many developing countries, complex and inadequate regulations, policies, and legal frameworks hamper the development of new RE or electrification projects and technologies (Blechinger, 2013; Brahim, 2014). Lack of financing for off-grid entrepreneurs and affordability of clean energy for poorer households is found to be a major challenge for the implementation of modern energy services (UNDP & ETH Zurich, 2018). Furthermore, the positive relations are highly dependent on the policy instruments in place. For example, if distributional costs of new energy policies (e.g. supporting RE and energy efficiency) fall disproportionately on the poor, then this could even work against the promotion of social, economic and political equality for all (McCollum et al., 2018).

In conclusion, the positive effects of SDG#7 on other SDGs have been widely studied and acknowledged on a global scale. Nevertheless, country specific contexts need to be considered when designing supporting policies. Thus, findings from interventions targeting SDG #7 in remote areas of the Philippines are of importance for more accurately and sustainably designing an appropriate technology policy in the future.

2.2. Country context: energy access in the Philippines

As an archipelago comprised of more than 7,000 islands the Philippines are a considerably fragmented country (Boquet, 2017). Continuous power supply is provided to the most populous and economic relevant “on-grid” islands through two main electric grids (IRENA, 2017b). Isolated grids supply the “off-grid” areas, which are defined as islands or remote areas not connected to one of the two main grids. Frequent power rationalization in off-grid areas is a consequence of high costs due to the use of diesel generators (Roxas and Santiago, 2016) and 24 hours supply is mostly not available

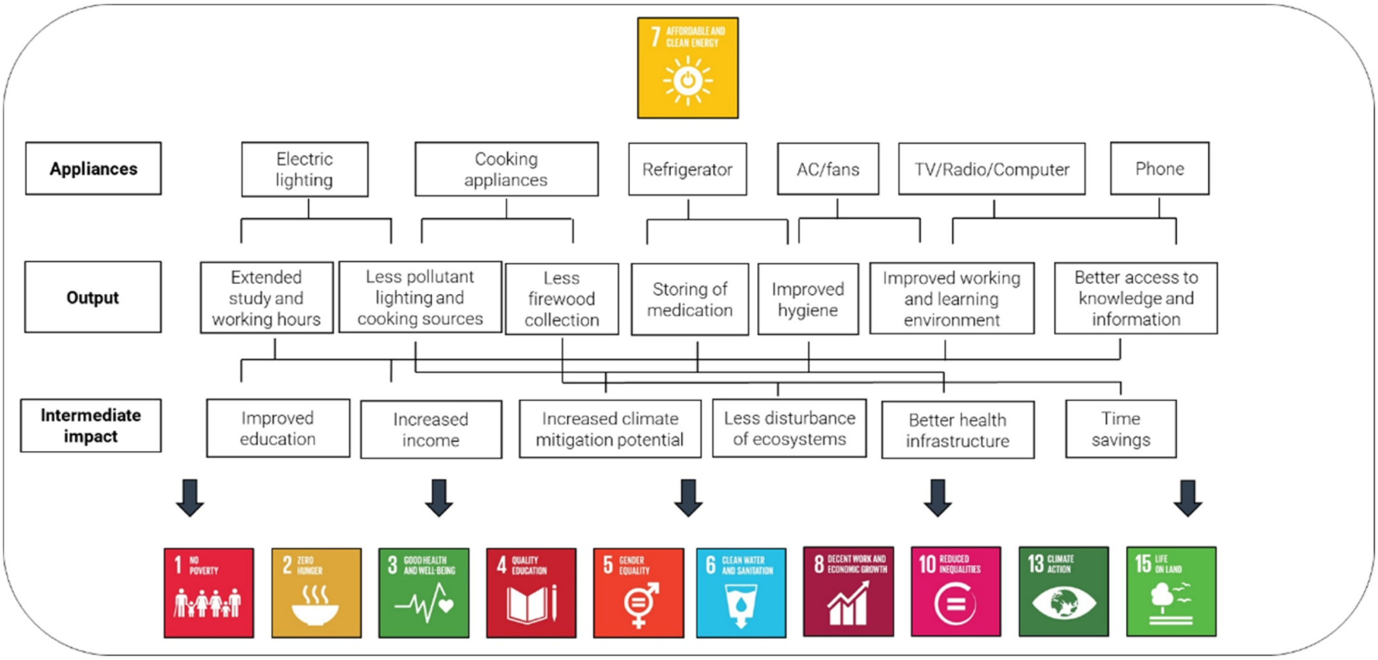

Fig. 1. Interlinkage of SDG#7 to other SDG (own illustration).

(DoE, 2016). Electricity users in the "off-grid" areas are only obliged to pay a socially acceptable generation rate (SAGR) which is defined per region by the Energy Regulatory Commission (ERC) of the Philippines. The difference to the true cost of generation rate (TCGR) is cross-subsidized from the universal charge for missionary electrification (UCME) which is a surcharge to electricity bills in the "on-grid" areas. The escalation of UCME subsidy is an increasing burden to the national funds of the country (Bertheau and Blechinger, 2018). The remaining non electrified areas ("missionary areas") are a large number of small islands with no power supply or informal power supply only. The objective of the government of the Philippines is to provide access to clean and continuous energy supply to all parts of the country for improving living conditions. Therefore, 100% electrification of all households by 2022 was set as target within the Philippine Energy Plan (PEP) (DOE, 2015). Nevertheless, the share of electrified households was only at 89.6% in 2016, reflecting 2.36 million households without electricity supply and many other with only basic and limited energy supply (IRENA, 2017a). The Philippine Renewable Energy Act (RE Act), inaugurated in 2008 (RA9513, 2008), serves as technology policy instrument for stimulating the deployment of RE technologies in the country (Roxas and Santiago, 2016). High expectation arose as a large number of fiscal and non-fiscal incentives was implemented under it (Rosellon, 2017), with specific schemes envisioned to facilitate rural electrification through private sector participation. However, a study on the risks and uncertainties of RE implementation on the Philippines (Bertheau et al., 2019), indicates that the lack of clear implementation of these policies hinder them from successfully supporting the energy transition on remote islands. Numerous attempts for RE based electrification in the framework of international development cooperation were undertaken in the Philippines. Early initiatives focused on deploying SHS (Heruela, 1992), followed by hybrid energy systems comprised of solar PV, batteries and diesel generators for back-up power supply (Hong and Abe, 2012). Although many donor-based RE projects have been conducted by USAID, GIZ, UNDP and others (Marquardt, 2015), little information on their evaluation can be found. Several studies (Hong and Abe, 2012; Marquardt, 2015; Yaqoot et al., 2016) indicate that most of the donor-based projects proved unsustainable due to weak local capacities for proper operation and maintenance of the systems which then led to low acceptance towards new technologies among the population. In summary, the Philippines are a renewable resource rich country which currently fails in exploiting its full potential to achieve SDG#7. More locally adapted interventions are necessary to facilitated the implementation of RE technologies on remote islands and provide access to energy.

2.3. Case study context: cobrador Island solar – Diesel project

Cobrador Island forms a single barangay[1] as part of the province of Romblon, located centrally in the Philippines. The island is small with an area of 2.6 km^2 comprised by a small beach stripe and mainly hilly terrains. It is home to approximately 1,000 people living in about 250 households scattered over seven sitios[2]. The island has a barangay hall (town hall), health station, a primary school and kindergarten and the main source of income is fishing. With these typical characteristics, Cobrador island is representative for a large number of small islands in the Philippines and the region (Meschede, 2018). Some households of the island were initially electrified in 1997 by means of SHS within a governmental electrification program. In 2010, the local electric cooperative (EC), installed a diesel generator of 15 kW capacity to address an increasing demand. However, due to high fuel costs electricity was provided for eight hours per day and due to difficult terrain to 138 HHs only. This situation changed with the inauguration of the Cobrador Island Solar – Diesel Project in August 2016, which facilitated 24 hour electricity supply. The new hybrid system consists of a solar capacity of 30 kW, battery (lithium-ion) capacity of 180 kWh and a diesel back-up generator of 15 kW. As a result it improved the reliability of supply (24 h), affordability (50% electricity price reduction) and environmental soundness (renewable energy share of up to 92% per day) (Bertheau et al., 2019). In the first year of operation the bulk of required electricity was supplied by the solar plant with 32.7 MWh and 10.6 MWh were supplemented by the diesel generator (Fajilagutan, 2018). This reflects an average RE share of 75%. Solar PV and battery storage was selected as appropriate RE technology given its matureness and ease of installation. Other RE technology options were not considered given the unfeasibility of installation (wind power) or

[1] Smallest administrative unit in the Philippines
[2] Part of a barangay

uncertain fuel supply (biomass). Hybrid energy systems are considered as important energy supply option for island and remote communities (Kuang et al., 2016), as existing fossil fuel systems can be stepwise transitioned to RE based energy systems and thereby gradually decarbonized (Neves et al., 2014). The intervention was realized through international collaboration in the framework of the Asian Development Bank's Energy for all (E4ALL) initiative which aims at contributing to SDG#7 through various activities. The project included technical and financial cooperation for the Romblon Electric Cooperative (ROMELCO) from the Asian Development Bank (ADB), Korea Energy Agency (KEA) and the National Electrification Administration (NEA) of the Philippines. The overall costs summed up to approx. 500 thousand USD split between KEA (300,000 USD grant fund), ADB (100,000 USD grant fund) and NEA (100,000 USD loan fund). ROMELCO contributed with workforce, constructed the powerhouse and purchased the necessary land. The outlined case study presents an example for the deployment of an innovative and sustainable energy solution through technology policy. The specific conditions of the island are comparable to a large number of islands in the Philippines and in the region. Given the remoteness of the island, external influences are low and clear system boundaries are defined. This makes the island a suitable research subject to understand the socio-economic implications of an intervention targeting SDG #7 with a focus on providing and improving electricity access through RE.

3. Material and methods

Our study mainly relies on primary data from Cobrador Island. The primary data collection builds upon a household survey since this allows for assessing the impact of an improved and RE based energy supply on the household level. By covering other characteristics of the studied HHs such as socio-economic data it is possible to study coherences and derive key findings. Surveys are a cornerstone of empirical research in the field of social science based energy research (Sovacool et al., 2018) and are combined with literature analysis and data on historical electricity consumption for this study. The material and methods section describes the development of the applied household questionnaire, the preparation of the field survey, the implementation of the field survey and the limitations faced during the data collection.

3.1. Questionnaire design

We developed the applied questionnaire in an iterative approach to assure its appropriateness and applicability (Preston, 2009). Specific challenges can occur when conducting questionnaire surveys in remote and marginalized communities of developing countries, such as low educational level of respondents, cultural traditions, gender roles, local languages (UN-DESA, 2005). To address these challenges, Philippine experts (scholars from University of the Philippines - Diliman), familiar with the case study region, were involved in the questionnaire design from an early stage on. Additionally, we analyzed relevant literature and questionnaires applied for addressing similar research questions, e.g. Sullivan and Barnes (2006), Hong and Abe (2012), and Sovacool et al. (2018).

The iterative development and design process included the following steps: (1) Design of first questionnaire draft based on literature analysis. (2) Feedback round with Philippine and international experts. (3) Design of second questionnaire draft based on feedback. (4) Double blind translation of questionnaire from English to Tagalog and Tagalog to English. (5) Design of third questionnaire draft based on issues revealed during translation. (6) Pretesting of questionnaire, workshop and training with group of enumerators. (7) Creation of fourth questionnaire draft based on feedback from pretesting and workshop. During the field survey, the team conducted daily meetings for feedback and necessary adaption of the research design. Fig. 2 illustrates the approach applied for developing and designing the questionnaire.

The finally applied questionnaire is comprised of four sections with 58 main questions, and additional follow-up and sub-questions. Most questions are closed-ended but few are open-ended questions to account for not anticipated responses (Sullivan and Barnes, 2006). Answering the questionnaire took approximately one hour during pretesting and during the field survey. Table 1 presents and describes the four main sections of the questionnaire.

3.2. Survey design

We applied a stratified random sampling technique for the selection of respondents to make sure that all households, within the predefined household classes, have the same probability of consideration. Data on monthly electricity consumption, of all households of the case study island, served as stratification variable. Data was classified by means of the Jenks optimization method for minimizing the deviation from the average within a class and for maximizing the deviation to the average of other classes (Jenks, 1967). We applied four classes since it provides an acceptable goodness of variance fit (GVF) value with 0.92. Table 2 presents the derived classes based on the electricity consumption of households.

We determined a statistically representative sample of at least 158 HHs questionnaires based on a population of 239 households, a 95% confidence interval, and 5% margin of error and non-response factor (Barlett et al., 2001). According to the share of the total population of each class, it was then determined how many households of each class had to be interviewed (Table 2). For each class the proportionate amount of respondents was randomly selected for the final sample. On site, the enumerators approached only the randomly derived households through asking the villagers for directions. For anonymization reasons, a code was assigned to each household in the questionnaire. In case that the assigned household was not available for an interview for any reason (e.g. declined to respond, absence, only underage household members available), the enumerator selected the next household of the same class from a randomly comprised list. Finally, it was possible to interview 170 HHs, considered as sufficient to expect a sampling error close +/- 5% at a 95% confidence interval for the given population (Sovacool et al., 2018).

3.3. 1.8. Household questionnaire survey

The author and a team of five enumerators, all volunteers and students from the University of the Philippines – Diliman, conducted the field survey. The team of enumerators conducted most of the questionnaires due to their proficiency in Tagalog and the local dialect (mix of Tagalog and Cebuano). Prior to the survey the local government unit, electric cooperative, barangay captain (community unit) and local leaders, as well as interested inhabitants were invited to a stakeholder meeting informing about content and purpose of the study, and assuring confidentiality of responses in order to meet the ethical standards of cross-cultural studies. The questionnaire were digitized and each enumerator was provided with a tablet applying KoBoToolbox© which is a free open source tool for mobile data collection. The tablet approach was selected to minimize survey costs and material use (Leisher, 2014). Before starting with the questionnaire, each enumerator explained about purpose, content and length of the questionnaire explicitly highlighting that the respondent can decline to respond to the entire questionnaire or single questions. The household head was addressed for the interview; in case of absence another full-aged household member was asked to respond to the questionnaire. Finally, 170 questionnaires were conducted (Fig. 3).

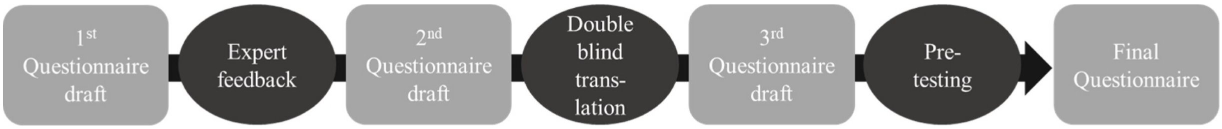

Fig. 2. Approach for questionnaire design (own illustration).

3.4. Statistical data analysis

In order to derive statistically valid conclusions based on the collected primary data, a range of tools and methods can be applied. Here, collected data was compiled into a single dataset and prepared for further processing. The statistical data analysis was carried out with the software SPSS©[3]. Minor data cleaning and the definition of variable types was necessary before statistical analysis were applied. Descriptive statistics served to gain a comprehensive overview of the current socio-economic situation as well as the general usage of electricity on the case study island. Frequency distributions, cross tables, and mean/median values were used to describe the collected data. In order to analyze the data with regard to differences between poorer and wealthier households, income groups were separated by the mean income per month. Households whose income was above the mean were classified as "above-average income households", households with an average monthly income below the mean were grouped as "below-average income households". On the basis of this classification, several hypotheses were tested by means of chi-square test, t-test and Mann-Whitney-U test based on the variable type and data characteristics focused on.

3.5. Limitations

Only a few households declined to respond to the questionnaire. In contrast to that, the arrival of the enumerator team were attracting a significant share of people of the visited communities. Thus, it was sometimes challenging to keep the privacy of interviews and it was necessary to request neighbors and passers-by to not disturb the interview. Additionally, neighbors of interviewed households offered or requested to hold an interview with them and it was necessary to explain that respondents are selected randomly. Another limitation from the approach is a probable bias in responses for several reasons: Although the enumerators were comprehensively trained in conducting the interviews, a bias based on the enumerator cannot be entirely ruled out. Another limitation could be a bias in responses to the interviews. Although enumerators made clear that they are not representing a governmental unit or the electric cooperative respondents may have responded according to what they perceived as the favored answer. No disaggregated baseline data on the aspects analyzed are available for the case study. The impacts assessed here might thus not represent long lasting developments. An attempt was made to reconstruct the pre-electrification state and examine the changes by including respective questions in the household survey. For all quantitative data gathered in the household survey, e.g. monetary data about incomes and expenses, uncertainty regarding the reliability and accuracy must be taken into consideration. For most of the information no exact accounts are held by the households and statements are mostly based on respondent's estimates. Another noteworthy limitation of the research approach is the sole focus on access to electricity since providing clean energy for cooking is another decisive factor for achieving SDG#7.

4. Results

In the results section we present the main findings from the household survey. We highlight socio-economic characteristics, electricity consumption patterns, electric appliances inventories and perceived changes of the hybrid system implementation for the surveyed households. We put a specific emphasize on differences between below and above-average income households to study the effect of providing sustainable electricity supply on inequality and poverty alleviation. The potential for income generation is considered as most important for alleviating poverty and inequality and is therefore focused on although other parameter, e.g. child education success rate or improved health rate could be eligible parameters for assessing the impact of SDG#7 interventions.

4.1. Socio-economic characteristics of households

We interviewed 170 out of 239 households for the survey. Table 3 summarizes key characteristics of the HHs. The average age of respondents is 46.7 years and more than 64% of respondents are female. On average, 3.6 persons live in one household which is below the national average of 4.4 persons (PSA, 2017). With the 170 HHs a population of more than 602 individuals (39% younger than 18) is represented.

The highest educational degree per HH is predominantly primary school (44.4%) (six years of education) followed by secondary school (32%) (ten years of education). HH income correlates with years of education for the highest degree in the household ($r = .284,\ p = .000,\ N = 162$). Analysis reveal that the mean income is 8,558 PHP (~165 USD[4]) per HH and month (Median = 4,841 PHP; SD = 10,109 PHP). For further analysis we classify HHs with monthly income larger than 8,558 PHP as above-average income HHs (n = 50) and HHs with monthly income lower than the average as below-average income HHs (n = 114). Mean HHs expenditures per month are 6,045 PHP (~116 USD) (Median = 4,531 PHP; SD = 5,748 PHP). High standard deviations for both income and expenditures reflect the large inequality among the HHs. Additionally, the responses show that a large share of 32% of households is poor (monetary wise) with a weekly income lower than 500 PHP (9.6 USD) compared to the World Bank's extreme poverty line of 1.9 USD/day (Warwick et al. 2018).

Many HHs have diversified their income sources and it is common that both, men and women participate in income generating activities with women often additionally taking care of the household chores. The main income source is fishing (47.7%). Followed by home business activities (17.6%) of which the most common is the operation of a small shop (sari-sari store). Further home business types are boat manufacturing, mat weaving and copra drying. Other income sources (10.1%) include charcoal production and selling, carpentry, construction and some support from government programs. More than 43% of the HHs receive remittances from relatives which contributes to overall income by 5.8%. Farming mostly serves as means for self-subsistence. Most HHs have very intermittent incomes due to the dependency on fish catches and selling.

The major share of the HHs' income is spent for food (59.9%). HHs with schoolchildren spend a large share of their income on education, with an overall expenditure of 14.7%. Older children have to visit secondary school on another island, where they stay during the week in paid accommodation. Domestic needs comprise drinkable water, medicines, toiletries and baby foods (9.7%). Transportation expenditures are relatively high due to the remoteness of the island (7.6%).

[3] IBM SPSS Statistics 25

[4] For PHP – USD conversion we apply a currency exchange rate as of 1st of March 2018: 1 USD = 52 PHP.

Table 1
Questionnaire structure.

Section	I	II	III	IV
Topic area	General socio-economic information	Electricity demand and usage	Subjective perceptions of changes	Challenges
Questions	Household size, adults/children, age, education status, main income sources and expenditures	Electricity bill, willingness to pay, appliances (what, how many, since when, how often used), activities with electricity	Impact of electricity access on health, security, education, safety and income	State major challenges for the household and the island within the next two years
Rationale	Setting basic socio-demographic context and providing key information for interpreting the survey results	Enables a detailed understanding of the usage of electricity	This data allows for an understanding whether residents perceive an impact of electricity on their daily life	Enables an understanding of the major concerns of the residents and if they are related to electricity access.

Table 2
Questionnaire structure.

Class	Lower boundary (kWh/month)	Upper boundary (kWh/month)	Count	Considered in sample
1	5	195	164	108
2	210	607.5	55	36
3	742.5	1,567.5	14	9
4	1,942.5	3,217.5	6	4
GVF			0.92	

Electricity is a minor share of expenditures (6.3%) and other expenditures are spend for leisure activities. Similar expenditure patterns have been reported for other regions of the Philippines (Agbola et al., 2017). A higher share of below-average income HHs (44.4%) spend more than 75% of their total expenditures for food compared to above-average income HH (24.5%). However no statistically significant differences in expenditure patterns between income groups were identified.

4.2. Electricity consumption patterns

Prior to the implementation of the hybrid system intervention, a steep growth in electricity demand was expected once the electric service was made available for 24 hours per day. Electricity for refrigeration and ice-making were among the identified uses e.g. in support of the island's fishing sector. Fig. 4 shows the annual energy sales development. Energy sales increased from 2015 to 2016 through the implementation of the hybrid energy system which included the connection of additional HHs and the provision of 24 hours supply. Energy sales further increased through appliance uptake from 2016 to 2017 and averaged at a daily demand of 142 kWh/d. Fig. 5 highlights the growth of the average peak demand on a daily basis. Compared to 2016 the maximal peak demand for 2017 and 2018 increased significantly during early afternoon and in the evening hours. The maximal daily electricity demand observed for 2017 and 2018 exceed the average demand by far with 270 kWh (2017) and 279 kWh (2018). Such extreme demands exceed the capacity limits of the implemented system. We can conclude that the provision of 24 hours supply increased electricity consumption and that large differences in mean and maximal daily demands occur.

.Almost all HHs use electricity from the hybrid energy system as primary source of electricity (97.7% of HHs). Other and additional devices such as automotive batteries (7% of HHs), SHS (12% of HHs) and small diesel gensets (2% of HHs) are applied by few HHs and rather occasionally as a back-up source. The majority of HHs have a relatively small monthly consumption of up to 30 kWh. According to the Multi-Tier Framework for Measuring Energy Access (MTF) most of the HH can be classified into Tier 2 and Tier 3 (Bhatia and Angelou, 2015). The cross tabulation (Table 4) indicates a clear difference between income groups since a high share of below-average HHs (34%) uses only very little electricity per month. Chi-square test reveals a significance with medium effect size, ($\chi^2(3) = 24.1,\ p = .000,\ \varphi = .394,\ N = 155$).

For a further understanding of the income's group capabilities to use electricity for income generation we explore for coherences between income groups, income generation through an own business (taking place at the HH – e.g. shop, handicraft, e.g.), and if electricity is required for such activity. Table 5 provides an overview on observed cell frequencies and expected cell frequencies for the presented questions.

The results show that income group not significantly affects the likelihood of income-generation through an own (home) business ($\chi^2(1) = 3.37,\ p = .06,\ \varphi = .0144$). However, above-average income groups are more likely using electricity for income generation in their HH, with $\chi^2(1) = 5.66,\ p = .017,\ \varphi = .187$ (medium effect size). The majority of businesses run by both income groups was set up before the implementation of 24 hours electricity supply.

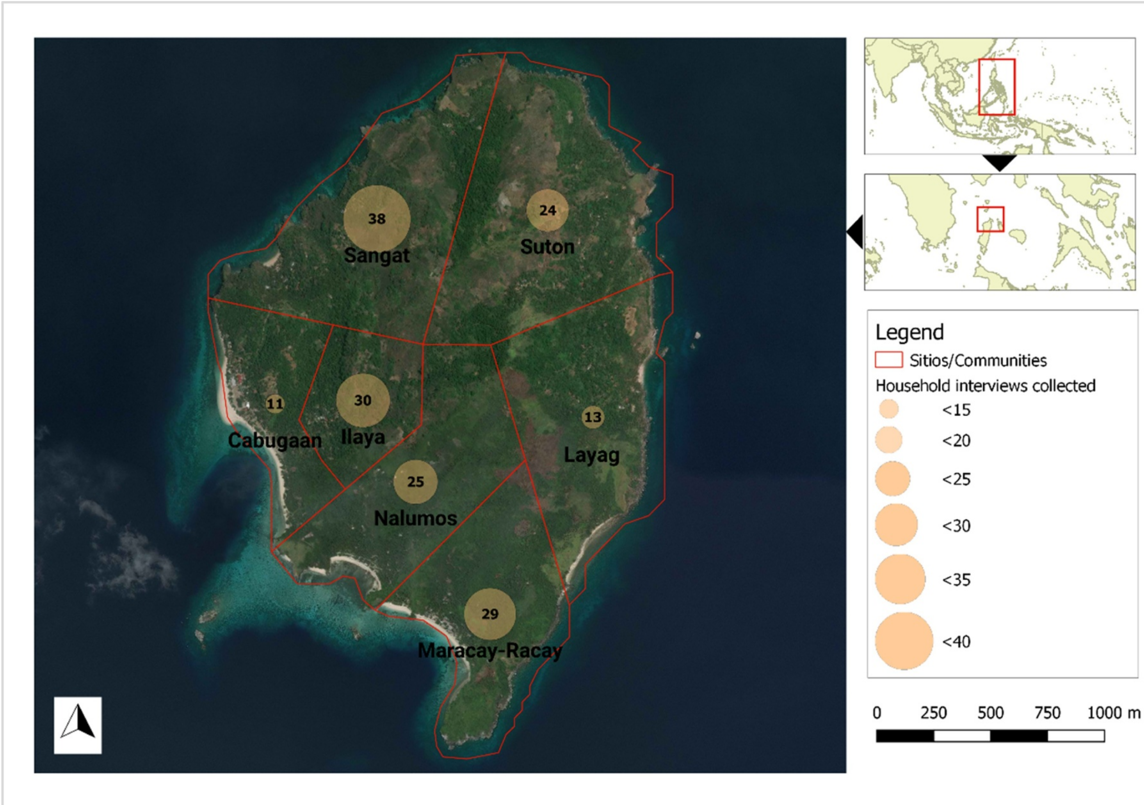

Fig. 3. Overview map for case study area and questionnaires conducted per sitio/community (own illustration).

Table 3
Respondent and household characteristics.

	Median	SD	Min	Max	n
Age of respondent	46.7	15.76	18	84	170
HH size	3.6	1.73	1	10	170
Male	1.9	1.11	0	5	170
Female	1.7	1.17	0	7	170
Children (<6)	0.4	0.63	0	3	170
Children (6-18)	1.0	1.27	0	9	170

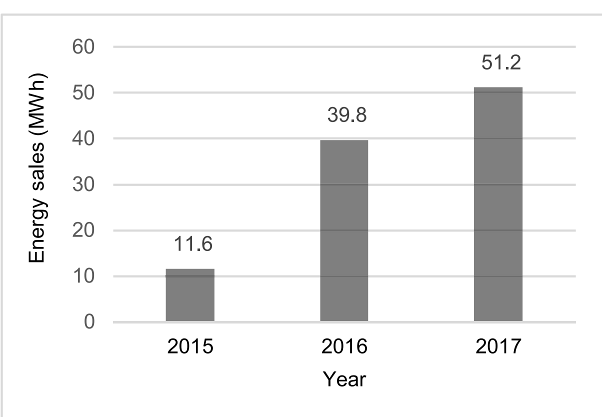

Fig. 4. Annual energy sales growth from 2015 -2017 (MWh) own visualisation based on Fajilagutan (2018).

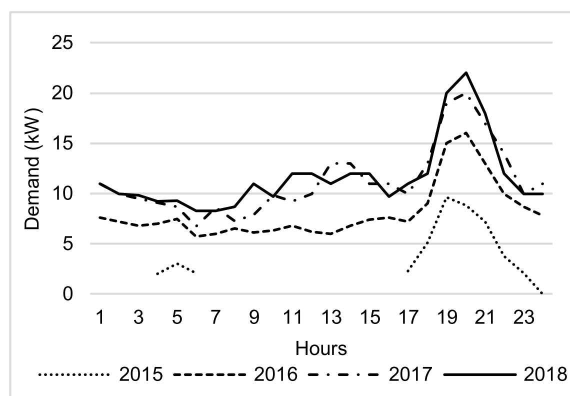

Fig. 5. Annual maximal peak demand growth from 2015 - 2018 (kW) own visualisation based on Fajilagutan (2018)

Table 4
Distribution of electricity consumption within below-average, above-average income groups, and total.

Income group	Electricity consumption per month				
	< 6 kWh	< 30 kWh	< 60 kWh	>60 kWh	N
Below-average	33.9%	60.4%	3.8%	1.9%	106
Above-average	8.2%	61.2%	18.4%	12.2%	49
Total	25.8%	60.6%	8.4%	5.2%	155

Most HHs approve (59.4%) the current electricity price of 15 PHP/kWh (approx. 0.29 USD/kWh). A certain dissatisfaction originates from many villager's knowledge that the electricity price of the neighboring larger island (determined through the SAGR) is half the price of their electricity charge. Above-average income HHs are less satisfied with the electricity price and occasionally demanded for an adjustment of the price to that of the neighboring islands during the interviews (Fig. 6), we reveal a significant difference between income groups by applying Fisher's exact test ($p = .039$, $\varphi = .255$, $N = 157$). Respondents stated

Table 5
Cross table highlighting the income group's home business activities.

		I: Do you generate income through an own business in your household?		II: Do you use electricity in your household for income generation purposes?		III: Since when do you run the own business?		
		No	Yes	No	Yes	After 24 supply	Bef. 24 h supply	No answer
Below-average	Count	86	28	92	19	6	11	2
	Expected	81.1	32.9	86.2	24.8	8.3	15.3	1.4
Above-average	Count	30	19	33	17	6	11	0
	Expected	34.9	14.1	38.8	11.2	3.7	6.7	0.6
	Total	116	47	125	36	12	22	2

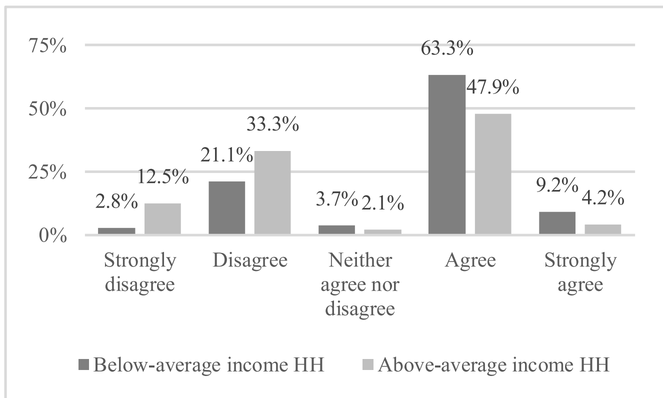

Fig. 6. HH responses for: "The price for electricity that we are currently paying is just fine".

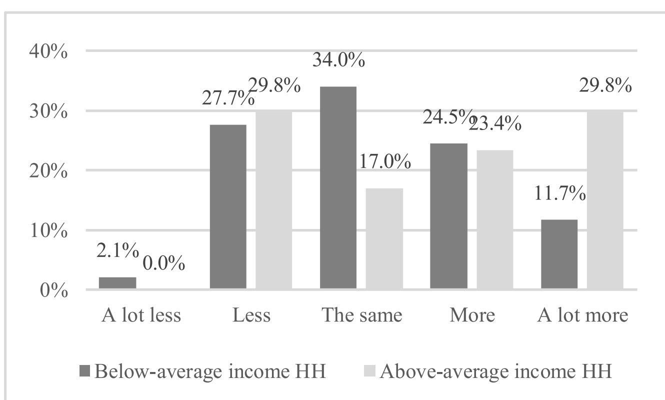

Fig. 7. HH responses for: "Did the HH pay more or less for electricity before the installation of the solar plant?

that they spent more (20%) and even a lot more (15.3%) money for electricity before the hybrid system intervention. Contrasted by 24.1% stating that they spent approximately the same amount for electricity or even less. Fig. 7 shows differences between below- and above-average income groups: A higher share of above-average income HHs states to spend less money since the hybrid system intervention. A significant difference was detected by applying chi-square test, ($\chi^2(4) = 10.0,\ p = .04,\ \varphi = .267,\ N = 141$).

When asked if respondents would pay a higher price for electricity the slight majority agreed to be willing to pay double the price (59.2% of above-average income HHs & 51.9% of below-average income HHs), which quickly decreases to overwhelming disagreement when asked for triple or quadruple the price (Fig. 8). No statistically significant correlation between income and willingness to pay for electricity supply was identified. The main problems with the electricity supply stated are power outages, damaged appliances through outages and high costs. Most of the HHs need electricity during evening hours when light is required or for gathering at home for jointly watching TV (Fig. 9). Another important use of electricity is for lighting purposes, as a high share of children (51.4%) study after sunset and require electricity (98.6%) to do so. Both income groups show similar patterns when asked for the most important period of the day for which they need electricity (Fig. 9).

Overall, our results indicate that electricity is primarily used for entertainment and information gathering, additionally constant lighting allows for increased study hours for children. Nevertheless, the direct impact on the HHs depends on consumption of electricity and electric appliance inventory. Here we find that above-average income HHs consume considerably more electricity and at the same time profit more from the reduced electricity prices. Paradoxically, above-average income HHs are less content with the applied electricity charge and both groups do not differ in their willingness to pay more for electricity. On the community level the hybrid renewable energy system improved access to health and education since the elementary school now provides computer classes and the services of the health center have improved through continuous access to electricity allowing to power more

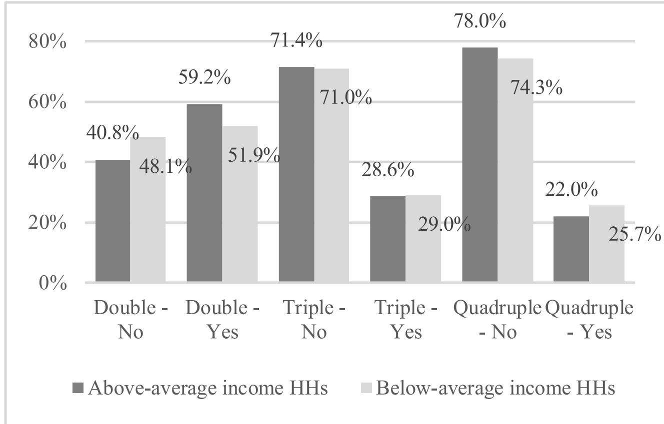

Fig. 8. Willingness to pay higher (double, triple, quadruple) electricity prices.

medical electrical devices. Since both school and health center are public entities these outcomes are accessible to all households. Additionally, the higher reliability of electricity supply allows for replacing some rather health-affecting appliances such as kerosene lamps, and more sensitive electric appliances, e.g. for entertainment, such as sound systems or multimedia devices, can be powered with a reduced risk of damage through power outages. For lighting purposes, a larger variety of sources besides electricity is used, e.g. candles (17% of HH), kerosene lamps (18% of HH) and rechargeable flashlights (70% of HH), which are important appliances for night fishing activities. The findings indicate that the HHs favor the electricity from the hybrid energy system over other and formerly used solutions.

4.3. Electric appliances

We asked the HHs for their electric appliance inventory to study the use of certain devices. Electric lighting is the main electricity appliance used in almost all surveyed households. 92% of the HHs use electricity for lighting, on average a typical HH possess 2.5 light bulbs. A typical appliance inventory consists additionally of cell & smart phones (88%), television (73%) and fan (70%). Followed by other entertainment appliances such as DVD players, sound systems and radios. Household appliances and IT appliances are less frequent. Wealthier households own generally more (Fisher's exact test: $p = .000$, $\varphi = .279$, $N = 164$) and more energy intensive appliances. Results show a significance between income groups and ownership of fridges by applying chi-square test ($\chi^2(1) = 12.80$, $p = .000$, $\varphi = .279$, $N = 164$), ownership of washing machines by applying Fisher's exact test ($p = .004$, $\varphi = .248$, $N = 164$) and ownership of water heaters by applying Fisher's exact test ($p = .01$, $\varphi = .224$, $N = 164$). Mainly firewood, charcoal and in few instances LPG stoves are used for cooking, but no electrical ovens are owned or used. Only one household owns an air conditioning system. Fig. 10 shows the quantity of HHs with certain appliances and the quantity of appliances purchased after the increase of electric service hours. The data indicates that HHs purchased some appliance types more often since the provision of 24 hours power supply. This is especially true for appliances outside the light, TV, fan, cell phone standard set. Appliances with highest growth rates are water heaters (86%), refrigerators (76%) and sound systems (73%), which are appliances with high or constant power demand or vulnerable to power outages. Increased appliance purchases and more frequent appliance usage contributed to the rapid demand growth in addition to new connections.

We asked for planned appliance purchases to investigate if the power demand is likely to further increase. However, the larger share of HHs (59%) stated not to plan to purchase any appliances in the next two years. This indicates that first demand for essential electric appliances is saturated. Nevertheless, a number of HHs still plans to purchase energy-intensive appliances like fridges (14%) and washing machines (4%) which can significantly add to the baseload and peak load in the hybrid energy system. Fig. 11 provides an overview on planned electric appliance purchases. Above-average income HHs plan to purchase more energy intensive appliances (fridge & washing machine).

4.4. Perceived impact of SDG#7 intervention

Due to the absence of socio-economic data characterizing the situation prior to the SDG#7 intervention and availability of 24 hours

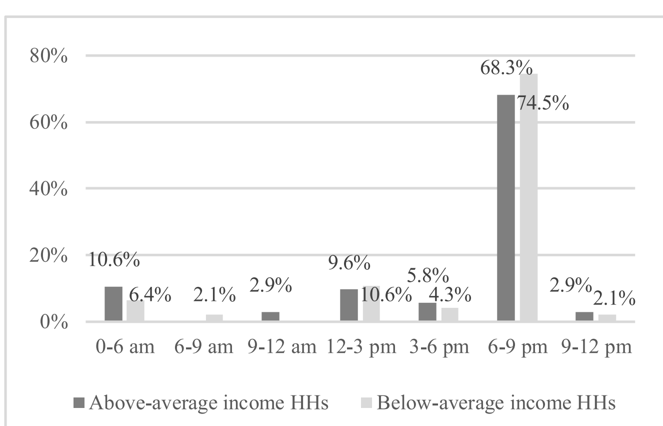

Fig. 9. Most important need for electricity during the day.

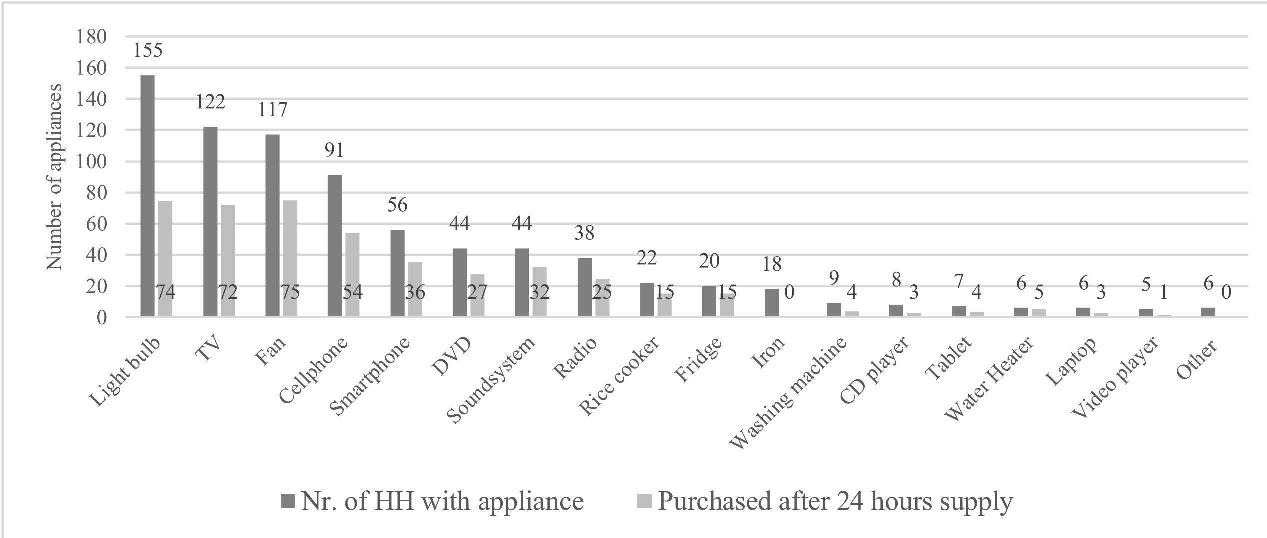

Fig. 10. Electric appliance inventory and purchases.

power supply, we asked for the respondents perceived changes after the hybrid energy system intervention for the six key target fields of safety situation, education, information, communication, income and health services. Respondents were asked to state to agree or disagree to the statements, using a 5-point likert scale (strongly disagree (1), disagree (2), neither disagree nor agree (3), agree (4), strongly agree (5)). Table 6 provides an overview about the perceived changes. The objective is to identify whether any significant differences in the perception of the aforementioned topic areas exist between below-average and above-average income groups.

The majority of HH respondents agrees or strongly agrees that the safety situation (>74%), access to education (>73%), information (>82%), communication (>89%) and health services (68%) has improved or increased. For the income situation, we find a less clear picture with 41% disagreement and 39% agreement. When taking into account the income groups we find only few noteworthy differences: A higher share of below-average income HHs (+15%) perceives the safety situation as improved and an additional 13% of below-average HHs perceives the education situation as improved compared to above-average income HHs. However, the responses of income groups towards the perception of the income situation differs distinctively: More below-average income households (+19%) overall disagree (sum of strongly disagree & disagree) that the HHs income increased after the intervention whereas more above-average income HH (+18%) overall agree (sum of strongly agree & agree) that the HHs income has increased. We applied further tests to explore if the differences between income groups are statistically significant. Since the considered six dependent variables are ordinal scaled and not normally distributed, the Mann-Whitney U test is applied. The only significant difference was detected for statement (5) regarding income generation: Below-average income households ($m = 3$) perceive significant less improved or increased income opportunities compared to above-average income groups ($m = 4$), with $z = 2.39$, $p = 0.017$, and medium effect size $r = 0.169$.

5. Discussion

Our findings indicate that upgrading the former diesel-based energy system to a hybrid energy system using solar power and battery storage clearly improved the livelihood and wellbeing of the local community. This was achieved by improving sustainability (increased RE share), reliability (establishing 24 hours supply) and affordability (tariff reduction). However, our findings reveal that HHs do not equally profit from the intervention. In the following we are highlighting the implications for energy access planning, implications for addressing further SDGs, implications for addressing poverty and inequalities and contextualize the findings of our case study.

5.1. *Implications for energy access planning and SDG#7*

The installed hybrid system successfully addresses SDG#7.

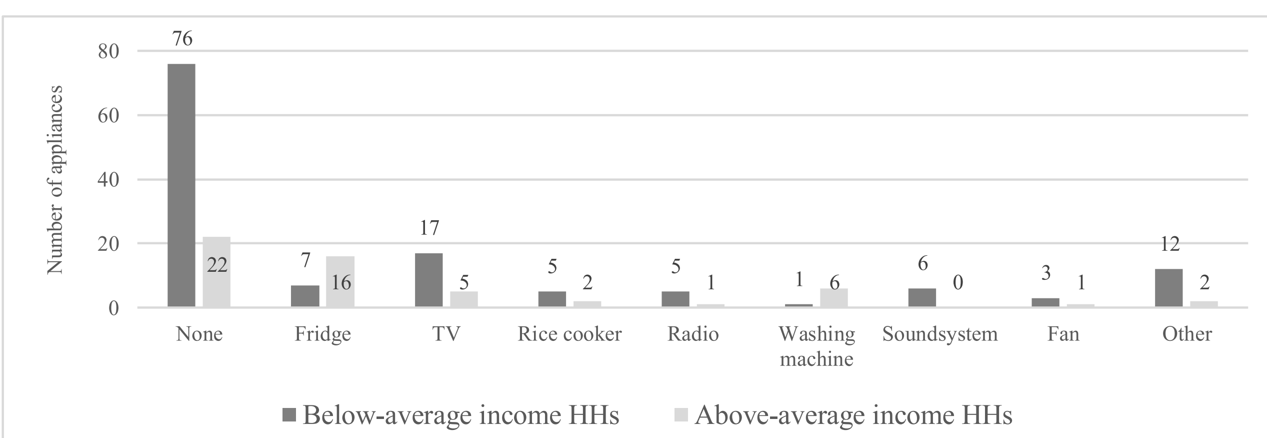

Fig. 11. Planned purchases in the next two years for HHs of both income groups.

Table 6
Subjective perception of changes after 24 hours electricity supply.

Statement	Income group	Strongly disagree (%)	Disagree (%)	Neither/Nor (%)	Agree (%)	Strongly agree (%)	N
(1) The safety situation has improved.	Below-average	1.8%	11.9%	7.3%	61.5%	17.4%	109
	Above-average	2.0%	18.0%	16.0%	46.0%	18.0%	50
	Total	1.9%	13.8%	10.1%	56.6%	17.6%	159
(2) Access to education and quality of education has improved.	Below-average	0%	4.7%	17.6%	58.8%	18.8%	85
	Above-average	0%	11.6%	23.3%	37.2%	27.9%	43
	Total	0%	7.0%	19.5%	51.6%	21.9%	128
(3) Access to critical information has improved.	Below-average	1.8%	9.1%	6.4%	54.8%	27.3%	110
	Above-average	0.0%	14.0%	4.0%	46.0%	36.0%	50
	Total	1.3%	10.6%	5.6%	52.5%	30.0%	160
(4) Access to communication means has improved.	Below-average	1.8%	5.5%	2.7%	58.2%	31.8%	110
	Above-average	0.0%	8.0%	6.0%	50.0%	36.0%	50
	Total	1.3%	6.3%	3.8%	55.6%	33.1%	160
(5) The income situation has improved and/or increased.	Below-average	10.9%	36.4%	19.1%	25.5%	8.2%	110
	Above-average	4.0%	24.0%	20.0%	42.0%	10.0%	50
	Total	8.8%	32.5%	19.4%	30.6%	8.8%	160
(6) Access to health services and quality of health service has improved.	Below-average	0.9%	19.3%	11.9%	53.2%	14.7%	109
	Above-average	2.0%	22.0%	8.0%	56.0%	12.0%	50
	Total	1.3%	20.1%	10.7%	54.1%	13.8%	159

However, we find that a large number of HHs use small amounts of electricity compared to few HHs with a larger consumption. This becomes obvious when comparing the identified consumption levels with the MTF (Bhatia and Angelou, 2015). The majority of HHs do not exceed tier 2 or 3 of the MTF characterized by a monthly consumption of <6 kWh and <30 kWh respectively (compare section 4.2). One could criticize the MTF for its inability to accurately access the demand for vital services required for HHs' wellbeing (Groh et al., 2016) and given its global scope it is inaccurate to national conditions (Pelz et al., 2018), but due to our locally collected data it can be a good guidance for energy access planning in the Philippines. The most common appliances (light bulb, fan, television, phone) owned by HHs of this case study reflect the typical appliance inventory for tier 2 HHs (compare section 4.3). It shows that an oversizing of supply systems would take place when assuming a Tier 5 level for all HHs. SHS are an appropriate technology to deliver electricity access at least for tier 1 and 2 (Narayan et al., 2019). Whereas tier 3 can be addressed with SHS as well, tier 4 and 5 are currently out of reach of SHS products. Thus, depending on the local situation, it could be reasonable to supply remote and low consumption HHs initially with SHS. However, electrification with SHS is less capable of powering productive loads (Bhattacharyya and Palit, 2014). A more accurate assessment of electricity demands and planning of the energy system can avoid oversizing and suitable approaches have been presented in the scientific literature (Riva et al., 2019). For future energy access planning for similar islands, it is necessary to decide if all HHs shall be connected to the hybrid system based on detailed electricity demand assessment. Deploying SHS to far away and scattered HHs with low present and low projected electricity demands can lower the overall costs while addressing the surveyed electricity demands. HHs could be connected to the hybrid energy system in a later step when an increased demand economically justifies a connection. Above all, it is important to consider whether two different electrification schemes would lead to increased energy injustice as demonstrated for other case studies (Monyei et al., 2018).

5.2. Implications for addressing further sustainable development goals

HHs use electricity mainly for leisure and entertainment (TV, cell phone, sound system) and well-being (light bulb, fan) as indicated through the analysis of the HHs' appliance inventory (see Fig. 10) which is in accordance with other findings for the Philippines (Hong and Abe, 2012). The majority of HHs is satisfied with the electricity service/costs (compare Fig. 6) and consider supply safety and reliability as most important, similar findings have been found for case studies in South Asia (Sharma and Chan, 2016). Further SDGs have been addressed through implementing SDG#7: As an example SDG#3 "Good health and well-being" by realizing more reliable electricity supply in the health station, SDG#4 "Quality education" by using appliances such as computers and fans in the school and by using electric lighting for studying at home, and SDG#6 "Clean water and sanitation" by powering devices for sterilizing water. We focus with this case study on electricity supply but recommend that future studies and interventions targeting SDG#7 have to address energy demand for cooking. For the case study, observations reveal that cooking is largely based on fuelwood and in few cases HHs use LPG stoves. Thereby the potential of clean energy supply for addressing SDG#3 "Good health and well-being", SDG#5 "Gender equality" and SDG#15 "Life on land" is not fully exploited as cooking based on fuelwood negatively affect these three SDGs (Das et al., 2017). Recent studies have revealed that innovative electric cooking technologies can be beneficially incorporated in hybrid energy systems (Lombardi et al., 2019). Our findings additionally indicate that HHs of different income groups are not equally capable to profit from the realization of SDG#7, therefore the leverage effects on SDG#1 "No poverty" and SDG#10 "Reduced inequalities" are not fully harnessed.

5.3. Implications for addressing poverty and inequality

Our results show that the HHs perceive an overall positive impact on their livelihoods. However, the perceived impact on income generation is divided among the income groups. Here, we identify that the majority of above-average income HHs perceive a positive impact on income generation whereas a high share of below-average HHs perceives no impact on income generation (compare section 4.4). It can be concluded that there is so far no significant increase in income generating activities through electricity on Cobrador Island. Other case studies have found similar results for India (Khandker et al., 2012), Brazil (Obermaier et al., 2012) and Rwanda (Lenz et al., 2017). There are however significant differences between above-average and below-average income HHs in terms of electricity usage. The results show that above-average HHs use electricity more frequently for income generating activities and own more appliances with which income can be generated. We propose that projects addressing SDG#7 must incorporate specific poverty reducing measures coupled with the implementation of more reliable, affordable and sustainable electricity. Such measures could include to offer micro-finance products (MFP) for appliance purchases, to implement a cross-subsidy scheme within the community or initiating cooperative-based companies. MFP could enable below-average income households to profit from the improved electricity supply through small loans for purchasing important appliances, such as refrigerators or appliances allowing for productive use (Gutiérrez-Nieto and Serrano-Cinca, 2019). However, an analysis of potential markets for the producible products needs to be conducted first to ensure that products find sufficient demand (Lenz et al., 2017). A cross-subsidy scheme within the community could enable a higher usage of electricity for below-average income HHs subsidized by above-average income HHs. Most probably the social acceptability of such an approach would be a challenge. Nevertheless, for hybridization projects on other islands the communities could be consulted if they would agree to implement a cross-subsidy scheme if this would increase the likelihood of project realization. Finally, strengthening cooperative based business models could contribute to poverty alleviation and could even contribute to balance power demands in the system. As an example, a cooperative owned cold storage could be implemented through selling out cooperative shares. Ice for cooling fish catches and food is an important product. If that could be offered in an affordable manner to cooperative shareholders it would reduce HHs expenditures, reduce the demand for individual refrigerators and could even serve for balancing the power grid (through dumb charge). Future research should focus on incorporating one of the aforementioned measure into the planning of rural electrification and SDG#7 interventions.

5.4. Contextualization of findings

Case study research as applied here allows for an in-depth examination of a particular subject (e.g. the impact of RE and addressing the SDGs on local communities) but lacks breadth and external validity (Sovacool et al., 2018). Nevertheless, contextualization provides some crucial findings for further energy access planning in insular framework conditions. With a population of approx. 1,000, fishing as main source of income, an accessibility of 45 -60 minutes by boat and a formerly unreliable power supply our case study is representative for a large number of similar islands in the Philippines (Bertheau and Blechinger, 2018). The specific number is difficult to access, however a recent geospatial analysis estimated a number of 2,200 islands with a population of 1.49 million without any known electricity supply for the Philippines (Bokharee et al., 2018). Fishing as main source of income was identified for other cases studies in the Philippines (Hong and Abe, 2012) and islands with a population of up to 1,000 have been found as the largest group among surveyed not electrified Philippine islands (Meschede, 2018). The mean income (8 thousand PHP) and mean expenditure (6 thousand PHP) are lower than the national monthly mean HH income of 22 thousand PHP and mean expenditure of 18 thousand PHP (PSA, 2017). Reflecting that the case study island represents typical islands deprived of development and growth. With 32% the share of HHs living below the poverty line is higher than the national average of 21.6% (PSA, 2017). Hence our findings can be extrapolated for other similar islands and serve for deriving policy recommendations. Furthermore, a large number of small islands with characteristics similar to our case study can be found in the region but outside the Philippines, in particular in Indonesia, Malaysia and Pacific small island states (Blechinger et al., 2016).

6. Conclusion and recommendations

A household questionnaire survey was conducted for the case study of Cobrador to assess the impact of providing continuous renewable based power supply on local development and on the SDGs. The implemented hybrid RE system was found as an appropriate solution to address SDG#7 as affordability, reliability and sustainability of power supply were improved. Based on the data collected, we can address the three research questions as outlined in the introduction section. First, we find that daily consumption and peak demands increased most rapidly in the first year of operation. Electricity is mostly used for entertaining purposes as television and sound systems belong to the most frequently owned electric appliances besides light bulbs, fans and cell phones. However, most HHs consume only small amounts of electricity and would be best described by tier 2 or tier 3 of the MTF. Second, we find a positive impact on SDG#3, SDG#4 and SDG#6, as all households, regardless of their income profit from improved access to education and health services. Third, we find mainly the above-average income households using electricity for income generation purposes. We conclude that SDG#1 and SDG#10 are insufficiently addressed in the implementation scheme and recognize a threat of further increasing inequalities in communities provided with access to electricity through SDG#7 interventions. We consider this as an important finding and starting point for future social science based energy research.

The implications of our findings are that future technology policies supporting the SDG#7 need to address the following issues: Appropriate energy access planning and supporting measures for addressing poverty and inequality. More appropriate and evidence based energy access planning has to be enhanced for all involved stakeholders. Future planning should discuss if low consumption HHs should be initially supplied with SHS and if then a stepwise connection of HH based on the projected electricity demand could increase the feasibility and replicability of hybrid RE systems. Supplementary measures are necessary to prevent that SDG#7 interventions lead to increased inequalities in terms of income and opportunities in small island communities. Stimulating productive use could be an appropriate measure but has to be carefully designed according to local conditions and accessible markets. Supporting cooperative ownership and business models (e.g. for cold storages) could enhance communities and even serve for balancing small power grids. Leverage effects of SDG#7 on other SDGs should be more effectively harnessed with supporting measures especially with regard to clean cooking. As an example the promotion of electricity use in schools, health stations and barangay halls increases the impacts on SDG#3 and SDG#4. Incentivizing the purchase of clean cooking, water sanitation and food preservation products can address further SDGs.

Furthermore, this case study finds important aspects for future interdisciplinary research focusing both on technical and socio-economic aspects. Energy and economic related research should focus on tools for the cost-effective design of hybrid energy systems incorporating the socio-economic framework conditions. Social science based energy research should focus on the potential integration of community cross subsidy schemes, cooperative anchor clients and productive use in SDG#7 interventions for delivering added value to beneficiaries.

Acknowledgements

The author thank the Reiner Lemoine-Foundation for co-financing this research work. This work is part of the Research Project entitled, "Ener PHIL – Research Cooperation supporting the Energiewende on the Philippine Islands" that was funded by the German Federal Ministry of Education and Research (O1DP17041). The author also thank the University of the Philippines - Diliman for supporting this research and especially Joseph Yap IV, Eugene Esparcia, Imee Saladaga, Clarisse Aquino, Billy Esquivel and Prof. Josephine Dioniso for their support during the fieldwork for this research. The author also thanks Clara Jütte and Philipp Blechinger for methodological support and proof-reading.

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6. Challenges for implementing renewable energy in a cooperative-driven off-grid system in the Philippines

Environmental Innovation and Societal Transitions 35 (2020) 333–345

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

Original Research Paper

Challenges for implementing renewable energy in a cooperative-driven off-grid system in the Philippines

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ARTICLE INFO

Keywords:
Philippines
Cooperative
Community energy
Energy access
Decentral energy
Risks

ABSTRACT

Implementing renewable energy on Philippine islands is essential for sustainable development. Electric cooperatives play a key role to provide renewable energy to marginalized and remote communities not profiting from private sector interest. However, a low-carbon transformation of energy systems implies political, economic, technical, and societal risks and uncertainties. Here, we investigate those faced by the Romblon Electric Cooperative (ROMELCO) in installing one of the Philippines' first off-grid, hybrid energy system in the small and remote island of Cobrador. We apply a transdisciplinary mixed methods approach including expert interviews, surveys, and focus group discussions. We identify the most serious implementation risk faced by ROMELCO as the discontinuity between the policy pronouncement and implementation practice. We contribute with an analysis of ROMELCO's actions to address the complex bundle of implementation policies and programs for a wider replication and scaling up of cooperative based power supply.

1. Introduction

Pursuing a low-carbon energy transition pathway is essential for the Philippines since the country is one of the most vulnerable to climate change (Viña et al., 2018). Disasters like the Super Typhoon Haiyan (2013) underlined the threat of extreme weather events on the country's infrastructure and are projected to occur more frequently with increasing temperatures (Holden and Marshall, 2018). Additionally recent research highlighted that effects of climate change threaten societal peace and may increase the intensity of conflicts in the country (Crost et al., 2018). The Philippine government finally ratified the Paris agreement in 2017 and committed itself to cut emission by 70% compared to the business-as-usual (BAU) scenario (Crost et al., 2018). But as one of the fastest evolving countries in Southeast Asia (Mondal et al., 2018; Viña et al., 2018), the Philippines is also compelled to meet an increasing energy demand for economic development. As it is, more than 11% of the population have no access to electricity and a much higher share of the population suffers from unreliable power supply (IRENA, 2017). Given these conditions, it becomes evident that it is in the country's inherent interest to increase power generation capacities in an environmentally sustainable manner.

As early as 2008, the Philippines implemented one of the most ambitious renewable energy (RE) acts of the region, which includes several mechanisms and schemes to support private sector initiated RE deployment (Mouton, 2015). The intention was to encourage private sector investment in RE deployment in the country's remote islands and thus contribute to improving energy security and energy access in those remote islands. However, 10 years after the implementation of the RE act, private sector involvement in

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https://doi.org/10.1016/j.eist.2019.03.002
Received 13 September 2018; Received in revised form 19 December 2018; Accepted 12 March 2019
Available online 18 March 2019
2210-4224/

providing electricity access through RE is still low (DoE, 2016a). Therefore, alternative institutions are considered to advance energy access and RE deployment. Rural electric cooperatives (EC) were encouraged to fill in the gap in energy generation. EC are customer owned corporations whose original mandate initially focused on power distribution in its service areas.

Yadoo and Cruickshank (2010) highlighted that EC can advance rural electrification when private sector involvement fails. Advantages are lower revenue expectations and higher interest in local development (Yadoo and Cruickshank, 2010). Additionally, experiences from community owned and locally initiated low-carbon energy supply projects highlighted societal, economic and environmental benefits (Brummer, 2018). With growing societal interest in clean energy supply in the Philippines, EC could enable integrating local initiatives and interests leading to RE development. However, EC face risks and uncertainties when stepping into RE development and expanding their services to not electrified islands.

This study looks into the risks and uncertainties confronted by one exemplary electric cooperative in the Philippines as they clear a pathway towards low-carbon transition in their franchise area. Uncertainty is conceptualized as a state of perception, which may be lacking, incomplete, or contested due to variability or lack of knowledge (Asselt, 2013). We further distinguish uncertainty as epistemic uncertainty (lack of knowledge), paradigmatic uncertainty (what is known), or translational uncertainty (disagreements on what is known). Risk is defined as the probability of loss, failure, or negative outcome on different dimensions (Haimes, 2009). Risks can be classified as implementation risk (barrier) or as consequential risk (outcome). In this study, we identify risks and uncertainties through a mixed methods approach that combines quantitative and qualitative research, the nature of the uncertainties faced by the Romblon Electric Cooperative (ROMELCO) and the types of risks they encounter as a consequence of installing one of the Philippines' first off-grid, hybrid energy system in the small and remote island of Cobrador. The perspectives of different stakeholders are taken into account: Through a household survey, expert interviews, and focus group discussions, the diverse vantage points of energy sector experts, EC officers and members, island community leaders, and household heads and members were gathered to gain a holistic assessment of risks and uncertainties. The result is the transdisciplinary understanding of a specific pathway to a low-carbon energy system.

2. Background: low carbon energy development in the Philippines

This chapter serves for the contextualisation of the presented case study on challenges for cooperative-driven off-grid system in the Philippines. Therefore, we present relevant findings from academic literature (2.1), provide an overview about the remote island landscape of the Philippines (2.2), outline the policy framework for low carbon development (2.3) and introduce the specific case study (2.4).

2.1. Renewable energy and island electrification

This case study of a cooperative-driven RE off-grid system in the Philippines builds upon previous findings on RE-based island and off-grid electrification, which find that RE is a suitable technology for powering islands due to their isolation, remoteness, and lack of conventional energy sources (IRENA, 2014; Kuang et al., 2016). Given the prohibitive costs for submarine power cable interconnection (Kuang et al., 2016; Schell et al., 2017), island energy systems are most commonly isolated systems, also referred to as off-grid or decentralized energy systems. Such energy systems are considered hybrid, if more than one power generation technology is applied (e.g. solar-battery-diesel hybrid system); an overview on hybrid system configurations is provided by (Bajpai and Dash, 2012). Specific characteristics of insular energy systems and challenges for RE integration are described by (Erdinc et al., 2015). Neves et al. (2014) analyse 28 hybrid energy systems on islands: The majority is located in Europe and serves a small population (< 10,000), mainly with a mix of wind power and diesel generators.

Studies that quantify the market potential for RE hybrid systems based on case studies (Gioutsos et al., 2018) or based on global scale analysis (Blechinger et al., 2016; Meschede et al., 2016) find a significant market potential for RE in the Asia-Pacific region. Weir (2018) underlines the relevance of RE deployment for the pacific island states (PIS), with regard to vulnerability to climate change, dispersed geographies and dependence on fossil fuels. The same motivation holds true for the Philippines with very similar natural conditions (Brahim, 2014). Nevertheless, main barriers for wider deployment are the complexity and maintenance efforts of hybrid energy systems, combined with financial and institutional shortcomings in PIS (Weir, 2018). Hazelton et al. (2014) reviewed experiences with PV-hybrid energy systems and found that energy demand uncertainty and inappropriate business models are the most decisive barriers to wider deployment. Yaqoot et al. (2016) summarized technical, economic, institutional, socio-cultural and environmental barriers to the dissemination of decentralized RE systems described in the academic literature. They found that for RE mini-grids, technological appropriateness and skill requirement (technical), high cost and lack of access to credit (economic), and an inappropriate regulatory framework (institutional) are the most decisive barriers. Other case studies highlight challenges for the wider deployment of off-grid technologies in remote regions and for island electrification, such as customer reliability and low project profitability (Lahimer et al., 2013), remoteness and low population densities (Mandelli et al., 2016) and unpredictable energy demands (Boait et al., 2015; Riva et al., 2019). Moreover, rural communities are inadequately integrated prior to project implementation which leads to a lack of social acceptance and inappropriateness of services (Sovacool, 2012; Hirmer and Cruickshank, 2014). Lack of education, proper technical training and awareness, which often leads to failure in proper installation, operation and maintenance of RE systems are also significant barriers to wider deployment in developing countries (Yadoo and Cruickshank, 2012).

For the Philippines the deployment of RE for remote area electrification is promoted since the early 90 s (Heruela, 1992). A significant potential for RE on remote islands specifically for the Philippines has been identified by (Barley et al., 1999) and more recently by (Bertheau and Blechinger, 2018). Foley and Logarta (2007) identify that widely scattered islands, poorly developed infrastructure and communication systems hinder universal electrification. Additionally, they find that insufficient institutional capacities decelerate remote island electrification. Marquardt (2017) comes to a similar conclusion by identifying unclear political responsibilities, conflicting regulations and weak local capacity as major obstacles for the electrification of remote islands through RE in the Philippines. Rationalization of planning and implementation procedures for RE projects is needed to take into account the specific characteristics of small-scale RE projects for smaller islands (Roxas and Santiago, 2016). A sustainability assessment of a RE-based hybrid energy system for the case study of Pangan-an island found that the eventual failure of the project and deterioration of the energy systems was a result of non-affordable electricity rates and the low quality of the applied technology (Hong and Abe, 2012). Weak managerial capacity and insufficient maintenance then led to the ultimate malfunction of the energy system (Hong and Abe, 2012; Hong et al., 2015).

2.2. Remote island landscape & energy access in the Philippines

In terms of power supply, the Philippines distinguish between “on-grid” and “off-grid” areas. The main islands in Luzon, Visayas and Mindanao are considered as “on grid” areas whereas the remaining islands are “off-grid” areas (Boquet, 2017). The on-grid areas profit from relatively stable power supply provided through two main electric grids (IRENA, 2017). RE generation make up a share of 25% (mainly geothermal and hydropower) in the on-grid areas, however, in order to cover the increasing demand, a massive expansion of coal-fired power generation is projected. The electricity costs are among the highest in entire Southeast Asia, and almost as expensive as Singapore’s (DoE, 2016b).

Most of the off-grid areas suffer from insufficient or even no power supply at all. More than 280 small island grids are operated (DoE, 2016a), mainly applying diesel generators for power supply (Roxas and Santiago, 2016). This does not meet the economic and environmental targets of the country for several reasons: (1) The lack of substantial domestic oil sources lead to a dependency on global oil markets (Roxas and Santiago, 2016). (2) High generation costs make the subsidization through the universal charge for missionary electrification (UCME) scheme necessary. (3) Combusting diesel fuel comes with emissions and the risk of oil spills (Viña et al., 2018). (4) Only in 36% of the small islands, is electricity available for 24 h (DoE, 2016a). However, for these islands, a high potential for RE was identified (Bertheau and Blechinger, 2018). Pursuing a low-carbon development in “off-grid” areas is important. Low-carbon energy systems can increase energy access (Surroop et al., 2018) and energy security (Wolf et al., 2016). Additionally, successful low-carbon energy projects can serve as a blueprint for further RE deployment.

The government of the Philippines (GoP) acknowledges the importance of developing clean energy technologies in smaller grids not only for the reduction of emission but also for the improvement of living conditions as stated in the definition of Sustainable Development Goal (SDG) #7 (Gupta and Vegelin, 2016). 100% electrification of all households by 2022 was set as target within the Philippine Energy Plan (PEP) (DoE, 2016c). Despite many ongoing projects and initiatives to improve electricity access, the share of electrified households was only at 89.6% in 2016, reflecting 2.36 million households without electricity supply (IRENA, 2017).

2.3. Policy framework for low carbon energy development in the Philippines

After the experience of a nationwide shortage of electricity supply lasting for an entire decade (1990s) the restructuring of the power sector was initiated (Mouton, 2015). The once entirely state-owned electricity sector was reformed and largely privatized in 2001 with the enactment of the Electric Power Industry Reform Act (EPIRA) (RA9136, 2001). The adoption of the Renewable Energy Act (RE Act) in 2008 (RA9513, 2008), was intended to accelerate the deployment of RE technologies in the country (Roxas and Santiago, 2016). High expectations were put on the RE Act given the number of fiscal and non-fiscal incentives to be implemented under it (Rosellon, 2017). Both the EPIRA and RE act are policies aiming at stimulating private sector involvement in supplying the off-grid areas besides the “on-grid” sector. Therefore, two basic schemes for private sector investment were designed: The qualified third party (QTP) scheme and the new power producer (NPP) scheme. The QTP scheme allows for power generation and distribution in an “off-grid” area, whereas the NPP scheme enables the private sector to take over power generation from NPC-SPUG (National Power Corporation – Small Power Utilities Group), the residual unit of the former state-owned monopolist. Fig. 1 visualizes all options for supplying off-grid areas and the entities involved. The remaining not yet privatized public power generation and private power generation (NPP & QTP) is regulated and supervised by the Department of Energy (DoE), the Energy Regulatory Commission (ERC) and the National Electrification Administration (NEA). Power distribution is handled by the EC or QTP, purchasing power from one of the before introduced entities. Recently, the EC have been encouraged to expand their activities into power generation by Rep. Act. No 10531 (RA10531, 2012). For a large but not quantifiable number of very small islands power supply is informally organized.

The QTP and NPP scheme should facilitate rural electrification through private sector participation. However, the impact is disappointing. As of now, two QTP projects were realized (DoE, 2016a) and NPP investment focuses on few economically attractive areas. Main reasons are the very complex application procedure, which imply high risks and uncertainties for project developers. Additionally, the remote areas do not pose a very attractive market for private sector investment, calling for another type of institution to step in. Given the lack of interest of the private sector and the incapability of the public sector in implementing low-carbon energy systems in remote islands of the Philippines, the question arises which other institution could take over this task. With this study, we consider the EC as eligible for fulfilling the role of advancing energy access and at the same time deploying low-carbon energy systems in the country. Nevertheless, if EC can fulfil this role is diversely discussed: EC are accused of underperformance and considered as blocking universal electrification (Lectura, 2018a). In fact, the management of some EC is subject to corruption, local political influence, and non-performance. However, such an accusation cannot be generalized to all EC, since the majority of EC received positive ratings by NEA, which oversees the EC (Lectura, 2018b). High potential arises from the EC lower profit interests,

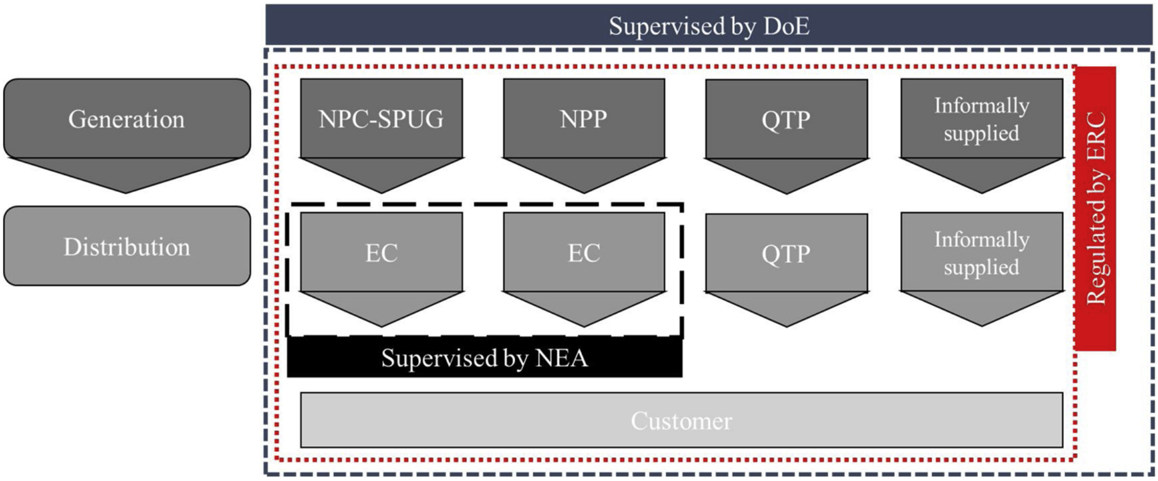

Fig. 1. Draft visualizing the options for supplying off-grid areas highlighting entities in generation, distribution and regulation (own visualization).

higher interest in local development, more detailed understanding of community's needs, and ownership structure.

2.4. Case study: Electric cooperatives as driver for low carbon energy development

This study focuses on the Romblon Electric cooperative, one of the most active EC in deploying RE in the Philippines. ROMELCO is situated in Romblon island and supplies a population of more than 23,000. The case study is focused on ROMELCO's latest low-carbon energy development project on Cobrador island. It has a total land area of 2.6 km^2 and a population of around 1000 people or 239 households. Before 2016, electricity was provided to the community by a diesel generator (15 kW peak capacity) for a total of eight hours per day. In 2016, ROMELCO together with the Asian Development Bank (ADB), the Korea Energy Agency (KEA) and NEA has implemented a joint project on Cobrador Island, leading to the installation of a solar-battery-diesel hybrid system in August of the same year. The hybrid system consists of a solar capacity of 30 kW, battery (lithium-ion) capacity of 200 kW h and a diesel back-up generator of 15 kW. The hybridization improved the reliability of supply (24 h), affordability (50% tariff reduction) and environmental soundness (RE share up to 90% per day).

3. Material and methods

A mixed-methods approach that combined focus group discussions, expert interviews, and a household survey was used to analyze the uncertainties and risks as defined by (Asselt, 2013), faced by EC when pursuing low-carbon energy development in the Philippines. The results of the expert interviews that serve for a macro-level analysis, of the focus group discussions (FGD) with local leaders that provide micro-level perspectives, and of the survey that give empirical evidence on the household-level were triangulated to get a richer account of the uncertainties and risks of low-energy transition in remote islands in the Philippines. The different activities of our approach were conducted in February and March 2018, starting with expert interviews in Manila. During the subsequent field stay, the FGD were held first as they also served for informing the local government unit about the overall goal of the study. The household survey was then conducted within three weeks in late February/early March.

3.1. Expert interviews

Expert interviews were conducted to map out the institutions and actors involved in low-carbon energy development and to identify risks and uncertainties for such development. A total of ten semi-structured interviews were conducted over a three-week period in February 2018. Key criteria for the selection of experts was to represent stakeholders from the government sector, business sector, civil society, development cooperation, and academia. The individual experts were approached based on the extent of their

Table 1
Overview on experts considered for interviews.

Expert background	Description	Number (10)
Government institution (GI)	Senior staff of Department of Energy & National Electrification Administration	3
Electric cooperative (EC)	Senior management staff	1
Civil society (CS)	Senior staff of NGO	1
Development cooperation (DC)	Senior staff of foreign development agency	2
Academia (AA)	Research staff involved in technology, policy and economic research	3

Table 2
Guiding interview questions.

No.	Question
1	What is your current position and how are you involved in electrification through RE in the Philippines?
2	What are key driving forces of electrification in rural areas in the Philippines?
3	What are major risks and uncertainties for electrification planning in rural areas?
4	What do you consider as possible solutions and strategies to mitigate the uncertainties and risks?

involvement in off-grid electrification through EC in the Philippines. Each of the experts hold positions related to clean energy development partly with special focus on the off-grid sector in the Philippines. An overview on involved experts is provided with Table 1. They are also involved in policy development/analysis, RE research and RE implementation. Additionally, the selected experts have been involved in the case study project directly through implementing the project (e.g. representatives of electric cooperative or government institutions) or indirectly through providing advice to involved stakeholders (e.g. academia). Therefore, extending the group of experts to a wider field was not considered in order to maintain a comparable level of expertise.

Most interviews were conducted face-to-face, only one interview was conducted via teleconference. The interviews were held in English and each interview lasted 30–60 min using open-ended questions. Respondents were guaranteed confidentiality and anonymity to encourage unbiased responses and respect institutional review board procedures concerning research on human subjects (Jong et al., 2016).

Table 2 provides an overview of the lead questions for the expert interviews, which were developed based on a review of related literature (Lamnek, 2010). The interviews were recorded and subsequently transcribed into a written summary, focusing on the essential contents for the research interest (Flick, 2007; Reuber et al., 2013). For the analysis, the interviews were thematically coded, following the stepwise approach of Flick (2007): First, specific statements directly related to the central questions are summarized. In a second step, categories according to the research questions are built for each interview, followed by thoroughly, comparing all different interviews using those categories and thereby identifying overlaps and differences.

3.2. Focus group discussion

FGD were conducted to examine the narratives of shared experiences of those directly involved in the implementation of the island energy project at the ground level. The FGDs were an exploration into the ‘lived experience’ of people on the ground, who are blazing a pathway to a low-carbon energy system (Creswell and Clark, 2010). The FGDs provide the specific examples based on actual experiences that elaborate on the themes that were eventually, generated from the expert interviews and help explain some of the results of the household survey. They probed beyond the macro-structural level of analysis (i.e. market-oriented, technology-driven, or policy environment assessment of risks and uncertainties) that pervades most energy studies, to render more audible the voices of people on the ground who confront these risks and uncertainties in daily life, and to render more visible the emotional labor that energy projects require. These FGDs are therefore a useful complement to the other methods used in this study.

Participants were considered for the FGD based on their shared experience of the process of implementing a low-carbon energy system in Cobrador Island. For this study, the identified focus groups were the group of ROMELCO officers and the group of local leaders in the island of Cobrador. Two (2) separate FGDs were conducted, with each FGD lasting for approximately an hour. Five (5) officers and members, including the General Manager, attended the FGD with ROMELCO. The FGD in Cobrador island involved ten (10) island residents and representatives of sectoral organizations in the island. The discussions were mainly about their recall of the most important factors, which made possible the low-carbon energy system’s emergence, the problems and difficulties that they encountered and how they transcended these, their assessment of the key outcomes of the project in various areas of life in their communities, and their main motivation in maintaining the system. The discussions were audio recorded with permission from the participants and researchers noted down process observations. These recordings and the researchers’ observation notes were then transcribed to enable the generation of themes (Stewart et al., 2006).

3.3. Household survey questionnaire

The survey questionnaire consists of 58 main questions, with additional follow-up and sub-questions. The questionnaire is comprised mainly by closed-ended questions but includes some open-ended questions (Sullivan and Barnes, 2006). The focus of the survey was to investigate on the socio-economic impact of low-carbon energy development projects on local beneficiaries, thereby indirectly anticipating risks and uncertainties for EC driven low-carbon energy development. Sections and descriptions on the questions are provided in Table 3.

Students from the University of the Philippines Diliman who served as enumerators implemented the survey. The questionnaires were in Filipino (Tagalog) and the assisted completion of each using a tablet lasted for approximately 60 min. In order to meet the ethical standards of cross-cultural studies, appropriate local government units, local leaders, and interested inhabitants of the island along with the interviewed households were provided with comprehensive information on the study’s content, purpose, and safeguards on keeping the confidentiality of data.

Based on UN recommendations for designing household surveys in developing and transitioning countries (UN-DESA, 2005), the

Table 3
Questionnaire structure.

Section	Description of questions	Rationale
General socio-economic information of the households	Household size, adults/children, age, education status, main income sources and expenditures	Setting basic socio-demographic context and providing key information for interpreting the survey results
Electricity demand and usage	Electricity bill, willingness to pay, appliances (what, how many, since when, how often used), activities with electricity	Enables a detailed understanding of the usage of electricity
Subjective perceptions of changes	Impact of electricity access on health, security, education, safety and income	This data allows for an understanding whether residents perceive an impact of electricity on their daily life
Energy sources	Rating of different energy sources in terms of environmental friendliness, costs, appropriateness for island	This data enables an understanding if residents are aware of different energy sources and if RE play a role in their choice of electricity source
Challenges	State major challenges for the household and the island within the next two years	Enables an understanding of the major concerns of the residents and if they are related to electricity access.

following steps were done as part of a stratified random sampling technique: Data on monthly electricity consumption of all 239 households of the case study island obtained from the responsible electric cooperative ROMELCO, served as stratification variable. At first, natural breaks were used to categorize the entire sample size of households according to the electricity consumption by means of the Jenks natural break method (Jenks, 1967), thereby minimizing the average electricity consumption deviation within each household class and maximizing the deviation of each household class from the electricity consumption average of other classes. In doing so, four different classes were derived of which each should be proportionally represented in the final data sample. The next step was to determine a representative sample size. Taking into account different parameters such as a 95% confidence interval, 5% margin of error and non-response factor (UN-DESA, 2005), a statistically viable sample of 171 out of 239 households was identified. These 171 households were then, randomly selected from all households and the predefined consumption classes by applying a programming code ensuring that each class is proportionally represented. On site, the enumerators identified the randomly sampled households by the help of local government staff or the villagers. For anonymization reasons, households were given codes that were used in the questionnaires.

4. Results and discussion

The presentation of the results of this study is based on van Asselt's definition of uncertainty and risk (Asselt, 2013). As briefly outlined in the introduction section uncertainty is conceptualized as a state of perception, which may be lacking, incomplete, or contested due to variability or lack of knowledge (Asselt, 2013). Based on Asselt's aggregation of causes of uncertainty we further distinguish uncertainty as epistemic uncertainty (lack of knowledge), paradigmatic uncertainty (what is known), or translational uncertainty (disagreements on what is known) (Asselt, 2013). Whereas risk is defined as the probability of loss, failure, or negative outcome on different dimensions (Haimes, 2009). People identify, give meaning or value, and measure risks from different social position and different periods in time. Risks are therefore context-specific, and can be classified as implementation risk (barrier) or as consequential risk (outcome). Risk and uncertainty are interlinked as risks are arising of the magnitude of uncertainty (Asselt, 2013). For our case study, we understand a "higher" risk with the likelihood of failure of the low-carbon energy system implementation. Uncertainties lead to such risks. Consequently, for each item identified with our mixed method approach we define the type of uncertainty as categorized above and define the resulting type of risk.

4.1. Findings from transdisciplinary research: Risks and uncertainties

Table 4 shows the identified uncertainties and risks from the expert interviews, FGD and household survey. For analyzing our findings, we apply an approach similar to Li and Pye (2018) categorizing the identified uncertainties and risks in the field of Politics (P), Economics (E), Society (S) and Technology (T). We add the category geography (G) and are not considering the category global dimension as it is not appropriate for our research focus (Li and Pye, 2018).

4.1.1. Political factors

The UCME subsidy scheme does not distinguish between carbon intensive and low-carbon technologies. Given that low-carbon energy technologies, such as solar PV, are not yet mainstreamed and still costly in the Philippines, using low-carbon technologies in missionary areas poses greater risks for EC. The shift is therefore not necessarily more attractive compared to pursuing the already established and well-known procedures related to the operation of diesel generators.

Fee requirements are the same regardless of the size of an energy supply project. A kW-sized plant has to meet the same bureaucratic and financial requirements as a MW-sized plant. Small and medium-sized enterprises and EC are in effect not encouraged to engage in small or medium-sized low carbon energy development projects, which are in fact the most suitable scale for small and remote islands in the Philippines.

Approval of the tariffs is a requirement for obtaining subsidies from the UCME scheme. In our case study of ROMELCO, tariffs have not been approved even after two years since they filed their application. As of now, the price the EC is charging its customers is

Table 4
Uncertainties and risks identified from transdisciplinary research.

Category	Uncertainty	Risk	Source
Politics (P)	Policy implementation: undifferentiated incentive scheme (epistemic uncertainty)	Implementation risk: failure of the UCME scheme to incentivize the shift to low-carbon energy technologies	Interview with experts FGD with cooperative officers and members
	Policy implementation: undifferentiated fee requirements (epistemic uncertainty)	Consequential risk: high upfront costs even for small and medium-sized cooperatives	Interview with experts FGD with cooperative officers and members
	Energy sector planning and coordination: lack of comprehensive plan and inadequate coordination (epistemic uncertainty)	Consequential risk: stranded assets of cooperatives	Interview with experts
	Bureaucratic procedures: delayed tariff approval and delayed access to subsidy (paradigmatic uncertainty)	Consequential risk: threatened fiscal position or viability of the cooperative	Interview with experts FGD with cooperative officers and members
	Bureaucratic procedures: complex, slow, and rigid (paradigmatic uncertainty)	Implementation risk: failure to attract private sector investment and delayed project implementation for cooperatives	Interview with experts
Economics (E)	Financing and Credit: EC are viewed as lacking in track record and creditworthiness (paradigmatic uncertainty)	Implementation risk: difficult access to finance by small and medium-scale EC, thus disincentivized to engage in RE development	FGD with cooperative officers and members
	Joint venture with private sector: EC are viewed as lacking in capabilities (paradigmatic uncertainty)	Implementation risk: joint venture with cooperatives in RE development remains unattractive for private sector investors	Interview with experts
	Private sector investment into RE: complicated bureaucratic procedures of government (paradigmatic uncertainty)	Implementation risk: investment into RE development remains unattractive for private sector investors	Interview with experts
	Private sector investment into RE in small and remote islands: lack of existing or potential revenue generating economic activities in small and remote islands (epistemic uncertainty)	Implementation risk: investment into RE development in small and remote islands remains unattractive for private sector investors	Interview with experts
	Customer consumption patterns: Inadequacy of energy supply system due to underestimation of increase in customer consumption (epistemic uncertainty)	Implementation risk: Economic viability and system reliability	Interview with experts Survey of household members in island
	Customer income patterns: Unstable and seasonal income of customers (epistemic uncertainty)	Implementation risk: lower revenue stream	Survey of household members in island
	Customer reliability: Lack of commitment and capability of low-income customers to pay electric bill on time (epistemic uncertainty)	Implementation risk: lower revenue stream	Interview with experts
Society (S)	Skilled technicians: lack of locally available technicians in remote islands (epistemic uncertainty)	Implementation risks: - higher cost of operations because of need to incentivize experts to serve in remote islands - delays in necessary repairs	Interview with experts FGD with cooperative officers and members FGD with local leaders in island
	Skilled laborers: lack of locally available workers in remote islands (epistemic uncertainty)	Implementation risk: delayed project implementation	Interview with experts FGD with cooperative officers and members & FGD with local leaders in island
	Resistance: Contending information of the community and the EC regarding the environmental soundness of proposed RE project (translational uncertainty)	Implementation risk: No/delayed project implementation	Interview with experts FGD with cooperative officers and members
	Acceptance of RE: lack of public acceptance of RE due to negative experiences in the past	Implementation risk: No/delayed project implementation	Interview with experts
Technology (T)	Awareness for RE: EC lack of knowledge about RE (epistemic uncertainty)	Implementation risk: Low-carbon energy solutions (off-grid, hybrid) are not explored by many rural EC and local manufacturers	Interview with experts FGD with cooperative officers and members
	Availability of RE technologies: lack of locally available RE technologies (epistemic uncertainty)	Implementation risk: high cost of RE development threaten viability of EC and delays in repair and maintenance	FGD with local leaders in island
	Disaster resilience of RE technologies: lack of RE technologies that are adapted to remote island conditions (epistemic uncertainty)	Implementation risk: low reliability of low carbon energy systems	FGD with local leaders in island
Geography (G)	Accessibility: inaccessibility of remote islands (paradigmatic uncertainty)	Implementation risk: No/delayed project implementation	Interview with experts
	Infrastructure: lack of necessary transportation infrastructure for small and remote islands (epistemic uncertainty)	Implementation risk: No/delayed project implementation	Interview with experts FGD with cooperative officers and members FGD with local leaders in island
	Dispersion of population: difficulty in communicating with customers and in providing service (epistemic uncertainty)	Implementation risk: No/Delayed project implementation	FGD with local leaders in island

not covering its expenses anymore, as it had to adjust the power generation to the increasing demand of its customers. Consequently, when EC develop small-scale projects in small islands, their upfront costs are relatively higher.

The selection procedure for accrediting private sector partners is tedious and slow. In order to get the private sector to participate in missionary areas, the competitive selection process (CSP) was introduced by the government. EC have to go through the CSP in selecting private partners for joint ventures. At least three competing parties are required before a winning bidder may be chosen to negotiate a power supply contract with the EC, which has then to be submitted to the ERC for approval. However, if there is only one party placing a bid, the whole process has to be cancelled and restarted.

Coordination and communication between the involved stakeholders (DoE, NEA, NPC-SPUG, EC) are not sufficient to keep all institutions adequately informed. For example, one expert reported that for the case of one island, the contract for supplying diesel-based power of the public operator was renewed although an NPP was already assigned to replace the public operator. Ultimately, this leads to the risk of stranded assets.

4.1.2. Economic factors

EC could get financing either from financial institutions or from private sector partners. The results of this study reveal that both sectors are reluctant to provide financial support to EC given their low level of trust towards cooperatives. EC are generally perceived as lacking the necessary business track record and creditworthiness.

Officers of ROMELCO identified lack of access to the required capitalization as the crucial factor that hinders small or medium-sized enterprises and cooperatives to venture into power generation in general, and even much less into RE generation. When asked to narrate the story of their own venture into the hybrid energy system in Cobrador island, they preferred to discuss the longer history of their effort: Their experience in their first venture in another island, the Catingas Mini Hydro in Sibuyan island. In that first venture, and based on the stability of their fiscal position as an electric cooperative, they were able to secure a loan from the Development Bank of the Philippines for their initial capitalization in a power generation project. They consider this as a key factor in their eventual ability to venture into another power generation project in Cobrador island as the success of that first venture in Sibuyan island built up their track record and their creditworthiness in the eyes of other key financial institutions in the energy sector.

It is unattractive for private companies to invest in small island electrification as partners of EC, also because of their perception about the existing capabilities of EC. Experts say that most private companies view many of the existing EC as needing to undertake comprehensive organizational and financial restructuring to attain sustainable commercial viability.

Energy projects rely mainly on the returns from the provision of electricity, which means that the potentials for high and increasing revenues remain uncertain. Households use electricity for lighting, and recently for cell phone charging, however electricity usage on a bigger scale and for productive use may not be yet be apparent on most of the small remote islands.

Inadequate energy planning due to underestimation of increase in customer consumption patterns is a major uncertainty for the EC. This comes especially true when a low-carbon energy system is being implemented servicing a community without universal electricity supply yet. For our case study, the electricity demand quickly increased after the implementation of 24 h service in 2016 (Fig. 2).

Although a strong growth of the energy demand was expected, the development exceeded the expectation of experts and planners. One year after implementation the daily energy demand projected for 2021 (180 kW h) was already surpassed. This is underlined by our findings from the household survey. Although a specific inventory of appliances was typical prior to the implementation of the system, there was a surge in the number of appliances purchased after implementation of the system (Fig. 3).

Seasonality in customer income patterns has identified as major uncertainty through the household survey. The greatest share of the households has an income of less than 1000 PhP (< 20 USD) per week. In order to take into account seasonal variations, the households were additionally asked how much they earn in a “very good” and in a “very bad” week. For a very bad week, almost 40% of the respondents reported the absence of any income. The main source of income is fishing (61%), followed by remittances of relatives (43%) and farming (34%).

Although our findings clearly highlight the improvement of the safety situation, education, access to information and health

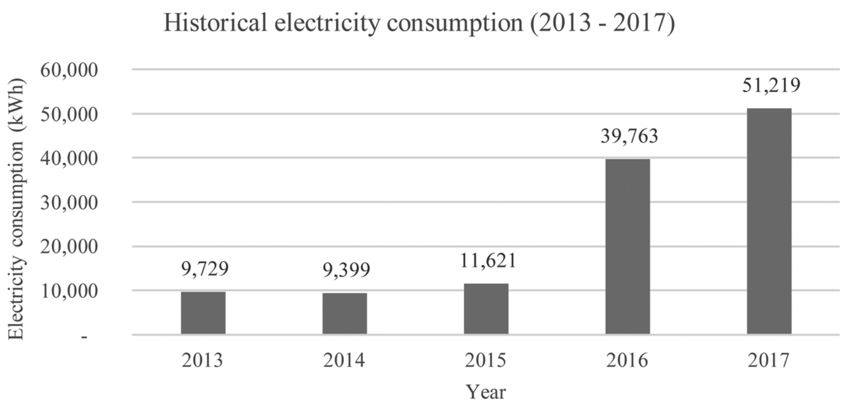

Fig. 2. Historical electricity consumption (2013–2017).

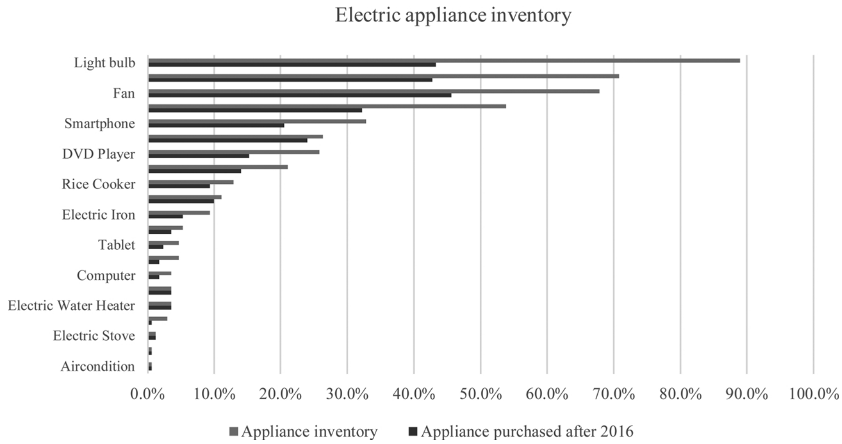

Fig. 3. Electronic appliance inventory and share of appliance purchased after implementation of 24 h electricity supply.

supply, the majority of respondents have not experienced an uptake in income since the implementation of the project (Fig. 4). The economic situation on the case study island remains similar to the situation prior implementation of the hybrid system.

Customer reliability is another problem expressed by the local leaders in Cobrador. There are subscribers who are in default of paying their electricity bills. Local leaders say that these consumers tend to ignore their bills when they are still small up until their bills have accumulated and become more difficult to pay. This consumer behaviour poses a threat to the financial viability of a cooperative with limited resources and that relies mainly on customer patronage for sustainability. A pre-paid billing system could be an option to avoid the problem of unpaid electricity bills but would add extra investment costs (Kambule et al., 2018). When asked, consumers with lower electricity bills said that they do not have the financial capability to pay for an increased consumption of electricity even if it becomes available, and that they are consciously cutting down on their electricity cost.

4.1.3. Societal factors

The lack of skilled technicians relates to the novelty and complexity of RE technologies. Since these technologies are not yet often applied in remote islands, it is difficult to find experienced technicians. Additionally, technicians tend to leave rural areas to seek better income sources in urban areas after finishing their training. Skilled labourers are necessary during the construction of facilities and can sometimes not be recruited from remote islands. This lack of locally available skills entails higher cost for constructing, operating, and maintaining energy systems as EC resort to incentivizing workers and technicians to regularly go to or to move to these small and remote islands.

Officers of ROMELCO and the island residents of Cobrador discussed the difficulty of securing access to land for the construction of the power plant and its distribution cables. Most of the lands were privately owned and the reluctance of the owners to give access to their property posed a threat to the realization of the EC low carbon project. The long and tedious process of negotiations pushed ROMELCO to seek legal advice and research support which resulted to their 'discovery' of an existing law that provided for the appropriation of private lands when it is necessary for infrastructure development. This experience makes it clear that a supportive policy or legal environment while important is not sufficient to enable RE ventures in small and remote islands such as this.

While it was public clamour, which at times was violent, for cheaper and more stable power supply that instigated ROMELCO's bold move to go into power generation, proposed RE solutions were also met with resistance from the community at first. In the case of a hydro power plant in Sibuyan island (another RE project implemented by ROMELCO), the people in the area argued that the

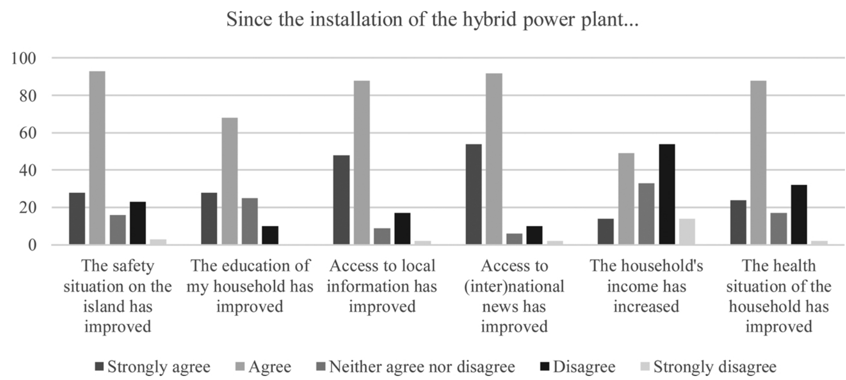

Fig. 4. Impact of low-carbon energy supply on remote community in the Philippines.

hydro project would cause the deterioration and eventual death of their river resources. It took patience and persistence in information and education work on the part of ROMELCO to finally convince the villagers about the measures they have undertaken to ensure the ecological sustainability of the hydro power project.

The local leaders and plant operators in Cobrador also narrate their experiences of having to contend with irate customers in the island when there is a breakdown in the plant or when a customer's electricity service is cut due to unpaid bills. The local leaders represent ROMELCO in the island and are therefore regarded as the village-level cooperative representative. While it is easy to dismiss this as a customer relations issue, which can be easily managed away through outsourcing, one has to bear in mind that at the village-level, these operators and customers are interwoven into networks of social relations as neighbours, extended families, or kinship based on rituals, and are locked in face-to-face interactions. The success or failure of the cooperative venture in small and remote islands would depend on the success or failure in maintaining an appropriate level of trust and cooperation among the villagers.

According to interview partners, many international donor organizations implemented projects to foster the use of renewable energies in remote areas in the 1990s. Most commonly they distributed solar home systems (SHS) to households, however once the projects were over, there was a lack of ownership and know-how of maintenance among the villagers, which resulted in the decay of the systems and villagers' distrust of RE projects.

One interview partner recommended to include influential players of the island (e.g. priests, barangay captains) in the project planning process in order to gain the trust of the villagers. Creating new job opportunities for the villagers through e.g. the construction of the site, the maintenance of the power plant or collecting the electricity bills from the various users could also facilitate social acceptance. Regular information meetings with the community and inclusion of the island residents in every phase of project implementation is crucial for community empowerment and social acceptance.

4.1.4. Technological factors

Many EC still consider the national grid extension as the main and most feasible option, even though the main grid is often far away and the connection via submarine cables is very costly (Kuang et al., 2016). This is partially due to the availability of a public fund for line expansion and submarine cables in order to eliminate the high subsidies in the long term. For off-grid solutions, most EC consider diesel-powered generation or SHS as the only alternatives. However, there are many limitations to SHS as they cannot meet the electricity demand of the households adequately, let alone electrify public entities such as schools or health centers. EC are seldom aware of the option to hybridize their existing power systems or hesitate to invest in new technologies as it also bears further risks in terms of maintenance and monetary returns. There are few local developers, most of the companies that build hybrid power plants on Philippine islands come from foreign countries such as Korea, Japan or Germany. Local engineers have to be trained to maintain new power systems and adequate incentives for them to stay rather than to seek job opportunities elsewhere would have to be put in place.

The energy project in Cobrador is a joint project with a Korean-based firm, which provided the entire technology bundle. Delays and difficulties were encountered during instances of breakdown within the warranty period as it takes a long time for repair materials and technical experts to reach the island and to do the necessary repairs. The joint venture is apparently in the framework of a turnkey agreement rather than a transfer of technology framework, which would enable local innovators to build, replicate, or replace the technology based on locally available resources and technical expertise. Instead, the local residents were trained to become operators of the imported technology bundle. The complexity of the system includes the interaction of system parts like battery, solar panels and diesel generators, which have to be synchronized. Uncertainty was formulated regarding the disaster resiliency of the low-carbon technologies, since most of their parts are directly opposed to the natural surroundings. As most small and remote islands in the Philippines are exposed to frequent extreme weather events, RE technologies that are deployed in these islands need to be designed and adapted for disaster resilience.

4.1.5. Geographical factors

Small islands in the Philippines are mostly remote. There is a general lack of reliable and appropriate transportation systems and related infrastructure to facilitate access to these small islands. The transportation of the equipment for a power plant to remote islands is often very complicated and exposed to several challenges. The current may not be strong enough, so that boats cannot run the planned schedule, which can lead to delay in the delivery of the needed materials and equipment. Additionally, the equipment is often highly vulnerable to damage and has to be handled very carefully. Many islands do not have a jetty, which means that just docking the ship to the island is a challenge itself. Transporting the equipment from the port to the site where the power plant is to be located is another effort and requires a lot of labor force. Before the transportation of the power plant material, similar challenges apply for the construction of the power plant itself. In many cases, construction materials have to be transported from a neighboring island via boat and then to be carried to the project site. The dispersion of the island population is an obstacle when it comes to connecting the houses to electricity and putting up the electricity posts. In many cases, population is highly dispersed and in order to access the houses rivers have to be crossed or houses are located on hills with poorly constructed or non-existent roads.

4.1.6. Strategies to address uncertainties and risks

This section summarises how the EC in this case study, in spite of odds, build up capability to implement a low-carbon energy project successfully. Finally, it provides lessons-learnt for the implementation of cooperative-driven low carbon energy projects in the Philippines in the future.

We consider the motivation of the EC, embodied by their staff, to realize the low-carbon energy system as a cornerstone for successful implementation. This motivations stems from a broader vision to supply the entire franchise area of the EC with RE in the midterm. First, the EC built and nurtured continued engagement and collaboration with policy makers, industry experts, and community stakeholders. Therefore, it used conferences and meetings, to share its experiences, highlight bureaucratic hindrances and put forward its policy advocacy. Second, the EC went ahead with implementation even when the bureaucratic procedures took a long time and permits were still pending. In effect, the EC shared the risk of higher costs with the community while their claim for subsidy was still pending in a government office. Although the customers were initially unwilling to pay higher tariffs than family members and friends in neighbouring islands, they concluded that it is in their own interest to pay higher tariffs if this would accelerate the implementation of the clean energy system. This was a result of information campaign and dialogues with community stakeholders to gain their acceptance and support. Third, the EC cooperated closely with international donor organizations and technology providers, which proofed essential since the project was eventually realized with grant funding. The EC harnessed the interest of technology providers to realize a proof of concept of its product for their own purpose to provide clean energy to their deprived customers. Although this cannot be a generalized model for the entire country, it contributed to building trust in RE in the Philippines since many interested stakeholders are visiting the project. Fourth, the EC looked for provisions in the law that would work in their favour and applied it when landowners resisted infrastructure projects due to individual business interests. Fifth, the EC addressed the lack of skilled technicians and labourers by training residents for operating the low carbon energy system. This was realized through investing into their staff, e.g. paying for their vocational training. This resulted in job opportunities for several villagers.

Finally, success factors and lessons-learnt for the future implementation of cooperative-driven clean energy projects can be derived. A clear development vision is necessary to ignite the motivation of an EC to advocate politically for its projects and implementing it despite of bureaucratic odds. Thereby addressing political risks and uncertainties. Cooperation with technology providers and donor organizations alleviated economic and technological risks and uncertainties. Stakeholder engagement and training of local staff builds trust and engages people, thereby addressing societal factors. While geographical factors cannot easily be addressed, the experience in Cobrador island instigated interest in developing containerized solutions for transportation requirements that would leverage the cost and labour intensive construction of power houses in the future.

5. Conclusions

Policies and regulations are important but unless implementing guidelines that make it easier for cooperatives to venture into RE generation are put into place, the policy environment will not effectively induce their active support for energy transition. This study identified the most serious implementation risk to low-carbon energy transition in the Philippine context, which is the discontinuity between the present administration's policy pronouncement and its policy implementation practice. A sustained and focused conversation on how to incentivize local innovation and technology to produce local parts for local resources, and to develop local knowledge and capacities to innovate, to do reverse engineering, or to design appropriate local technologies is also lacking. This is a challenge to local engineers and higher education institutions in general. It has already been recognized that managers of EC play a pivotal role in leading the transition to low carbon systems, hence they have been given numerous skills trainings related to grid planning, management, etc. What is missed, however, is that managers of EC would also need to navigate what are usually challenging terrains of local politics and power dynamics. They would need to develop the capacity to insulate themselves from vested interests and to focus on the service-oriented mission of EC. The uncertainties faced by EC who venture into low-carbon energy options in small and remote islands in the Philippines seem insurmountable at first glance. The interrelatedness of lack of access to finance and the high upfront costs for RE technologies are risks for EC in the Philippines. The hidden costs for EC for venturing into RE projects in small islands are generally ignored by an undifferentiated incentive scheme and a sluggish bureaucracy. Without a policy environment and a private sector that are unequivocal in their support and promotion of RE projects for small islands, the implementation risks are placed squarely on the shoulders of the cooperatives. EC need support in building their credibility and capabilities to promote a paradigmatic shift in financial institutions and prospective private sector investors. The pathways to low-carbon transition are marked by persistent opposition and struggles. It is equally important to recognize and pay attention to the emotional labour input of the implementers on the ground. Their ability to reflect upon their experiences and recognize their own achievements which then become their motivation to persist along the path towards low carbon and RE transition add to the resilience of low-carbon energy transition projects in missionary areas. Enabling the sharing of these experiences with other communities and leaders is an important conduit to facilitate the flow of energy that would create the critical mass of grassroots enablers towards energy transition. The pathways to low-carbon transition require a critical mass of trailblazers. The risks and uncertainties that mark these pathways are best transcended through public, direct, and participative deliberations. Because of these, EC remain as a promising pathway for low carbon energy transition.

Acknowledgements

The authors thank the Reiner Lemoine-Foundation for co-financing this research work. This work is part of the Research Project entitled, "Ener-PHIL – Research Cooperation supporting the Energiewende on the Philippine Islands" that was funded by the German Federal Ministry of Education and Research (BMBF). The authors also thank UP Diliman for supporting this research and especially Joseph Yap IV, Eugene Esparcia, Imee Saladaga and Billy Esquivel for their support during the fieldwork for this research.

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7. Synthesis

The final chapter summarizes and discusses the research results of the presented publications. The most important conclusions are synthesized and their relevance to the field of research are discussed. Finally, the limitations of the research approach are discussed and important fields for future research are defined.

7.1. Summary and discussion of research results

The summary is oriented along the five presented research questions. The research results of each publication address one specific research question as shown in chapters two to six:

RQ1: How cost-effective can RE be integrated into existing diesel-based island grids?

Chapter 2 shows that the implementation of solar PV in combination with Li-ion battery storage into existing diesel-based island grids in the Philippines leads to an average cost reduction of 0.02 USD per kWh and an average optimal RE share of 24%.

The feasibility of RE integration is investigated for 132 existing diesel-based island grids and three different scenarios: The first scenario takes into account the current operating times, which are limited to few hours in many island grids. For this scenario, an implementation of 226 MWp solar PV and 50 MWh battery storage leads to an average cost reduction of USD 0.02 per kWh with an average RE share of 24.2% in 58 island grids. No hybridization potential is found for 74 mainly very small island grids due to operating times limited to the morning and evening. For the second scenario, the goal of a nationwide 24/7 electricity supply is taken into account by modelling extended operating hours, which increases the electricity demand by 30 GWh reflecting an increase of 2.2%. Most interestingly, the extension of service hours increases the potential for the implementation of RE, as economically feasible designs are identified for almost all existing diesel-based island grids. The cost reduction compared to pure diesel power supply remains at an average of USD 0.02 per kWh and the RE share increases slightly to 24.9%. Since the demand for electricity increases by only 2.2% in the scenario, the required capacities increase slightly to 237 MWp for solar PV and 54.5 MWh for battery storage. In the third scenario, the expected load growth over a 10-year scenario is included, which increases the electricity demand by 108%. Here, too, the LCOE reduction is 0.02 USD/kWh with a RE share of 24.8%. Much larger capacities of 429 MWp solar PV and 111 MWh battery storage are required to cover the load growth. Hybridization with RE is not only cost effective and advantageous for providing 24/7 supply, but would also save a large amount of diesel fuel and respective CO_2 emissions: From 105 million liters (equals 279 million kg/CO_2) in scenario 1 to more than 228 million liters (equals 607 million kg/CO_2) in scenario 3. However, substantial initial investments are required of 375 million USD for the first scenario to 817 million USD for the third scenario. The identified RE potential can be regarded as very conservative, since high capital costs are applied for RE investments, while no capital costs and reinvestments are applied for diesel generators. Sensitivity analyses show that variation in diesel fuel costs affect power generation costs more significantly than variation in solar PV, battery and capital costs. A sensitivity scenario applying favorable assumptions for RE implementation reveals a much greater potential for RE hybridization that could offset more than 55% of diesel generation.

In conclusion, RE can be cost effectively implemented into island grids without any subsidization and offer cost savings compared to diesel power generation even under very conservative assumptions.

RQ2: How cost-effective are RE island grids compared to grid connection?

The assessment of costs for submarine power cable interconnection, presented in chapter 3, reveals that the development of RE island grids is more cost-effective in at least 23 out of 30 island groups of the Philippines.

At the national level, connecting all 132 existing diesel-based island grids to the main grid by submarine power cables is not cost-effective compared to the development of RE island grids under the applied cost assumptions. A grid extension of 2,239 km by submarine cables and 1,752 km by land cables would be necessary for the connection of all diesel-based island grids if an optimized spatial grid development plan were to be implemented. The total investment amounts to more than 3.2 billion USD for grid infrastructure alone, without taking into account the power generation capacity required to meet the demand on the newly connected islands. In contrast, RE implementation in the considered systems would require approximately 708 million USD for the implementation of 363 MW of solar PV and 102 MWh of lithium-ion battery storage capacity. In this scenario additional operational expenditures for diesel fuel are required as the average optimal RE share remains at approximately 30%.

A simplified power generation cost comparison of submarine power cable grid interconnection and RE integration considering individual island groups reveals that submarine interconnection to the seven island groups of Basilan, Catanduanes, Camotes, Marinduque, Masbate, Mindoro and Palawan is the more cost-effective option. Sensitivity analyses addressing the uncertainty in submarine power cable costs show a high robustness of the findings to an increase in investment costs. Priority should be given to submarine power cable connection to Basilan, Marinduque and Mindoro based on their short submarine power cable requirement and high electricity demand on these islands. Additional power generation capacity in the main grid would be required to meet the additional annual electricity demand of 935 GWh/a (for all island groups with potential for submarine connection) or 471 GWh/a (for three recommended submarine interconnections). Connecting the recommended islands could reduce the TCGR and allow for a stepwise graduation from the UCME subsidy scheme. This can reduce the amount of national funding needed to subsidize electricity tariffs on off-grid islands substantially. A portion of the funds saved could be invested in RE-based hybrid system development on islands where submarine interconnection is not viable to improve economic feasibility.

The findings underline the cost-effectiveness of RE integration into existing island grids compared to submarine power cable interconnection for most off-grid islands in the Philippines.

RQ3: How can RE island grids supply the remaining not-electrified islands?

As presented in chapter 4, the average RE capacities to supply the not-electrified islands are 0.18 kWp solar PV, 0.33 kWh battery storage and 0.02 kWp wind power on a per capita basis. This reflects that solar PV and lithium-ion battery storage form the backbone of fully renewable electrification, while wind power capacities are supplementary.

The chapter contributes with a quantification of the electrification demand and identifies a total of 1,920 not-electrified and inhabited islands, which corresponds to 14% of the non-electrified population of the Philippines. Out of this group, 649 islands with a population of more than 50 people are considered suitable for RE island grid development, representing a total of 650,000 people. Cluster analysis is applied to divide the islands into four typical groups based on population, and the availability of solar and wind resources. Three groups cover the majority of the islands (88%) and are characterized by a typical population of around 500 people, although they differ in the availability of resources: While the first group has both high solar and wind resource availability, the second is characterized by lower solar resources and the last group by lower wind resources. The fourth group consists of 76 islands with a larger population of around 3,500 people. Islands representing the group medoids serve as case studies for assessing the feasibility of RE only systems through energy system simulation. Electricity generation costs in the range of 0.53 to 0.61 USD/kWh are derived for systems with 100% reliability. Despite the varying availability of resources, solar energy in combination with lithium-ion battery storage is the essential component of cost-optimized system configurations, while wind power capacities remain supplementary due to large seasonal variations. A sensitivity analysis shows that a 1% reduction in the reliability level can reduce electricity generation costs by 20%, as the required solar PV and battery capacity is significantly reduced. The results for the four case studies are generalized to the identified not-electrified islands of the Philippines: A capacity of 118 MWp solar energy, 212 MWh battery capacity and 10 MWp wind capacity is required for 100% RE-based electrification at a reliability level of 99%. The total investment would amount to USD 350 million under the applied cost assumption, but would only require USD 540 per capita.

The analysis highlights that solar PV and battery storage can cost-effectively provide reliable electricity supply for not-electrified island communities.

RQ4: What is the impact of RE island grids on local communities and the SDGs?

The case study analysis presented in chapter 5 shows that the implemented RE island grid complies with SDG7 by improving sustainability (high RE share), reliability (establishing 24 hours supply) and affordability (tariff reduction). Further its implementation has improved household livelihoods through better health and education service and access to information and communication. However, the level of wealth determines the capability of households to profit from RE island grids.

Analysis of electricity consumption statistics show a rapid increase in the first year after implementing the RE island grid. In the second and third year peak demands stabilized and exceeded the initial demand by factor 2.5 which can be an important guideline for the design of future RE island grids. An empirical analysis of 170 households shows that electricity is mainly used for entertainment and communication purposes, as television (71% of households) and mobile phones (83% of households) are among the most frequently owned electronic devices on the island, along with light bulbs, fans and sound systems. Electricity consumption depends on household wealth, and 34% of less affluent households consume very small amounts of electricity per month (<6 kWh). However, the majority of both above and below-average income households report a positive impact on SDG3 ("Good Health and Well-Being"), SDG4 ("Quality Education") and SDG6 ("Clean Water and Sanitation"), as all households, regardless of income, benefit from improved access to communal education and health services. In contrast, the majority (52%) of above-average income households state that their income situation has improved compared to just 37% of below-average income households. The results show that above-average income households use electricity more frequently for income generating activities and own more appliances with which income can be generated (e.g. fridges).

It is concluded that while SDG7 and other important SDGs are met through the introduction of RE into this specific island grid, SDG1 (“No Poverty”) and SDG10 (“Reduced Inequalities”) are insufficiently addressed. Improving electricity supply through RE runs the risk of exacerbating inequalities in island communities due to differences in household wealth. Measures to balance historical inequities, such as pro-poor tariff structures and the stimulation of productive use of energy access, must be incorporated into RE integration efforts.

RQ5: What are the challenges and risks in implementing RE island grids?

Chapter 6 focuses on the challenges faced by an electric cooperative in the implementation of RE island grids. The analyses identify the delay in approval and subsidy issuance, difficulty to raise capital and lack of technical expertise as key challenges for the EC.

While the private sector has not met expectations to accelerate the deployment of RE in the off-grid sector, ECs may be better placed to do so because of their detailed understanding of community needs, lower investment return expectations and a greater interest in local development. The case study presented in chapter 5 discusses evidence drawn from expert interviews, focus group discussions and surveys, focusing on the challenges in form of uncertainties and risks faced by the EC in carrying out the case study project: The challenges identified are categorized in political, economic, societal, technological and geographical factors. In particular the slow issuance of incentives undifferentiated across technologies (fossil/non-fossil) and extensive formal and fee requirements even for small-scale projects hinders the implementation of RE island grids by ECs. Lack of access to capital and uncertainties about consumption and ability to pay of a largely poor customer base are challenges in the field of economics. The novelty and complexity of RE island grids in the Philippines adds to challenges in the field of society and technology: A general lack of skilled technicians and laborers requires project developers or ECs to train locals prior to implementation. As many parts of RE island grids (e.g. solar panels, battery storage) are not locally manufactured it is necessary to closely cooperate with international partners. Finally, the remoteness and lack of infrastructure (e.g. jetty) on many small islands challenges the appropriate transportation of energy system components.

The investigated EC developed several strategies to address these challenges. First, the EC assumed the risk of continuing with implementation while permits were pending. Second, the EC collaborated closely with donor organizations and technical experts to address the lack of capital and expertise. Thirdly, the EC invested in and trained local staff to operate the RE island grid. In the end, this proactive approach proved successful in implementing a RE island grid in compliance with SDG7.

Findings outside the research questions

The specific character of this cumulative dissertation is to present a comprehensive research narrative based on five individual publications. Choosing five research questions as guiding framework allows to synthesize the most important findings of each publication for this dissertation. Nevertheless, along the way of this research project additional interesting and not expected findings were collected not intentionally to address the five main research questions. These additional findings are summarized in the following:

Chapter 2 reveals that providing 24/7 power supply would result in only a demand increase of 2.2% since supply additions are only required in small island grids with low electricity demands. Additionally, providing continuous electricity supply increases the RE potential which was an anticipated result but not expected in the identified scale. Chapter 4 indicates that the not supplied population on remote islands comprises 12 – 14% of the not electrified population of the country. A higher share was expected, although the reliability of population statistics needs to be further considered, the findings highlights that further electrification efforts have to be focused as well on remote regions and informal urban settings in the main grid sector, especially in Mindanao the least developed region of the Philippines. Further the simulation of 100% RE island grids (chapter 4) finds excess electricity shares above the expected levels and above levels reported in literature (c.f. [86]). This findings underlines the necessity to focus on the use of excess electricity in high RE share systems in future research. Chapter 5 highlights that the provision of improved power supply through RE had only a slight impact on overall income generation, although differences between households with regard to wealth were identified. Observations and exchange with community representatives during field research indicated many households focus on producing goods for own use or for the demand of the small island community. In combination with the difficulty to access markets for potential goods due to the remoteness of the island, no clear incentive motivates households to use electricity for productive use or income generation.

7.2. Main conclusions

The dissertation highlights the techno-economic feasibility of RE island grids to improve and provide power supply in the off-grid sector in the Philippines. Interdisciplinary research methods have been used to identify challenges that need to be addressed for a broader, faster and more socially acceptable deployment of RE in island grids. In this context, the key contribution of this dissertation is that the research results and the applied methods and tools can be used to inform decision and planning processes for a low-carbon development of the off-grid island sector. In the following, the main conclusions are highlighted and the research hypothesis is addressed by synthesizing the findings of the five presented paper:

Renewable energy based island grids represent a cost-effective, environmentally sound and socially acceptable development pathway for the electricity supply of Philippine islands.

It can be concluded that renewable energy based island grids represent a *cost-effective* development pathway to improve power supply in existing diesel grids in the Philippines. Even under conservative cost assumptions an implementation of solar and battery storage is nationwide effective up to an average share of 24% (Chapter 2). Considering projected cost reductions for RE technologies and more favorable investment conditions (lower capital costs and higher fuel costs), the RE potential quickly increases and provides cost advantages over diesel fuel supply. However, for the largest island grids comprising most of the demand in the off-grid sector a submarine power cable connection to the main grid can be the more cost-effective development option (Chapter 3). This could even have advantages for RE island grid development: Island grids connected to the national grid can graduate from the UCME scheme which could release funds for developing RE island grids elsewhere. For not electrified islands 100% RE island grids are a feasible option but come with relatively high power generation costs (Chapter 4). However, diesel generation is no alternative, since it would imply the need of constant fuel supply and high maintenance efforts. Instead, 100% RE island grids can be more affordable if the reliability levels are slightly reduced and excess electricity is used for deferrable loads in form of water purification or cold storages providing additional benefits to communities.

RE island grids represent an *environmentally sound* development pathway for the electricity supply on off-grid islands. The use of RE mitigates the combustion of diesel fuel, however the scale of emission reduction depends on the RE share. Chapter 2 highlights that under conservative assumptions more than 100 million of liters of diesel can be saved annually with a RE share of 24% by implementing RE on only 58 out of 132 diesel-based island grids. This leads to estimated savings of 279,000 tons of CO_2 emissions per year. Since investment costs for RE technologies are projected to further decline, more RE can be installed cost-effectively which increases the emission reduction potential. For few islands the potential for submarine interconnection has been identified (Chapter 3). Such an interconnection would not be environmentally sound since power generation in the on-grid sector is fossil-fuel based and fossil fuel intensity is projected to intensify. However, such interconnection could allow for the export of RE sources installed on off-grid islands and potentially allow for an increase of the overall RE share. Not electrified islands can be supplied entirely with RE (Chapter 4). This avoids any emissions directly and also reduces the transportation of fuels within the archipelago. This should not be underestimated since the inappropriate handling of fuels leads to pollution that harms local environments.

RE island grids are *socially acceptable* and contribute to sustainable development on remote islands (chapter 5). However, the case study analysis reflected that wealthier members of the community benefited more from improved electricity supply through RE implementation and were able to better diversify income sources relative to less wealthy households. Measures for balancing inequalities are required when implementing RE-based island grids. The utilization of the potentially large amounts of excess electricity in RE island grids is an important consideration as highlighted in chapter 4. Excess electricity could be utilized in appliances with deferrable loads e.g. ice-making or water purification. If such facilities are owned and operated by the community or a cooperative the products (clean water, ice) could be sold at an affordable price to the community members. This could potentially allow a larger share of the population profiting from RE-based island grids. Electric cooperatives could be a suitable entity to implement integrated RE island grids in combination with the above mentioned income generating activities in a socially acceptable way. However, ECs would need more support in access to capital, issuance of governmental incentives and training of technicians to do so (chapter 6).

Overall, the main hypothesis was confirmed through the five published paper and the applied mixed methods approach, showing the positive effects of RE implementation for Philippine island grids. In order to make these results more applicable they are translated into specific recommendations in the next section.

7.3. Policy recommendations

Finally, specific recommendations are presented for the further development of the Philippine off-grid sector based on the summarized findings:

- First, of all, policy makers should define and communicate which island grids shall be interconnected with the main grid system using modern least-cost planning methods. This thesis formulates a clear recommendation to focus on the three specific island grids of Basilan, Marinduque and Mindoro for short-term interconnection based on a least-cost planning approach. However, more detailed investigation is required into technical (e.g. voltage levels) and political-regulatory issues (e.g. role of stranded assets). Further the potential for graduation from the UCME scheme need to be assessed under a socio-economic perspective and should serve as a decision criteria.
- Second, the hybridization of existing diesel-based island grids is cost-effective even at current cost and demand levels in the larger grids with 24-hour power supply. Although the hybridization potential is quite similar for most islands, this dissertation provides information in which island grids the LCOE reduction potential is highest. Out of this group, the particular grids with the highest electricity demand should be targeted first for hybridization with solar and batteries to maximize the mitigation of diesel power generation. The target of providing 24 hours is in line with the implementation of RE, since additional operating times are usually required during the day. As a first step, solely solar PV could be integrated for direct consumption in a solar PV-diesel system, for later upgrade to solar PV-battery-diesel systems with higher RE shares. It is therefore recommended to push hybridization of larger island grids first to keep the UCME requirements low. In addition, it should be mandatory that the extension of service hours is combined with the implementation of RE systems to keep the required amount of subsidies for power generation stable.
- Third, the dissertation showed that the not-electrified islands can be clustered into characteristic groups and that solar PV and lithium-ion battery storage form the core part of entirely RE systems for electrification. This provides an opportunity for economies of scale. For each group and population size specific solar PV –battery system configuration should be developed and tested for wider deployment. Such systems should be implemented as containerized solutions, which enable for sheltering components in case of extreme weather events and facilitate inter-island transportation. Such standardized energy solutions need to be extended by components delivering important services to the island communities. This could include water purification systems, cold storage systems or similar load-deferring energy consumers. This holds a potential to use excess electricity and provide more

affordable services to all customers, thereby reducing the risk of deepening inequalities in island communities.

- Fourth, the analyses have shown that there is no one-suits-all approach for implementing RE on the island grids. Policy-makers and project developers should use decision support tools to understand the local techno-economic potential of RE systems for each island grid. Several approaches and tools were presented in this dissertation.
- Fifth, electric cooperatives need to be equipped to accelerate the shift towards low-carbon energy systems in the Philippine islands. ECs have access to detailed knowledge on the specific demand of remote island communities and do not require high returns on investment. Improving the ECs technical capabilities to implement RE island grids and raising the necessary funds can facilitate accelerated deployment of RE island grids. Specific challenges such as managerial and technical capability as well as corruption need to be addressed and overcome. As an important first step the ECs should have access to technical support or consulting units. In cooperation with such experts bankable project proposals could be developed for raising investment capital.

The Philippines are in the unique position to transform their off-grid power sector to low-carbon technologies if the aforementioned recommendations are implemented. Besides the reduction of power generation costs and the mitigation of emissions, a high potential for improving livelihoods in remote communities is presented if the outlined improvements are considered. RE-based island grids in the off-grid sector can serve as role model for RE development in the main grid sector and neighboring countries with similar framework conditions.

7.4. Scientific contributions, limitations and future research outlook

7.4.1. Methodological contributions

This dissertation contributes to energy research on islands with an interdisciplinary approach that combines the disciplines of energy economics and social sciences. Consequently, the dissertation presents a mixed methods approach consisting of a range of applied and tested methods. Thereby it addresses the call for more interdisciplinary research and the inclusion of social sciences in energy research to design socially acceptable transformation pathways [120].

In the field of energy economics, this includes the application of geospatial analyses to define the study area, to assess the status of the power supply and to derive input parameters for the later techno-economic analysis. Furthermore, the feasibility of combining geospatial and cluster analyses to identify patterns of island characteristics for electrification planning was presented in detail (Chapter 4). Such approaches are easily adaptable for electrification planning purposes in another context, e.g. Sub-Saharan Africa. A novel approach for an initial cost estimation of submarine power cable interconnection based on a geospatial optimization of the grid network was developed and presented (Chapter 3). The approach is replicable to study areas with similar research questions, e.g. Indonesia. For the evaluation of the power generation costs, this dissertation focuses on the calculation of LCOE and applies open source energy system simulation tools that have been validated with HOMER Energy as the reference model [123] (chapters 2 and 4). The applied tools are available online [124] and can be applied as well as further processed for assessing the viability of RE island grids in other study regions.

In the field of social sciences, typical approaches to obtain primary data are applied in the form of household surveys (Chapter 5), expert interviews and focus group discussions (Chapter 6). The design of the aforementioned methods were jointly developed with Filipino researchers and adapted to fit to the Philippine context and can be applied immediately to other regions of the Philippines.

An additional contribution of this dissertation is the application and testing of open source software and models as well as utilization of openly available data as far as possible in order to maximize transparency and reproducibility of the research [125]. Therefore, accessibility and transparency of software applied was a key selection criteria and explains the use of Quantum Geographic Information System (QGIS) for geospatial analyses (chapter 2, chapter 3, chapter 4), R for most statistical analyses (chapter 4), KoboToolBox for household surveys (chapter 5) and open source energy system simulation tools (chapter 2, chapter 3, chapter 4).

With its interdisciplinary approach and the diversity of the applied methods, this dissertation proves that combined approaches are capable to address the outlined research question and reveal unexpected challenges, e.g. the threat of increasing inequalities in island communities through providing electricity access (cf. chapter 5). Since the presented approach and methods developed are accessible and reproducible they can be transferred to similar research areas or other island landscapes.

7.4.2. Empirical contributions

The dissertation provides new quantitative and qualitative data to the field of renewable energy supply on Philippine islands and provides relevant information for evidence-based energy sector planning. Throughout the research work a large amount of primary and secondary data was collected or retrieved. This includes detailed technical characteristics of the existing diesel-based island grids, which enabled a detailed assessment of the renewable energy potential (chapter 2). In addition, modern, state-of-the-art technologies (e.g. Li-ion batteries) are taken into account and cost reduction projections are included in sensitivity analyses to replace previous and outdated research results (chapter 2 and chapter 4). New cost estimations are provided for the interconnection of island groups to the main grid (chapter 3). So far, no analysis has been carried out in a comparable level of detail. The latest and most detailed data from the National Mapping and Resource Information Authority of the Philippines (NAMRIA) has been collected in order to identify the islands in need of electrification and to quantify the measures needed to achieve the 24/7 supply target. Such data was not available earlier and contributes to efficient electrification planning. In addition, an assessment of 100% RE systems for electrification is presented, which has not yet been conducted on a large scale for the Philippines (chapter 4). New quantitative data is provided for the evaluation of RE island grid interventions (chapter 5), providing crucial information for the planning of future electrification projects. The data collected through expert interviews and focus group discussions provide information on the potential role of electricity cooperatives in the implementation of RE island grids in the Philippines (Chapter 6) and provides recommendations on how to support this stakeholder group. Finally, the empirical data generated supports evidence-based planning for the development of the off-grid sector of the Philippines.

7.4.3. Contribution to capacity development

Capacity development was provided in the framework of this dissertation through close collaboration with Filipino researchers and students. The publications presented in chapter 5 and chapter 6 were realized in cooperation with the University of the Philippines - Diliman. Training in the application of good scientific practice and social science based research methods was provided (household surveys) and feedback of the Filipino researchers was included to adapt the research approach to the local context. In addition, a simplified planning tool (SPT) was developed in parallel to the dissertation, which was based on the applied modelling tool in chapter 2, but was simplified and implemented in Microsoft Excel to allow a broader application. Extensive capacity training on this tool was provided through workshops in Manila and elsewhere in the Philippines. The SPT is applied by Philippine stakeholders including DoE to assess the economic viability of RE island grids and contributes to streamlining application procedures. The SPT is presented in more detail in a published book chapter [126].

7.4.4. Research limitations

The aim of this dissertation is to evaluate practical implications for the expansion of sustainable energy systems on the Philippine islands. While new and valuable insights were presented for key aspects of the deployment of renewable energy, other aspects could not be considered in detail and are presented in following:

Techno-economic models of energy systems as presented in chapters 2 to 4 depend on the quality of input data. Extensive collection, processing and evaluation of data as well as the exchange with relevant stakeholders took up a large part of this dissertation effort, which resulted in the collection of a very detailed dataset. Nevertheless, statistics on the status of electrification and electricity supply, further technical data of existing electricity generation plants, more precise cost data of the technologies and more detailed cost projections could increase the robustness of the research results. Such particular uncertainties were, however, countered with sensitivity analyses.

Energy system simulation tools generally reflect a simplification of technical processes and power flows. A temporal resolution of one hour is applied in this dissertation (chapter 2 - 4) due to processing limitations, which can neglect power flows caused by the harmonization of intermittent renewable energy sources and diesel generator capacities in shorter temporal resolutions. Another limitation is that diesel generators were simulated as single units per island grid (chapter 2) due to lack of more precise data on the units implemented. This could potentially over- or underestimate fuel requirements.

An assessment of the effects of RE implementation on grid stability and voltage levels is required but is outside the scope of this thesis (chapter 2). Therefore, the identified RE potential is subject to grid stability constraints. The voltage levels of submarine power cables were estimated based on peak demands of island grids and cable length (chapter 3). However, a more thoroughly approach is required for the dimensioning of power cables which could add to more precise cost calculations. Bathymetric maps served for optimizing grid routes (chapter 3) whereas sea currents, seabed texture, marine activity and potential obstacles were not considered due to the lack of data, the use of such data could alter the identified optimized cable routes.

The consideration of more renewable energy technologies in addition to solar PV, wind power and lithium-ion battery storage could increase knowledge about the feasibility of low carbon development (all chapters). While the technologies under consideration can be characterized as the most technologically mature [9], have the highest resource potential [81] and the most promising cost reduction potential [127], other technologies could represent a side-specific cost-optimal solution. In the Philippine context, the use of biomass for electricity generation e.g. from agricultural residues and small-scale hydropower is worth further investigation, although the security of supply on many islands can be questioned. The consideration of further energy storage concepts holds potential for adding further insights on the potential of RE island grids. Electro-chemical energy storage concepts in form of lithium-ion batteries were considered due to its general applicability and suiting features [28], however pump-hydro storage or hydrogen use through electrolyzers may be alternatives were applicable and could add insight to the cost-effectiveness of RE island grids.

The findings of the implemented household survey provide important first insights for the sustainable implementation of RE-based island grid in the Philippines (chapter 5). The reliability of such surveys is subject to certain assumptions and limitations including the anticipation of correctness of responses as well as probable bias through the enumerators. Both could influence the study results but was addressed through disclaiming the goals of the survey to respondents and with iterative training rounds with the enumerators while implementing the survey. A larger sample size could have generated more accurate results but was not possible due to budgetary and time restrictions. Overall, more impact studies are needed to validate the results of a case study and to allow for the generalization of the findings. This includes as well to focus on more ECs with similar analyses as presented in chapter 6. Future impact assessments should accompany the process of RE developments over a longer period. This could include conducting baseline studies prior to the electrification of unserved islands to establish causal effects on key development outcomes following RE implementation.

Overall, the limitations show that opportunities exist for improvement and for further – more interdisciplinary research – in the fields of techno-economics and social sciences in the context of island electrification studies. Nevertheless, the applied methods and achieved results are of high quality and approved through several peer-reviewed processes. In the next section future research needs are outlined for overcoming the identified limitations.

7.4.5. Future research outlook

The dissertation contributes a detailed techno-economic assessment of the role of RE island grids in improving and providing access to electricity while highlighting important societal aspects for their successful implementation. Nevertheless, several aspects could not be considered in full scale or have evolved as new research fields. The most important future research needs are summarized along the presented chapters.

Hybridization of existing diesel grids is cost-effective as presented in chapter 2. However, the impact of intermittent RE sources into the often weak distribution grids should be studied in more detail using specialized grid stability software to assure grid stability after RE implementation. This could include to simulate the harmonization of diesel generators and RE sources in more detailed temporal resolution (e.g. one minute). Further, more RE technologies should be considered on a case by case level if resources are available (e.g. biomass, hydro).

As presented in chapter 3 submarine power cable interconnection can be the most cost-effective intervention for certain off-grid island groups. Nevertheless, a more detailed cost-assessment is required taking into account the capacity in the main grid, voltage requirements of submarine connections and seabed texture. More economic research is required to assess the impact of such connections on overall off-grid subsidy requirements and potential use of savings to develop more remote RE island grids.

Islands in need of electrification can be supplied with entirely RE island grids (chapter 4). However, the costs per kWh are high and may prevent wider deployment. Reducing costs is considered as the key aspect for future research derived from this dissertation. Product innovation in battery storage or cost rationalization through containerized solutions should be investigated. Further the application of more dispatchable RE sources (e.g. biomass) should be evaluated which could allow for a reduction of required battery storage capacity. Allowing power curtailments can reduce costs, these need to be limited to a socially acceptable level which should be investigated by means of social science based research. Using excess electricity for productive loads such as cold storage application or water purification holds the potential for decreasing costs while delivering added value to beneficiaries. Further economic analysis is required to confirm the aforementioned potential.

Chapter 5 highlighted that RE island grids comply with SDG7 but the capability to benefit from improved power supply depends on household wealth. An important future field of research is to develop measures to alleviate existing inequalities through pro-poor tariff structures and stimulating productive use of electricity. In accordance with the research presented in chapter 4 the feasibility of communally owned income generating appliances and activities, such as those essential for all customers (water purification, cold storage) should be investigated.

Finally, chapter 6 provided insights on challenges faced by electric cooperatives when venturing into RE island grids. Generally, the lack of technical expertise and access to capital for small scale projects in the Philippines is a challenge and should be targeted in combination with reducing bureaucratic hurdles within the policy scheme. Such recommendations are rather tasks for policy makers and international development cooperation but can as well be future research fields for political and economic scientists.

This dissertation focused on electricity provision through RE island grids but a more integrated approach is recommended for future research. Future simulations should consider the integration of other sectors of the economy in low-energy development planning. On larger islands this could include the transport sector through electric vehicles or demand for cooling/heating in the RE island grids. For smaller islands integrated energy systems considering the energy-water-food nexus are of high interest. The Philippines are very vulnerable to impacts of climate change, therefore future research should consider how to implement RE island grids in a way that resilience to climate change is maximized. This could include research into how such grids could provide essential services in case of natural disaster. The mixed-methods approach and the presented results can provide a solid base for the outlined future research to further support the research and sustainable development of RE on island grids.

7.5. Impact of dissertation

The aspiration of this dissertation is to inform policy makers and academia in the Philippines about the research results and its potential for evidence based sector planning and decision making. This objective was achieved through the involvement of the author in two major projects in the Philippines: The EU funded Access to Sustainable Energy Program (ASEP) and the BMBF funded *Energiewende* on the Philippine Islands (EnerPHIL) project. The ASEP provided a lot of exposure and facilitated presentation of the research findings to key decision makers of the Philippine Department of Energy (DoE). Furthermore, the Simplified Planning Tool was developed in the context of the program which is a simplified simulation model based on the approach presented in chapter 2. Training on the usage of this tool was provided by the author to more than 150 participants from DoE, NEA, NPC, ECs and the private sector. As of today, the tool is used by DoE for the evaluation of RE island grids. Additionally, the author provided trainings for more than 50 participants in the application of geospatial software for planning energy access projects to EC and DoE staff.

The EnerPHIL project facilitated an intensive collaboration with several faculties of the University of the Philippines – Diliman. The activities included the training of students in applying social science based research methods and the case study analysis presented in chapter 5 and 6. A group of students were invited to Germany and visited several key projects, research institutions and companies involved in Germany’s energy transition.

Besides the two projects the research results and scientific publications were presented at several conferences and discussed with fellow researchers. Most notably the research was presented at ADB’s Asia Clean Energy Conference 2018 and 2019 in Manila. First measurable impacts of the scientific publication include more than 25 citations. Furthermore, in 2019 a symposium titled *Philippine-German collaboration for an energy transition on Philippine islands* which facilitated the exchange between different stakeholder groups on RE island grid development was organized by the author and funded by the German Embassy in Manila and the German Foreign Office.

Finally, four master theses at the Europa-Universität Flensburg, Technische Universität Berlin, Freie Universität Berlin and University of Applied Sciences Trier were supervised in the framework of this dissertation.

Future plans of the author include to focus more on the design of integrated energy-water-productive use energy systems for providing electricity access on Philippine islands for which the aforementioned developed research ecosystem shall be harnessed.

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Eidesstattliche Erklärung

Erklärung gemäß §13 (5) der Promotionsordnung der Europa-Universität Flensburg vom 30.01.2017:

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