Feasibility Study:

Green hydrogen technology in off-grid areas in the Philippines

ENVIRONMENTAL PROTECTION made in Germany

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AIEC	Association of Isolated Electric Cooperatives
DOE	Department of Energy
DU	Distribution Utility
EC(s)	Electric Cooperative(s)
EPIRA	Electric Power Industry Reform Act
ERC	Energy Regulatory Commission
EU	European Union
EVs	Electric Vehicles
FDI	Foreign Direct Investment
GPCCI, AHK	German-Philippine Chamber of Commerce and Industry
GSP+	Generalised System of Preference
GWh	Gigawatt-hour
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LGU(s)	Local Government Unit(s)
MDC	Multi-Purpose Cooperative
MEDP	Missionary Electrification Development Plan
MGSP(s)	Microgrid Service Provider(s)
MW	Megawatt
Napocor, NPC	National Power Corporation
NEA	National Electrification Administration
NPC-SPUG	National Power Corporation Small Power Utilities Group
NPP	New Power Providers
QTP	Qualified Third Party
RE	Renewable energy
RLI	Reiner Lemoine Institute
SAGR	Subsidized, Approved Electricity Consumption Rate
Sc	Scenario
SIIG	Small Island and Isolated Grid
SPUG	Small Power Utilities Group
TCGR	True Cost of Generating Electricity
TEP	Total Electrification Program
UCME	Universal Charge for Missionary Electrification
UTC	Coordinated Universal Time

1. Executive Summary

Feasibility Study Scope

The German Philippine Chamber of Commerce and Industry (GPCCI), in collaboration with the Reiner Lemoine Institute (RLI), conducted a techno-economic feasibility study to investigate the optimal configuration for a hybrid system of renewable energy (RE) sources and hydrogen components that could replace diesel generators as a power source in off-grid areas in the Philippines.

Four off-grid islands were analysed, three of which are supplied with electricity by the public operator NPC and one island where a private resort operator supplies electricity. Two energy system configurations were examined: photovoltaic systems and wind energy systems with hydrogen systems as energy storage to compensate for seasonal fluctuations - as well as supplementary battery storage components. The areas analysed covered different geographical regions of the country as well as different energy system sizes to enable transferability of the results to other off-grid areas of public and private operators.

For the analysis, GPCCI and RLI compared different scenarios for the use of RE - 100% RE, 95% RE and a cost-optimized system' - with a supply from a diesel generator (usually status quo). Battery and hydrogen systems were also compared as energy storage systems. The system size and components for a RE system were determined by the existing electricity demand and the expected photovoltaic or wind energy output. The economic costs for a RE system were then calculated and the costs (OPEX and CAPEX) were compared with the current supply via diesel generators. In addition, the cost development for diesel, capital costs, components for RE systems, batteries and hydrogen systems were considered as part of a sensitivity analysis.

Feasibility Study Results

The study was able to show that green hydrogen solutions in combination with RE from wind and sun can be an economical and sustainable alternative to diesel generators if costs are compared over a period of 20 years. Due to high fuel costs of between €1.23 - €1.73 per liter of diesel (including transport costs), the highest costs of electricity generation are incurred when supplied by diesel generators. Furthermore, the study showed that hydrogen systems are more cost-efficient as energy storage systems than battery systems for a 100% RE supply. In a location that uses solar photovoltaic systems, a cost-optimized system consists of a combination of larger battery storage systems and smaller hydrogen storage systems. In the case of wind power, a hydrogen system without an auxiliary battery is more cost-efficient.

Further, the sensitivity analysis shows, that diesel- and capital cost have the strongest effect on the economic feasibility of a hybrid RE-hydrogen-systems compared to an existing system with diesel generators. Rising diesel prices and lower prices for wind-, PV-, and hydrogen-systems improve economic viability of such systems. Potential higher capital cost in have the opposite effect. However hydrogen system remain competitive even with high financing cost.

According to the analysis, the gradual expansion of PV capacity with hydrogen storage is recommended for Lubang Island to reduce the Levelized Cost of Electricity (LCOE) to 0.30€/kWh and to achieve a RE share of 54%. For Calayan Island, the installation of a hybrid wind-hydrogen-diesel system to reduce electricity costs to €0.26/kWh and achieve a high level of autonomy with a 70% share of RE is the optimal solution. For Maripipi Island, a system with a RE share of 95% and electricity generation costs of €0.34/kWh without an auxiliary battery is recommended. Finally, for the private resort operator, a system with a 68% RE share is recommended, due to space constraints for the installations of PV capacity.

However, further questions and research needs arise from the results of the feasibility study as well. A more detailed elaboration of the simulated energy systems, environmental- and social impact studies, and an examination of the cost assumptions would be needed for the implementation of a possible demonstration project.

2. Introduction

This feasibility study delves into the viability of implementing green hydrogen technology in off-grid areas of the Philippines, shedding light on its potential benefits and challenges. The transition towards sustainable energy sources has become imperative in addressing the dual challenges of energy security and environmental sustainability. In the context of the Philippines, where off-grid areas often face energy accessibility issues, the exploration of green hydrogen technology emerges as a promising solution.

The study is a collaborative effort between the German-Philippine Chamber of Commerce and Industry (GPCCI) and the Reiner Lemoine Institute (RLI) and is structured as follows: The introduction provides an overview of the Philippines, off-grid areas, and hydrogen technology. The methodology section outlines the approach employed in conducting the feasibility study. Following that, the paper presents the results of the feasibility study, including a sensitivity analysis and main findings, along with recommendations. The conclusion section discusses future research directions, limitations, and outlines the next steps.

Leveraging their expertise and resources, GPCCI and RLI aim to contribute valuable insights into the potential of green hydrogen technology in addressing energy challenges in off-grid areas of the Philippines.

3. Country profile Philippines

The Philippines is a sovereign island state in Southeast Asia with 7,641 islands covering an area of 300,000 km².[1] It can be divided into three main regions: Luzon, which is located in the north of the country, Visayas, consisting of several islands in the center and the Mindanao region in the south.[2] Manila, the capital and economic epicenter[3] is located on the largest island, Luzon.

With a time difference to Germany of 6-7 hours, the local time is UTC+8.[4] Currently, the total population is 109 million people[5] and is expected to rise to 149 million by 2045.[6] The Philippines is a young nation with an average age of 25.3 years[7] and has a population growth rate of 1.5%.[8]

3.1. Political landscape

According to the 1987 constitution, there is a separation of powers in the legislative branch, which is modelled on the system in the United States of America, consisting of two chambers: the Senate and the House of Representatives. The executive, President and Vice President are elected by the citizens of the country for six years. The president appoints the cabinet members.[9] In May 2022, Ferdinand Romualdez

[1] Philippine Consulate General, year n/a.
[2] National Geographic, year n/a.
[3] City of Manila, year n/a.
[4] Timeanddate, year n/a.
[5] Philippine Statistics Authority, 2020.
[6] Philippine Statistics Authority, 2015.
[7] Philippine Statistics Authority, 2022.
[8] Germany Trade and Invest, 20222.
[9] Official Gazette, year n/a.

Marcos Jr. was elected as the new President.[10] As Vice president Sara Duterte, daughter of the previous President Duterte, was elected.[11] President Marcos Jr. is continuing the 'Build Build Build' infrastructure program and the reform agenda of his predecessors.[12]

3.2. Economic climate and trade relations

From 2012 to 2019, the Philippines' GDP grew by around 6% each year.[13] In 2023, GDP grew by 5.6%[14], as for 2024 the Asian Development Bank is forecasting 6.2% economic growth.[15] In absolute terms, GDP is above pre-pandemic levels. In 2022, this amounted to $404.28 billion compared to $376.82 billion in 2019.[16] When President Marcos took office in 2022, he set a 10-point priority list for his government. This defines an agenda aiming at economic renewal and long-term growth, part of which includes energy security. The Philippines aims to become less dependent on energy imports and increase local energy production.

The EU is the Philippines' fourth largest trading partner (after China, Japan and the USA) and accounts for 7.9% of total trade.[17] The EU's GSP+ (Generalised System of Preference) is a special scheme designed as an incentive for sustainable special arrangement for sustainable development and good governance in the form of zero tariffs. It is a unilateral trade regime that provides duty-free treatment for 6,274 goods from the Philippines.[18]

Germany and the Philippines have maintained diplomatic relations since 1954.[19] Being the destination of 3.9% of total exports, Germany is one of the Philippines’ main customers.[20] Electronics is the export hit of the Philippines, hence in 2021, electronics exports accounted for 48.8% of total exports.[21] From January 2023 until January 2024, Germany has a trade deficit with the Philippines, amounting to almost $200 million.[22] Philippine seafarers and nursing staff play a particularly important role for Germany.[23]

Since 2008, the German-Philippine Chamber of Commerce has supported economic cooperation with around 300 members. An AHK survey in spring 2023 revealed that a majority within the German business community has a positive view of the economic future in the country. Evidently, 62% of the participants are in a better situation than a year ago and 35% are in a satisfactory situation. 74% of respondents expect a positive business development, while none expect a deterioration. The three biggest risks are the shortage of skilled labor, supply chain disruptions and economic policy conditions.[24]

3.3. Investment climate

A series of reforms are intended to simplify entry for foreign investors. In 2018 the Ease of Doing Business and Efficient Government Service Delivery Act’ was introduced, which simplifies processes for businesses.[25] As of May 2023, most credit rating agencies give the Philippines a BBB rating. The current government opened access to the energy market to foreign investors, who are now allowed to own a 100% stake in renewable

[10] Helen Regan, Yasmin Coles, 2022.
[11] Sebastian Strangio, 2022.
[12] Ayman Falak Medina, 2022.
[13] The World Bank, year n/a.
[14] Department of Finance, 2024.
[15] Asian Development Bank, 2023.
[16] The World Bank, year n/a.
[17] European Commission, year n/a.
[18] Department of Trade and Industry, year n/a.
[19] Auswärtiges Amt, 2024.
[20] Germany Trade and Invest, 2022.
[21] Germany Trade and Invest, 2022.
[22] Destatis, 2024
[23] Auswärtiges Amt, 2024.
[24] German-Philippine Chamber of Commerce and Industry, year n/a.
[25] Anti-Red Tape Authority, Office of the President, year n/a.

projects.[26] These measures reinforce the fact that the Philippines is open to foreign companies and investors and recognize the need for modernization in the energy sector. The reform agenda also included the simplification of the tax system and the 'Public Service Act and the Retail Act'.[27] Foreign direct investment fell by 6.6% year-on-year, due to the fact that investors are cautious towards a subdued global economic growth and geopolitical risks.[28]

3.4. Socio-cultural characteristics

With an average age of 25.3 years, the Filipino population is very young and social media-savvy[29] and spends an average of 4 hours a day on social media platforms.[30] Companies therefore often use these platforms to promote products or services.

English is the language of business in the Philippines. In addition to English, Filipino (Tagalog) is the official language of the country. Filipinos are very relationship-orientated, which is why personal contact and communication in the context of business activities are very important. Thus, a great deal should be invested in cultivating relationships. Filipinos and Filipinas are personal and avoid confrontation, in contrast to the direct and factual business culture that prevails in Germany. 86% of the population is Roman Catholic, making the Philippines the only country in Asia that is predominantly Christian.[31]

4. Market information on the off-grid sector

Due to the archipelagic nature of the country, a standardized electricity grid for all islands is a difficult task. According to the DOE, there are 281 Small Island and Isolated Grid areas in the Philippines.[32] The southern part of the country, Mindanao, was only recently connected to the main grid of Luzon and Visayas. In addition to the topographical obstacles, the socio-economic situation of most rural areas means that the population in remote regions of the country is severely disadvantaged in terms of access to energy supply.

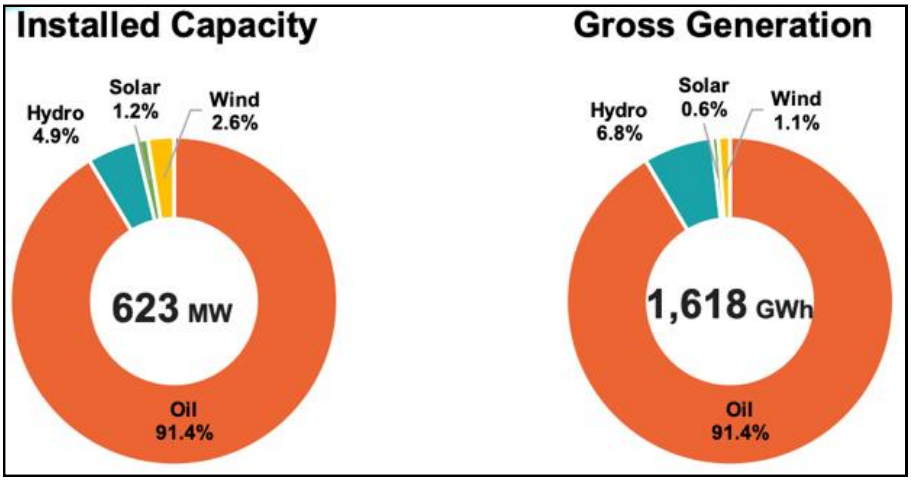

Figure 1: Energy mix of installed capacity and generation in off-grid, 2020

[26] Merkado Barkada, 2022.

[27] National Economic and Development Authority, 2019.

[28] Ian Nicolas P. Cigaral, 2024

[29] Philippine Statistics Authority, 2022.

[30] Statista, 2024.

[31] Jack Miller, year n/a.

[32] Department of Energy, 2020.

Table 1: Number of off-grid areas by consumption and supply hours, 2019 vs 2020.

Service Hours	2020		2019	
	No. of SIIGs	Demand, MW	No. of SIIGs	Demand, MW
5	134	1	134	1
8	49	2	48	3
12-16	11	2	20	5
24	87	266	77	293
TOTAL	**281**	**270**	**279**	**302**

Note: Numbers may not sum up to total due to rounding off.

The off-grid areas of the Philippines recorded a consumption of 1,481 GWh. The pandemic hit the commercial sector in these areas hard in 2020. They experienced a decline in electricity demand of 18.2% compared to 2019. The consumption share of private households remains the highest at 53% or 785 GWh, an increase of 9.8% compared to 2019.[33]

The total installed capacity on 281 small island and isolated grids increased by 18.5% from 526 MW in 2019 to 623 MW in 2020 (see Figure 1).[34] This is due to the additional capacity of the existing New Power Providers (NPP) and the National Power Corporation (NPC) Small Power Utilities Group. On the other hand, off-grid generation fell slightly from 1,623 GWh in 2019 to 1,618 GWh in 2020.[35] The energy mix in off-grid areas consists of just under 9% RE sources. These areas are largely supplied by diesel generators.

As part of the full electrification program, NPC supplied four new areas with electricity in 2020. In addition, NPC also increased its service level in various areas. Despite the developments in off-grid electrification, due to the COVID-19 pandemic, it led to a decline in electricity demand in 2020.

Table 1 shows that only about one-third of the areas are continuously supplied with electricity, whereas two-thirds are so-called under-served areas without continuous electricity provision with almost half of them supplied with electricity for five hours or less. This shows the high investment and diver-sification of energy sources needed to reach the stated goal of 100% electrification by 2026.[36]

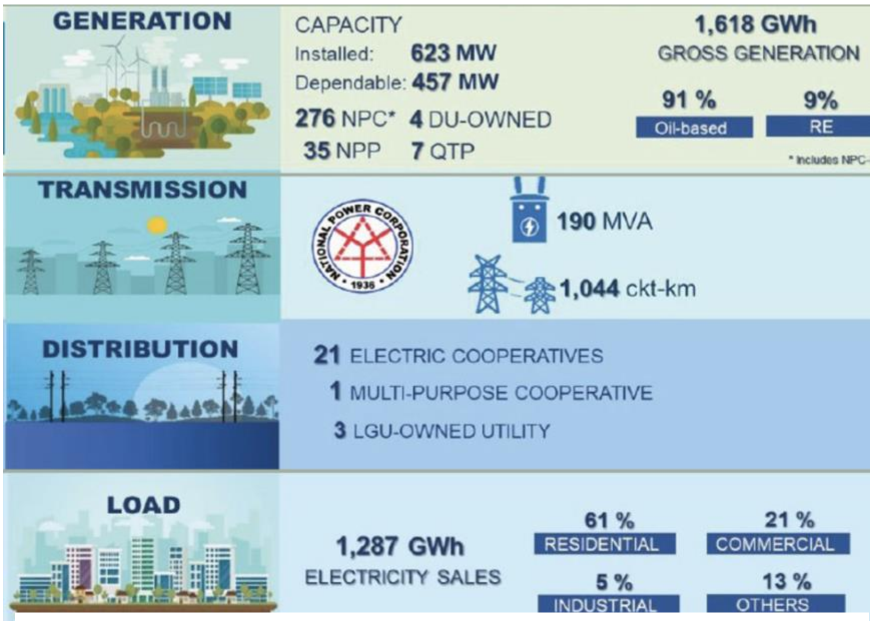

Figure 2: Overview of players in off-grid areas.

[33] Department of Energy, 2020.
[34] Department of Energy, 2021.
[35] Department of Energy, 2020.
[36] Department of Energy, 2023.

4.1. Overview of off-grid area stakeholders

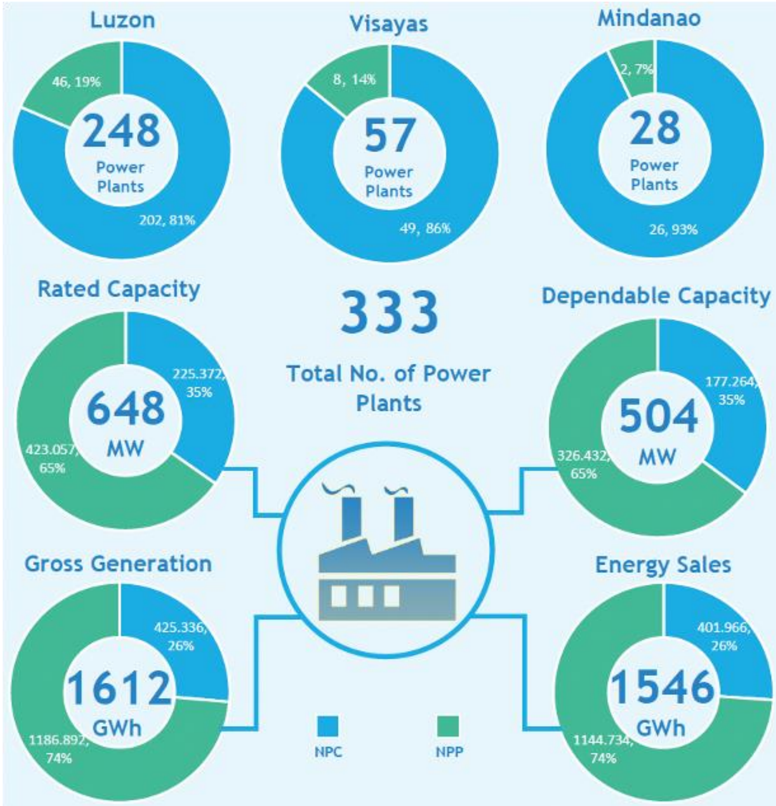

Figure 3: Overview of electricity generation in off-grid areas

Actors in off-grid areas can be grouped according to their functions: (1) policy-provision and regulation, (2) electricity generation, and (3) electricity transmission and distribution. Figure 2 and 3 give an overview.[37]

Policy and regulation

The Department of Energy (DOE) is responsible for ensuring energy security and promoting RE. It has sub-committees working on hydrogen and RE strategies. The National Electrification Administration (NEA) is responsible for supplying electricity to off-grid areas, promoting renewable energies and implementing the 'Rural Electrification Program'. The Energy Regulatory Commission (ERC) regulates the country's electricity industry, sets electricity tariffs, and monitors the quality and reliability of electricity suppliers. Microgrid Service Provider Organizations that specialize in the planning, design, installation, operation, and maintenance of microgrid systems.

Electricity generation

There are three different types of electricity generating entities in off-grid areas. The National Power Corporation (NPC), New Power Providers (NPP) and Qualified Third Parties (QTP).

NPC is a state-owned electricity supply company responsible for the generation and transmission of electricity in off-grid areas. The NPC Small Power Utilities Group (SPUG) was created by the NPC to take over the tasks of electrification in off-grid areas. In 2020, 276 off-grid areas were supplied by NPC-SPUG. The diesel generators operated by NPC-SPUG today are often old with low efficiency in power generation.[38]

There are also 46 off-grid areas which are supplied by the private sector, represented by New Power Provider (35) or Qualified Third Parties (11). NPPs are privatized electricity producers in off-grid areas that have built a new plant or have taken over existing plants from NPC-SPUG. QTPs refers to alternative private electricity suppliers, which operate in areas which were not previously served by NPC-SPUG. There are 11 QTPs in remote areas, 4 of which are operated as a hybrid energy system, using solar energy during the day and diesel power plants at night. With the other 7 QTPs, hybridization is also being sought after.

[37] Department of Energy, 2020.

[38] Michael Wollny, Bruno Willhelm, 2015.

Privatized NPP operators supply fewer areas than NPC-SPUG suppliers. However, the installed and secured capacity of NPP operators is greater as NPPs tend to supply areas with high electricity demand, whereas NPC SPUGs tend to supply areas with low electricity demand, where no privatized operator could be established (See Figure 4). NPC has started to hybridize some of the almost 270 diesel-powered plants with RE and is interested in further modernization.

Electricity transmission and distribution

There are three different types of distribution utilities (DU) in off-grid areas. A DU refers to an electricity co-operative (EC), a private company, a state-owned utility or an existing municipal entity that has an exclusive license to operate a distribution network in accordance with its license and the EPIRA.

ECs operate local distribution networks and are responsible for off-grid areas. There are a total of 21 cooperatives controlled by NEA. The electricity prices that the ECs collect are regulated and approved by the Energy Regulatory Commission.

Local Government Unit-owned Utility are operated by the municipality and supervised by DOE. There are a total of 3 municipally owned utilities. There is also one Multi-Purpose Cooperative that supplies electricity and is supervised by the DOE, too.

The Association of Isolated Electric Cooperatives is a group of electricity cooperatives in the Philippines, whose aim is to improve the supply of electricity in rural and remote areas of the country. Thus, it is committed to sustainable and affordable electrification solutions and provides support and representation for its member cooperatives.

Area	Genera. 2012 MWh*	Costs 2012 Th PHP**	True Costs 2012	Selling Rate 2012 PHP/KWh***	Predict 2020
1 Basco BATANES	5,378	75,555	14,04	6,59	34,27
2 Lubuagan KALINGA	722	11,942	16,52	5,76	40,10
3 Polilio QUEZON	5,511	76,720	13,92	6,59	33,50
4 Palumbanes CATANDUANES	20	439	21,56	6,59	48,92
5 Cabra MINDORO	47	937	19,80	5,75	42,11
6 Alad ROMBLON	106	2,976	28,03	6,59	67,90
7 Caluya LEYTE	1,433	27,066	18,89	6,84	41,94
8 Camotes CEBU	9,277	142,436	15,35	6,07	37,25
9 El Nido PALAWAN	5,397	80,599	14,93	6,59	37,79
10 Siquijor SIQUIJOR	18,206	281,932	15,49	6,07	n.a.
11 Talicud DAVAO D. NOR.	662	11,175	16,87	6,27	40,32
12 Basilan BASILAN	33,817	463,126	13,70	6,58	32,21
13 Manuk Mankaw TAWI TAWI	168	2,950	17,60	6,27	40,23

Figure 4: Overview and comparison of NPC SPUG's electricity generation costs and prices.

The areas within the concession area of an EC, that are classified as unprofitable by the cooperative, are generally not yet connected to an electricity distribution grid. In these areas, electricity is supplied, if at all, by privately operated diesel generators. However, this depends on whether a supply area is supplied by an EC via a local distribution network or whether this area has been declared unviable by the EC.[39]

4.2. Electricity Rates

To understand the electricity rates in off-grid areas a few terms need to be introduced. The true cost of generating electricity (TCGR) in unprofitable off-grid areas were typically between PHP 13 and 28/kWh in 2015 and have since risen further. However, the rate which is paid by end consumers, the so-called subsidized, approved electricity consumption rate (SAGR) is lower. Ecs charge their customers now around PHP9/kWh. The difference must be covered by the Universal Charge for Missionary Electrification (UCME), which is levied on all electricity consumers in the country. Figure 4 shows the differences between the true cost and the rate charged to end customers. [40]

4.3. Legal framework and government programs

The 'Electric Power Industry Reform Act' of 2001 (EPIRA)[41] is the basis for the creation of today's market-based energy system of the country. Further multiple government acts and bills specifically regulate the off-grid sector. The 'Microgrid System Bill' [42] of 2022 accelerates the electrification in unserved and underserved areas and reliable energy supply at reasonable tariffs through the installation of microgrid systems by accredited Microgrid Service Providers. ´The 'National Electrification Administration Reform Act' of 2013[43] aims to strengthen a national policy for complete electrification. The 'Missionary Electrification Development Plan' (MEDP)[44] is a government electrification program for off-grid independent areas. The agenda 'Total Electrification Program' (TEP)[45] aims to supply all households with electricity by 2040.

4.4. Current developments and market insights

As of 19 January 2023[46]: Due to high diesel fuel prices, Napocor's SPUG will reduce electricity services from February 1st, citing fuel shortages and delayed subsidy payments. This affects remote areas dependent on diesel generators. Napocor seeks alternative funding and plans to reduce power plant operations. It requests a P5-billion (€82.5) loan for fuel and urges Ecs for advance payments. NEA warns of a power crisis and instructs Ecs accordingly. ERC reviews Napocor's subsidy petitions, balancing interests of users in missionary areas and on-grid consumers subsidizing UCME.

According to active local experts in the off-grid market segment, entry is challenging due to the complex framework conditions. As described above, private players can apply as QTPs for areas tendered by DOE or take over franchise areas from Ecs. These are the areas that cannot be supplied by Ecs. The expert explained in an interview that these areas are put out to tender or are unattractive for Ecs because it is often uneconomical to develop them. For example, the area is topographically difficult or has only a few end users, making it difficult to develop. This means that the success of privatizing these difficult areas is limited.[47]

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[39] Michael Wollny, Bruno Willhelm, 2015.

[40] Michael Wollny, Bruno Willhelm, 2015.

[41] National Power Corporation, 2001.

[42] Official Gazette, 2022.

[43] Department of Energy, 2013.

[44] Department of Energy, 2021.

[45] Department of Energy, 2023.

[46] BusinessWorld, 2023.

[47] GPCCI Philippines, 2022.

It seems more promising to start with smaller projects, such as the hybridization of hotel complexes or other commercial players where one or a few end users are involved. There are two reasons for this[48]:

- Lengthy processes: The application as a QTP/ NPP via the relevant government agencies is very time-consuming. The registration of a small off-grid project of 50KW is as time-consuming as the registration of a 50MW project. The microgrid law, which was published in January 2022, aims to facilitate the processes, however the effects on implications are not clear yet.[49]
- Further outdated systems at NPC-SPUG: It is challenging to modernize existing government systems. These are already so technically outdated that they should be replaced. Above all, modernizations or even renewals are often viewed with skepticism. Experts have also reported that there are a few ECs that are open to testing out new technologies. This seems easier than via the public players.

There are only a few private players in the off-grid sector. According to the market experts, batteries also play a role, but the focus here is on cheaper Asian solutions. To date, the German company Tesvolt has also been active in the off-grid market.[50]

Also, due to the lack of coordination between the various government departments and the top-down approach of the government to electrification, progress is idle. In addition, the realignment of current initiatives and energy programs needed to pursue better access to electricity in unviable and unserved areas and self-interest of some industry players to maintain the status quo of electricity supply through diesel generators. Lastly there are some concerns about renewable energies due to insufficient involvement of local communities (LGUs).

5. Background on Green Hydrogen Technology

In off-grid areas, power supply predominantly relies on diesel generators operated by entities like the National Power Corporation (NPC), Independence Power Producers (IPPs) or makeshift barangay grids (localized community owned- and run electricity grids). While diesel generators are widely used for their operational flexibility, several drawbacks hinder their effectiveness. Power costs are heavily dependent on global oil prices, leading to escalating fuel costs in recent years. Moreover, diesel generators require high maintenance and often encounter technical issues, resulting in unreliable power supply. These systems also pose environmental concerns, contributing to greenhouse gas emissions, local pollution, and operational insecurity (see Figure 5).[51] Additionally, the limited operating hours of diesel generators exacerbate energy access challenges in off-grid communities.[52] To address these issues and transition towards a sustainable energy future, there is growing

[48] GPCCI Philippines, 2022.
[49] Official Gazette, 2022.
[50] GPCCI Philippines, 2022.
[51] Bertheau, 2013 and 2019.
[52] Bertheau, 2020.

Figure 5: Right: Non-operational diesel power barge after the explosion of a generator unit. Left: Remains of a makeshift barangay grid after damage due to over-charging.

motivation to adopt green hydrogen technologies on islands. Green hydrogen offers a clean, renewable alternative to diesel, mitigating the environmental impact while providing a reliable and secure energy supply. By leveraging abundant renewable resources, such as wind and solar, islands can produce hydrogen locally, reducing dependence on imported fossil fuels and promoting energy self-sufficiency.

Hydrogen technologies can be implemented in decentralized energy systems to produce, store and utilise hydrogen locally. The use of hydrogen technologies in decentralised energy systems has the potential to improve the flexibility and resilience of the energy system, and usually the technologies included are an electrolyzer for hydrogen production, a hydrogen storage tank for storing hydrogen with minimal losses and a fuel cell to convert hydrogen back into electricity. Hydrogen technologies are usually incorporated with RE sources, such as solar PV or wind, where the electricity supply is intermittent and likely to not match the electricity consumption. As a result of this, there will be times with excess electricity generation when the consumption is low, and times of consumption needs when electricity production is low or non-existent. By incorporating hydrogen technologies, the excess electricity generation can be utilised to generate hydrogen through electrolyzis.

Additionally, to electricity, water availability is required for the hydrogen generation. However, in an energy system with an electrolyzer and a fuel cell with a closed water circuit, the water that is produced by the fuel cell in the re-electrification process can supply the water demand of the electrolysis in very large parts. Without any significant water consumption, self-sufficient hydrogen systems are therefore ideal for use in in regions with water shortages.

The hydrogen is stored in tanks or other material (e.g., metal hydride), and has the possibility to be stored over a long period of time because of minimal storage losses. When electricity is required, hydrogen is reconverted to electricity using a fuel cell.

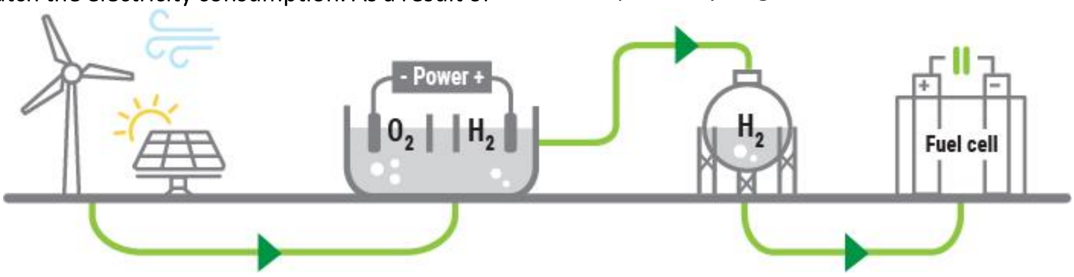


Figure 6: Green hydrogen in off-grid application (Source: New York ISO, 2021).

6. Methodology

6.1. Modelling tool

For assessing the feasibility of each case study, an energy system simulation and optimisation tool was developed and applied - namely, the Multi-Vector Simulator (MVS). The MVS is an open source tool that aids long-term investment planning by considering different energy system components (e.g. photovoltaics, wind power, battery storage, hydrogen electrolyzer, fuel cell, etc.) as well as their dispatch, and providing an initial recommended energy system configuration. The main goals of the MVS are:

- To minimize production costs of energy generation components by determining the optimal output to meet the total demand
- To optimize the invested capacities of energy generation and storage components with the least possible cost of energy

6.2. Structure of the MVS

The workflow of the MVS is represented as a flow chart (see Figure 7). The workflow can be understood as containing three distinct model steps:

Inputs

All data (project description, energy consumption and system configuration) are defined here by the users. Notably, the specific energy production time series of renewable resources as well as demand data must have been previously generated by an external tool in order to be used as an input for the MVS. This input is defined using CSV files.

System model

The MVS then processes and validates the input parameters and carries out the simulation of the energy system, which is based on the open source programming framework oemof-solph.

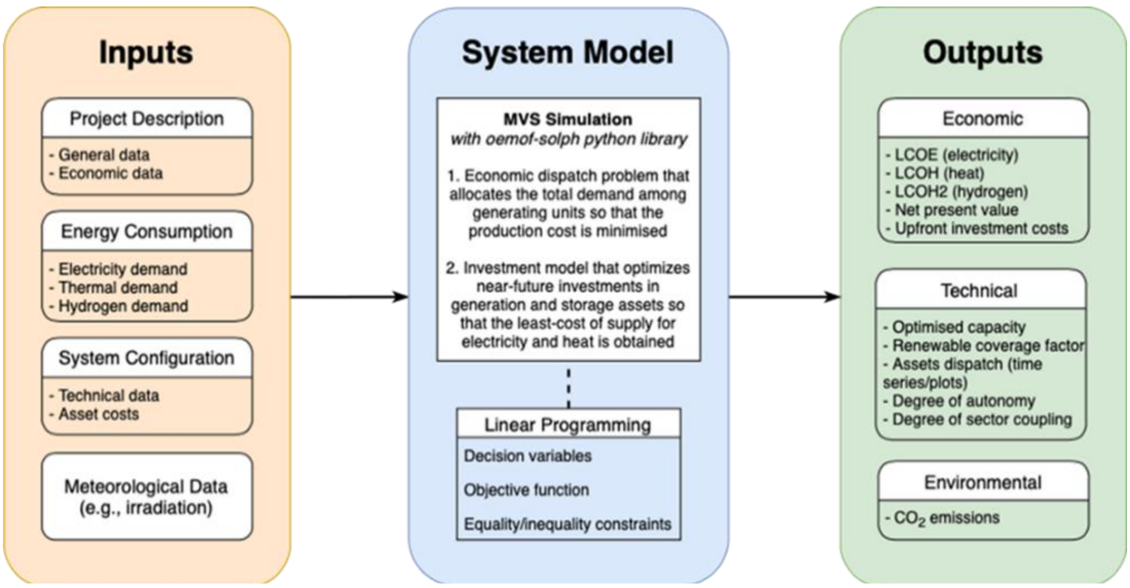


Figure 7: Flow diagram of MVS.

The main objectives of the simulation are to minimize the annual cost of meeting electricity demand and to optimize investments in generation and storage facilities while minimizing energy costs. Additional criteria such as minimum shares of renewable energies or maximum permissible emissions can be applied and stored in the MVS by the users.

Outputs

The MVS evaluates the simulation results by calculating the key performance indicators (KPIs) of the optimized energy system. These KPIs can be divided into technical, economic and environmental indicators and provide an overview of the optimized energy system. These are presented and evaluated for the individual case studies.

6.3. Limitations

Within the MVS, the energy system components are represented with linear component models, as the cost minimization equation is a linear problem. For example, diesel generators have an efficiency that does not depend on the load, storage systems have a charging efficiency that is independent of their state of charge (SOC), and electrolyzers are assumed to operate without ramp-up times and are modelled with one input (electricity), one output (hydrogen) and a constant efficiency. At present, water consumption is not taken into account, nor how much oxygen is produced as a potential by-product. Only CAPEX, fixed OPEX and variable costs are considered: all other costs, such as water costs, equipment transportation costs, water filtration costs, etc., are not included in the model. The reason for this is that the MVS is a tool for preparing pre-feasibility analyses. In pre-feasibility analyses, the use of simplified component models is common practice, especially for complex systems such as an electrolyzer. A pre-feasibility analysis enables a quick and preliminary assessment of the feasibility of a project, and provides valuable insights at an early stage as to which configuration of an energy system might be of interest. From a modelling perspective, the simplification of components also enables a quick assessment. After gaining an initial understanding of potential energy system designs through the pre-feasibility analysis, a much more detailed cost, performance and risk analysis should be carried out. The following link provides more information on how the MVS works and how to use it:

- https://github.com/rl-institut/multi-vector-simulator (GitHub)
- https://multi-vector-simulator.readthedocs.io/en/latest/index.html

6.4. Other tools

The online tool "Renewables.ninja"[53] was used to calculate the hourly electricity generation of PV and wind systems for the applied case studies. The tool takes into account weather information and data, particularly solar radiation at specific locations, and converts it into electricity generation using the Global Solar Energy Estimator (GSEE) model[54]. The chosen coordinates correspond to the location of the case studies and the optimal tilt and azimuth angles were calculated based on these coordinates.

6.5. Techno-economic data

As already described, the MVS requires a range of input parameters for the energy system simulation and optimization. The following table provides an overview of the assumptions made, which were applied to all case studies. The capital expenditures (CAPEX) are to be understood as investment costs for the energy system components, while the operational expenditures (OPEX) represent the operation and maintenance costs.

[53] https://www.renewables.ninja/

[54] Stefan Pfenninger and Iain Staffell, 2016

Table 2: Overview about techno-economic parameters.

Component	Parameter	Unit	Value	Source
System	Interest rate	%	10	Info from NPC
PV	CAPEX	EUR/kWp	1,100	E4tech for NOW[55]
	OPEX	EUR/kWp/a	14,3	
	Lifetime	a	30	
Wind	CAPEX	EUR/kWp	1,000	E4tech for NOW
	OPEX	EUR/kWp/a	40	
	Lifetime	a	20	
Diesel generator	CAPEX	EUR/kW	660	E4tech for NOW
	OPEX	EUR/kWh	19.8	
	Lifetime	a	10	
	Emission factor	kgCO2eq/L	2.7	Jakhrani et al.[56]
Battery storage	CAPEX	EUR/kWh	314	E4tech for NOW
	OPEX	EUR/kWh	7.85	
	Lifetime	a	15	
	State of Charge minimal	%	20	
	State of Charge maximal	%	80	
	C-Rate	-	1	
	Charge/Discharge effi.	%	87	
H_2 storage	CAPEX	EUR/kgH2	350	E4tech for NOW
	OPEX	EUR/kgH2/a	7	
	Lifetime	a	20	
	Charge/Discharge effi.	%	100	
Electrolyzer	CAPEX	EUR/kWp	610	E4tech for NOW
	OPEX	EUR/kWh	18.3	
	Lifetime	a	20	
	Efficiency	%	60	
Fuel cell	CAPEX	EUR/kWp	870	E4tech for NOW
	OPEX	EUR/kWp/a	22.2	
	Lifetime	a	20	
	Efficiency	%	50	

6.6. Scenarios applied

In order to compare different energy system designs and situations, the following scenarios are calculated and analysed for all four case studies:

- **Business-as-usual (100% diesel):** In order to analyse which energy system setup can bring advantages for the operators, the status quo must first be understood. This scenario attempts to map the current electricity supply (diesel only) in the case studies as realistically as possible.

[55] E4tech Sàrl, 2023

[56] Jakhrani, Abdul & Rigit, Andrew & Othman, Al-Khalid & Samo, Saleem & Kamboh, Shakeel, 2012

- **100 % renewable energies (H2):** In this scenario, 100% of the electricity supply is to come from renewable energies. Furthermore, only hydrogen components (electrolyzer, H_2 storage, fuel cell) are allowed for integration.
- **95% RE share (H2):** Similar to scenario 2, but RE share is set to 95% to understand the cost differences of high (95%) and full (100%) renewable scenarios.
- **100% RE share (battery storage):** In this scenario, 100% of the electricity supply comes from renewable energies. However, only battery storage is considered as energy storage. The scenario is intended to provide information on the economic viability of hydrogen storage compared to battery storage.
- **Cost optimization (technology agnostic):** The cost optimization scenario aims to determine the most economical solution for potential investments in renewable technologies for the case studies, taking into account factors such as site-specific RE potential and investment costs. Considered technologies are solar (Lubang, Maripipi), wind (Calayan), diesel, battery storage and hydrogen storage.
- **Cost-optimization (H_2):** Similar to scenario 5 but battery storage is excluded. The scenario serves to understand the role of hydrogen in a pure cost optimization.

6.7. Sensitivity analysis

The results from the energy system simulations and optimizations are heavily dependent on the selected input parameters and can change significantly in the event of fluctuations, e.g. in the price of diesel or the investment costs of a system component. Sensitivity analyses are conducted to minimize the uncertainty of how price fluctuations will impact the system and test the robustness of the optimal system design. For each case study, a sensitivity analysis is performed on the cost optimization scenario (scenario 5). The parameters that are the largest contributors to the total annuity of the energy system are chosen for the analysis, and price fluctuations of an increase of +25% or a decrease of -25% are considered alongside the original assumed costs. A sensitivity analysis is also conducted for the interest rate. Here two scenarios with a lower interest rate of 7% and 4% are studied.

6.8. Key Performance Indicators

In order to evaluate the performance of simulated energy system and facilitate comparisons between different scenarios for the case studies, the MVS calculates key performance indicators (KPIs). The main KPIs assessed in this study include:

- **Levelized cost of energy (LCOE):** The levelized cost of energy of the sector-coupled energy system, considering the total annuity and total demand (presented in EUR/kWh and PHP/kWh).
- **RE (RE) share:** The share of the total supply from RE generated within the local energy system.
- **Annuity:** The annuity of the asset costs over the project lifetime.
- **Upfront investment costs:** The costs which will have to be paid upfront when the project begins (year 0).
- **Excess electricity generation:** The percentage of generation not used within the local energy system (either exported or unused).
- **Power capacity:** Capacities of energy system components expressed in kW/MW (power generators), kWh/MWh (energy storage) and kg H_2 (hydrogen storage).

7. Feasibility Study results

7.1. Case study islands

Four islands were selected for this case study analysis: Calayan, Lubang Maripipi, and a private resort in Palawan. Figure 8 provides and overview about off-grid islands in the Philippines and shows the location of the three case study islands run by NPC. Prior to the selection of the case study islands, a consultation with the main stakeholder of this study, the NPC, was conducted.

In this consultation it was agreed that the case study islands shall reflect the geographic, demographic and economic diversity of Philippine off-grid islands. The three islands were then jointly selected from a short list provided by NPC. Table 3 provides an overview about population, peak demand, customers and main renewable source per case study islands.

Lubang and Maripipi represent islands with a good solar resource availability since both are located in the Central Philippines, where wind resources are rather low and show a high seasonal variation. Calayan instead is located at the Northern tip of the country and is located in a region with higher wind resource availability. To reflect both solar and wind potential, Calayan was included as a case study island. Lubang is the largest island in terms of population (>10,000 population), peak demand (> 1MW), and customers (>5,000 households) and is representative for a number of mid-sized off grid islands. Maripipi instead represents a typical smaller type of islands. In the country, there are a large number of islands with similar characteristics, which are currently supplied with diesel generators only for few hours per day. Calayan instead is comparable in population to Lubang but more similar to Maripipi in terms of peak demand and customers. This indicates a large supressed demand which is currently probably catered by individual or household power supply solutions (e.g. solar-home-system, small generator) if ever.

The private resort in Palawan was analysed as well to compare the results with the three islands run by NPC.

Figure 8: Overview map of off-grid power supply in the Philippines.

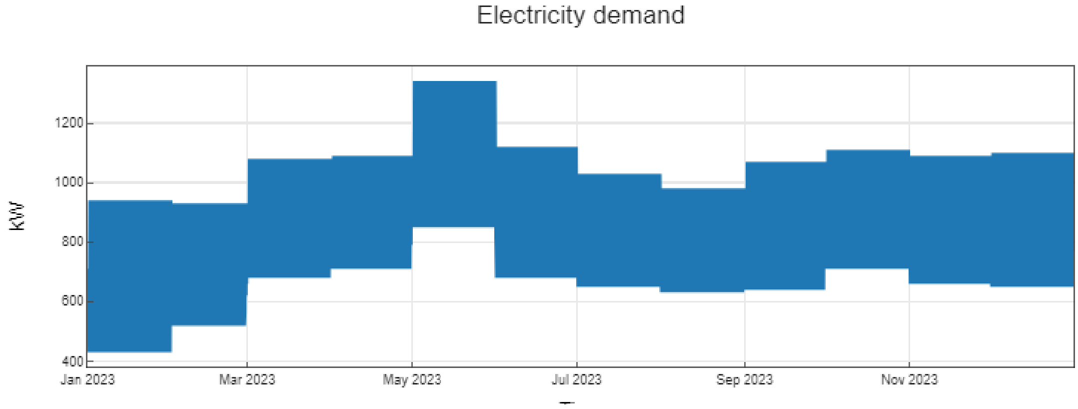


Figure 9: Annual load profile for Lubang island.

Table 3: Characteristics of case study islands

Case study island	Popu-lation	Peak demand	Custo-mer (HH)	Main RE source
Lubang	17,430	1.3 MW	6,700	Solar
Maripipi	6,300	276 kW	1,550	Solar
Calayan	17,410	247 kW	1,350	Wind

Power supply on off-grid islands is provided by generation companies such as the National Power Corporation and distributed to the customers through electric cooperatives or other distribution utilities. Furthermore, the electricity tariffs are heavily subsidized in missionary electrification areas and regulated by the Energy Regulatory Commission. The ERC defines a Subsidized Approved Generation Rate for each so called missionary electrification area. Subsidization is necessary to allow a larger part of the often-poor population on remote islands access to power supply. However, the SAGR are usually far below the True Cost Generation Rate which leads to a deficit. This deficit is compensated by the Universal Charge for Missionary Electrification which is charged from customers in the large island areas (e.g. from the National Capital Region). However, the UCME burdens national funds and is affected by global economic trends and global crisis (e.g. fluctuations in crude oil prices). Generally, it can

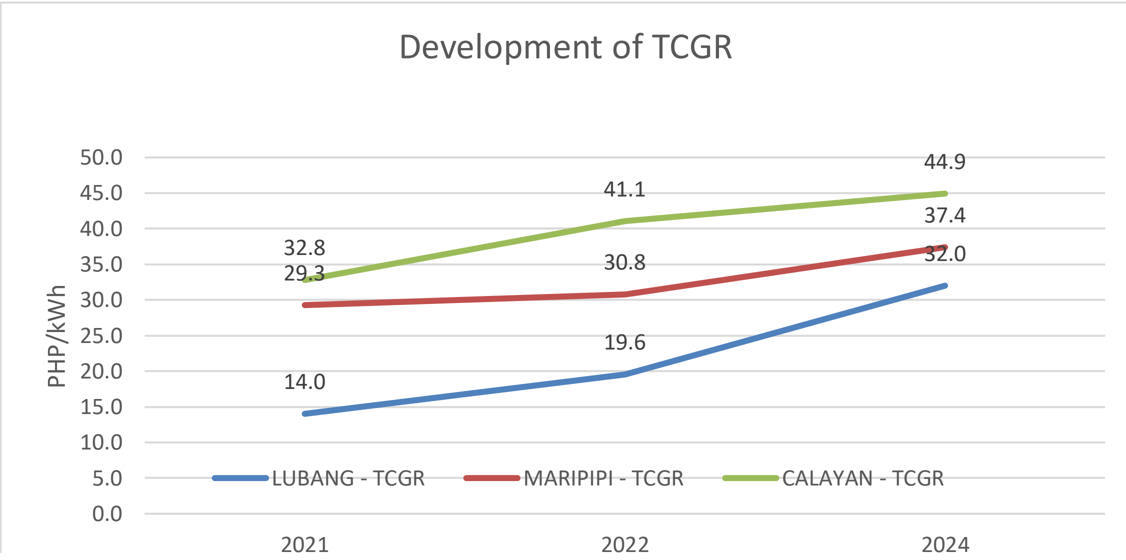


Figure 10: Development of TCGR for case study islands.

be observed that TCGR on islands with smaller demand are higher than on islands with larger demand due to lack of economies of scale. Global Oil cost developments have significant influence on the TCGR. As an example, the share between fuel and fixed costs of TCGR increased significantly between 2021 and 2022. The 2021 average was 56% of costs for fuel, 2022 average of 75% of costs for fuel.

Similar development can be observed for the case study islands as provided in Figure 10: The TCGR increased substantially since 2021, but the SAGR can only be increased moderately because otherwise poor households are deprived from power access.

Table 4: Estimation of diesel fuel landing costs.

Location	TCGR (PHP/kWh)	Fuel cost (PHP/kWh)	Diesel cost (PHP/l)	Diesel cost (EUR/l)
Lubang	32.01	24.01	75.11	1.23
Maripipi	37.41	28.05	87.78	1.44
Calayan	44.93	33.70	105.44	1.73

For the case study islands, it was only possible to collect the projected 2024 TCGR in PHP/kWh as no diesel landing costs could be provided by NPC. Therefore, diesel land costs were derived from the TCGR. We applied a share of 75% of the NPC. We assume an average diesel generator efficiency of 0.33 l/kWh as standard value. This results in diesel costs on site in a range between 75 PHP/l Lubang to 105 PHP/l Calayan. Diesel costs are then applied to energy system model as input parameter.

7.2. Lubang island

The first case study island Lubang is located in the North-western Philippines between the main island of Luzon and Mindoro (one of the largest "off-grid" islands) compare Figure 8. Lubang is part of the Occidental Mindoro province and as such located in the MIMAROPA region. Currently, power is provided by NPC and then distributed through the Lubang Electric Cooperative (LUBELCO) (local grid operator). LUBELCO and NPC have a power supply agreement with a minimum capacity of 1.77 MW. Nevertheless, NPC has several generator units installed on-site summing up to a total capacity of 4.9 MW and 2.8 MW dependable capacity. A 300 kW RE project is planned by LUBELCO but no detailed information is provided. As of 2023 more than 7,139 MWh were consumed. The largest group of consumers are residential customers with 62%, followed by commercial customers with 20%, industrial with 4% and other with 14%.

Electricity demand and Solar PV resources

NPC provided one load profile per month. From this data, an annual load profile was comprised (see Figure 10). This means that for each month only one specific daily load profile was applied. No demand increase was considered due to the large uncertainty of the potential demand

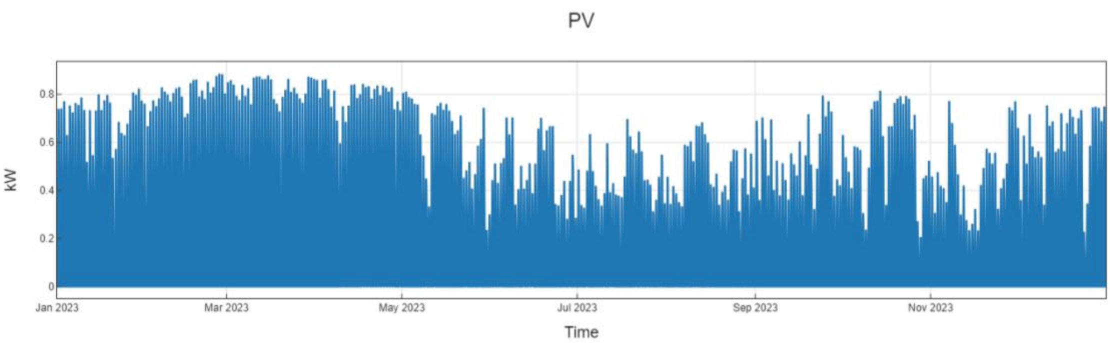


Figure 11: Solar yield curve in kW/kWp for Lubang island.

increase. The main characteristics of the annual load profile are as follows:

Table 5: Consumption characteristics Lubang.

Parameter	Unit	Value
Peak demand	MW	1.3
Mean demand	kW	815
Annual consumption	MWh	7,139
Peak month	-	May

Figure 11 illustrates the specific PV potential over the course of a year; the annual potential is high at 1,663 kWh/kWp/a (compare Berlin 1,068 kWh/kWp/a). Seasonality can be observed from the feed-in curve, with the lowest generation occurring from June to August.

Simulation results

In the following, the simulation results for the six scenarios are presented. Table 6 provides an overview about the main economic key performance (KPI) indicators per scenario. These KPIs are levelized cost of electricity (LCOE) expressed in EUR/kWh and PHP/kWh, RE share, annual annuity costs in EUR/year, upfront invest costs in EUR and excess electricity in MWh.

The results indicate that the status quo of pure diesel power supply (scenario 1) is very costly with 0.424 €/kWh. These costs are only exceeded by the 100% RE scenario with battery storage (scenario 4) which leads to costs of 0.553 €/kWh. The most significant power cost reduction can be achieved through the implementation of renewable capacities up to a share of 63% with 0.292 €/kWh (scenario 5), a cost reduction of 31% per kWh compared to the cost of pure diesel power supply.

Table 6: Economic simulation results for Lubang.

Sc.	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Excess Elec. (MWh)
1	Business-as-usual (100% diesel)	0.424	25.44	0	3,027,495	0[57]	0[58]
2	100% RE (H2)	0.400	24.00	100	2,862,209	21,293,176	6,948
3	95% RE (H_2)	0.349	20.94	~95	2,498,914	17,534,506	4,469
4	100% RE (battery)	0.553	33.18	100	3,950,177	25,606,813	15,024
5	Cost-optimization (technology agnostic)	0.292	17.52	63	2,087,551	10,129,304	473
6	Cost-optimization(H2)	0.302	18.12	54	2,160,798	8,584,288	438

Table 6 highlights the necessary power technology capacities to achieve the cost reductions. A significant increase in solar capacity is required for all scenarios ranging from 14.3 MW in 100% RE scenarios (No. 4) to 5.3 MW in scenario 6.

[57] No upfront investments are considered for the BAU-scenario since the diesel generators are already installed on site and no information of NPC was provided regarding potential depreciation costs.
[58] No excess electricity is applied for the BAU-scenario since it is assumed that the diesel generators can be operated according to the load.

Table 7: Technical simulation results for Lubang.

Sc.	Name	LCOE (€/ kWh)	LCOE (PHP/ kWh)	RE share (%)	PV (kW)	Electro -lyzer (kW)	Fuel Cell (kW)	H_2 Sto-rage (kGH_2)	Batt. Stor. (kWh)	Diesel (kW)
1	Business-as-usual (100% diesel)	0.424	25.44	0	0	0	0	0	0	4,904
2	100% RE (H_2)	0.400	24.00	100	13,667	5,592	1,340	4,805	0	0
3	95% RE (H_2)	0.349	20.94	~95	11,567	5,002	1,080	1,737	0	320
4	100% RE (battery)	0.553	33.18	100	14,370	0	0	0	31,209	0
5	Cost-optimization (technology agnostic)	0.292	17.52	63	5,438	1,896	388	3,345	6,780	617
6	Cost-optimization (H_2)	0.302	18.12	54	5,300	2,643	520	420	0	820

Business-as-usual (100% diesel)

The costs for supplying power with diesel generators is very high with more than 0.424 EUR/kWh. Additionally, we have assumed a fix efficiency rate of 33% per diesel generator, which probably overestimated the efficiency since generators are likely operated part-load under the fluctuating demand. Therefore, costs are likely to be underestimated and in addition no future fuel price increases and load growth was considered which might further increase costs through more diesel fuel consumption or larger capacities required. Overall, the current power supply leads to a consumption of more than 2.28 million liters diesel annually and requires more than 2.8 million EUR for fuel costs only. This comes with emissions of more than 6.1 million kg CO2eq annually.

100% RE (H_2)

100% RE supply with solar PV and hydrogen as the exclusive energy storage option can be realized at slightly lower costs than the current diesel power supply (compare 0.42 EUR/kWh to 0.40 EUR/kWh). However, a large upfront investment of more than 21 million EUR would be required. This would be necessary in order to install capacities of more than 13.6 MW solar PV, 5.5 MW electrolyzer capacity, 1.3 MW fuel cell capacity and a H_2 storage of 4.8 t. Annually more than 236 tons of H_2 is produced which consumes roughly 2.1 million liters of water (9 l H2O per kg H2). In case of an energy system with a closed water and hydrogen circuit, meaning that the hydrogen is not leaving the system for consumption in another place and is only used for re-electrification within the fuel cell ($2\ H_2 + O_2 \rightarrow 2\ H_2O$), the regained water can be re-used for the electrolysis process ($2\ H_2O \rightarrow 2\ H_2 + O_2$). The downside is that the electricity excess exceeds the demand as the system needs to be designed for the "worst" periods with regard to resource availability, which leads to overcapacities during most periods of the year. This excess could be utilized for further H_2 generation or to power beneficial applications, as there is a potential to generate another 56.9 tonnes H_2 annually with the installed electrolyzer. Assuming H_2 price of 10 PHP/kg this could lead to H_2 revenues of 569,000 PHP annually. Alternatively, excess electricity could be utilized to power community based cold storage facilities, water purification or water desalination plants.

95% RE (H_2)

The 95% RE share scenario serves to understand the additional effort in terms of cost to reach a full decarbonisation. Since a small and flexible diesel generator (320 kW) is still part of the system less capacities are required for solar PV, electrolyzer, fuel cell but especially for the hydrogen storage. As a consequence, less excess power is generated and the overall system has lower LCOE.

100% RE (battery)

Achieving 100% RE with battery storage is the most expensive power system studied with LCOE of 0.55 EUR/kWh even exceeding the costs of pure diesel generation. High costs are a result of the seasonality of solar resources, which requires the installation of large battery capacities only to cater few periods of the year. In addition to that, a large amount of electricity is not used.

Cost-optimization (technology agnostic)

The cost optimization scenario reveals that an energy system based on PV and battery storage with H_2 and diesel generator as back-up is the most affordable system with 0.292 €/kWh (17.5 PHP/kWh) (saving of 0.1 €/kWh vs BAU). Under these system configurations, a relatively high RE share of 63% is achieved. However, an upfront investment of 10.1 million € (606 million PHP) is required.

Cost-optimization (H_2)

A cost optimization considering solar PV in combination with hydrogen components leads to slightly higher LCOE of 0.30 EUR/kWh and a smaller RE share of 54%.

Sensitivity analyses – interest rates

In the first sensitivity analysis, we study the effect of capital costs on the 100% RE H_2 scenario (scenario 2) and the cost-optimized scenario (scenario 5). Initially, we have applied an interest rate of 10% as the project stakeholders communicated this as a likely applicable capital cost value. Costs for loans have a significant impact on the feasibility of RE and green hydrogen projects given the necessity of large initial investments in contrast to comparable low operational costs with increasing RE shares. Therefore, we have studied the effect of a decrease of the capital interest rates to 7% and 4%. The sensitivity analysis shall reveal the feasibility of RE in combination with hydrogen storage systems under more favourable financing conditions.

Table 8: Sensitivity analysis for capital costs on Lubang 100% RE H_2 scenario – economic KPIs.

Int. rate	Name	LCOE (€/ kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Excess Elec. (MWh)
10	**100% renewable (H_2)**	0.400	24	100	2,862,209	21,293,176	6,948
7	**100% renewable (H_2)**	0.332	19.92	100	2,371,028	21,295,513	6,985
4	**100% renewable (H_2)**	0.270	16.2	100	1,927,813	21,300,759	7,053

Table 9: Sensitivity analysis for capital costs on Lubang 100% RE H_2 scenario – technical KPIs.

Int. rate	Name	LCOE (€/ kWh)	LCOE (PHP/ kWh)	RE share (%)	PV (kW)	Electro -lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kgH_2)	Battery storage (kWh)	Diesel (kW)
10	**100% renewable (H_2)**	0.400	24	100	13,667	5,592	1,340	4,805	0	0
7	**100% renewable (H_2)**	0.332	19.92	100	13,689	5,574	1,340	4,775	0	0
4	**100% renewable (H_2)**	0.270	16.2	100	13,730	5,540	1,340	4,719	0	0

Table 8 and Table 9 highlight the impact of lower capital costs on the 100% RE H_2 scenario (scenario 2). Lower capital costs decrease the LCOE significantly to 0.332 €/kWh (7%) and 0.270 €/kWh (4%). This is possible because the annual expenditures for lending capital can be decreased by almost 0.5 million € annually (7%) or even by almost 1 million € per year (4%). This highlights the importance and necessity of loans and finance products with lower return expectations and longer lifetimes to realize a sustainable energy supply. Since the constraint of the scenarios is a 100%, RE supply the energy system design is no affected significantly. However, lower capital costs favour slightly larger investments in solar capacities with the effect of a smaller electrolyzer and H_2 storage size and more electricity excess.

Table 10 and 11 show the results for lower capital costs in the cost-optimized scenario. Here we can clearly observe the favourable effect of lower interest rates on RE investments: The RE share increases from 63% (10% interest rates) to 81% (7% interest rate) and even 88% (4% interest rate). This highlights that with slightly lower capital costs energy system configurations with very high shares of RE like 81% in the 7% scenario are competitive compared to the high diesel costs in the Philippines. The LCOE and annuity costs are decreasing with lower interest rates whereas the upfront investment increases from 10 (10%) to 14. 3 (4%) million € but can be compensated by lower operational expenditures (OPEX) due to larger renewable capacities.

Table 10: Sensitivity analysis for capital costs on Lubang cost-optimized scenario – economic KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Excess Elec. (MWh)
10	**Cost-optimization (technology agnostic)**	0.292	17.52	63	2,087,551	10,129,304	473
7	**Cost-optimization (technology agnostic)**	0.255	15.3	81	1,826,320	12,851,444	1,152
4	**Cost-optimization (technology agnostic)**	0.213	12.78	88	1,523,369	14,339,513	2,095

Table 11: Sensitivity analysis for capital costs on Lubang cost-optimized scenario– technical KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/kWh)	RE share (%)	PV (kW)	Electro-lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kgH_2)	Battery storage (kWh)	Diesel (kW)
10	**Cost-optimization (technology agnostic)**	0.292	17.52	63	5,438	1,896	388	335	6,780	617
7	**Cost-optimization (technology agnostic)**	0.255	15.3	81	7,116	2,521	552	479	8,079	454
4	**Cost-optimization (technology agnostic)**	0.213	12.78	88	8,300	2,785	588	859	7,786	381

Sensitivity analyses system components

Furthermore, the effect of varying system component costs on the overall economic feasibility needs to be studied to understand the robustness of the results. Initially, we studied the share of the single system components on the overall annuity based on the cost-optimization scenario (scenario 5) (Figure 12).

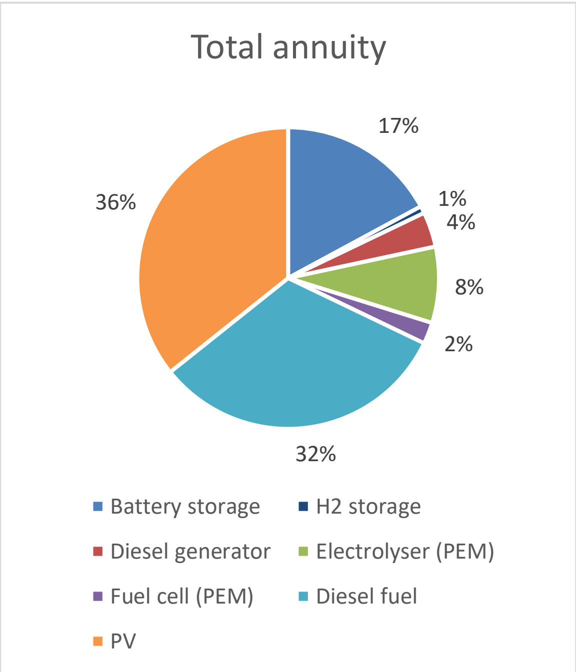


Figure 12: Share of system components to total annuity - Lubang

The analysis of annuity costs shows that PV (36%), diesel fuel (32%) and battery storage (17%) are the largest contributors to the total annuity costs. Therefore, a sensitivity analyses are conducted for PV CAPEX, diesel fuel price and battery CAPEX. A range -25%, 0%, 25% of the costs is applied (Table 12).

Table 12: Overview about applied scenario inputs for Lubang.

Sensiti-vity scenario	PV CAPEX (EUR/ kWp)	Diesel Fuel price (EUR/ liter)	Battery CAPEX (EUR/ kWh)
-25%	825	0.92	235.4
Base scenario	1,100	1.23	314
+25%	1,375	1.53	392.5

The effect of a cost decrease and increase of 25% for the PV components is highlighted in Figure 13 and Figure 14 Lower costs of 825 EUR/kWp (-25% scenario) reduce LCOE from 0.292 EUR/kWh to 0.266 EUR/kWh and make a RE share of already 73% profitable. An interesting effect can be observed on the system components: Lower PV costs facilitate larger H_2 capacities (electrolyzer, H_2 storage, fuel cell) as it becomes more profitable to store PV power in H_2 storage than in the battery. Given that costs for PV components are projected to further decrease.

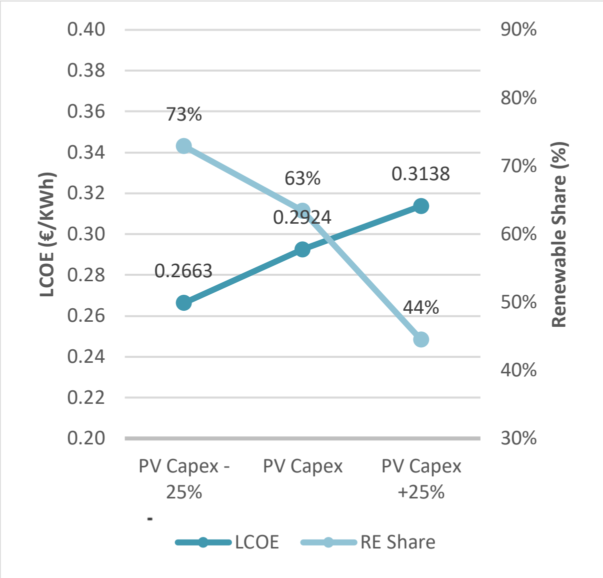


Figure 14: Effect of PV CAPEX on LCOE and RE share.

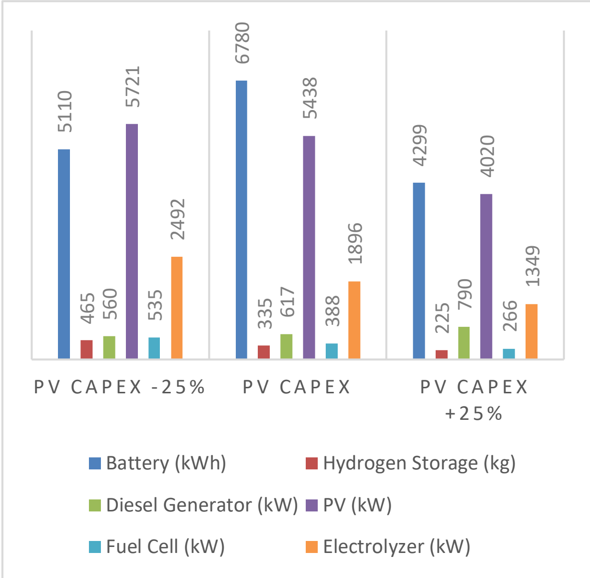


Figure 13: Effect of PV CAPEX on system components

Varying diesel fuel prices have a significant impact on the system design. With lower diesel fuel costs of 0.92 EUR/liter (-25%) the RE share decreases to 27%. In this scenario, solar power is mainly used for direct consumption during noon and only minor parts are stored. The findings highlight a tipping point between 0.9 and 1.2 EUR/liter. However, decreasing diesel fuel costs are not very likely. Much more likely is a further increase of up to 1.5 EUR/liter, which is already the case in other islands. For Lubang the RE share increases to 82% with a 25% increase in fuel costs. Diesel fuel price sensitivities are provided in Figure 15 and Figure 16.

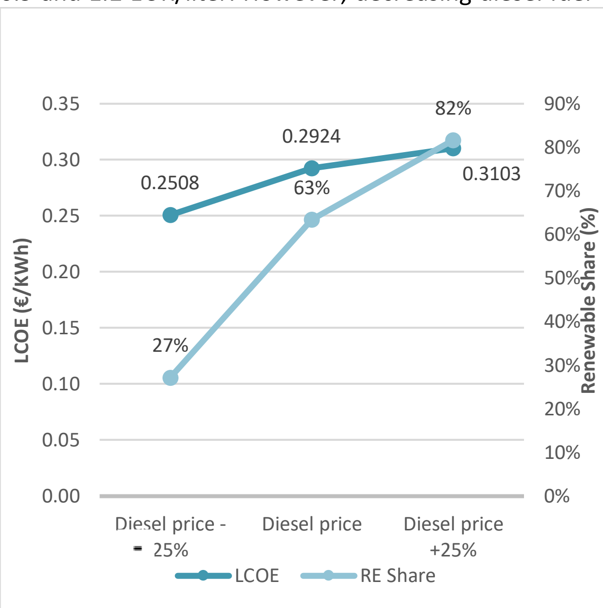


Figure 15: Effect of diesel price on LCOE and RE share.

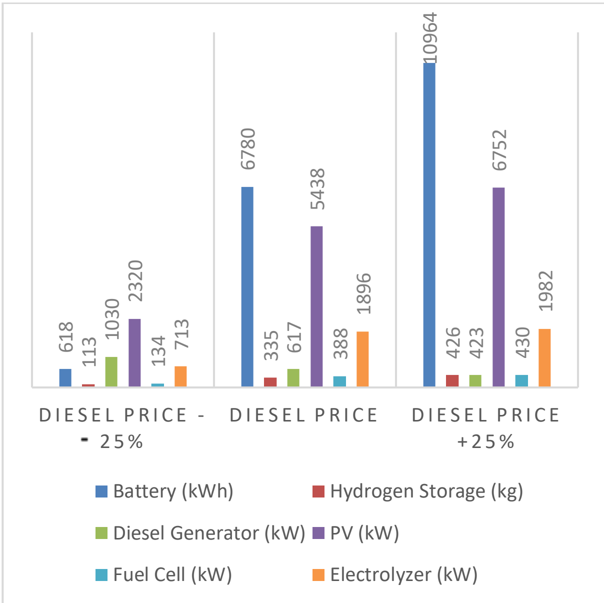


Figure 16: Effect of diesel price on system components

Battery CAPEX have the lowest impact on costs and RE share, but a significant effect on the system design (compare Figure 17 and Figure 18). Lower battery CAPEX allow for a larger battery capacity, which reduces the amount of excess electricity and returns lower LCOE. With higher battery CAPEX hydrogen as energy storage becomes more cost-effective and almost completely replaces battery storage as energy storage. Hence a tipping point for the cost-effectiveness of hydrogen components compared to battery storage lays between the narrow scale of 314 EUR/kWh and 390 EUR/kWh.

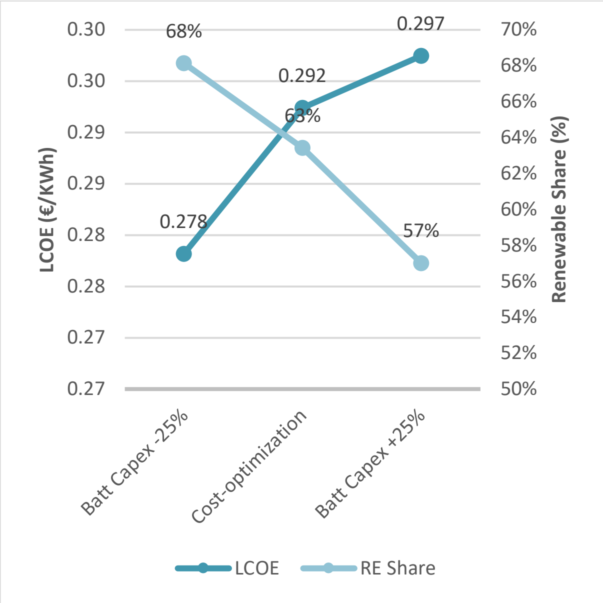


Figure 17: Effect of Battery CAPEX on LCOE and RE share.

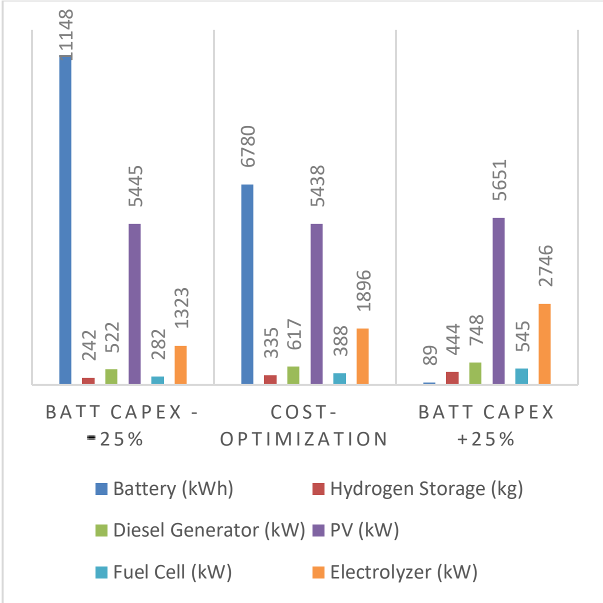


Figure 18: Effect of Battery CAPEX on LCOE and RE share.

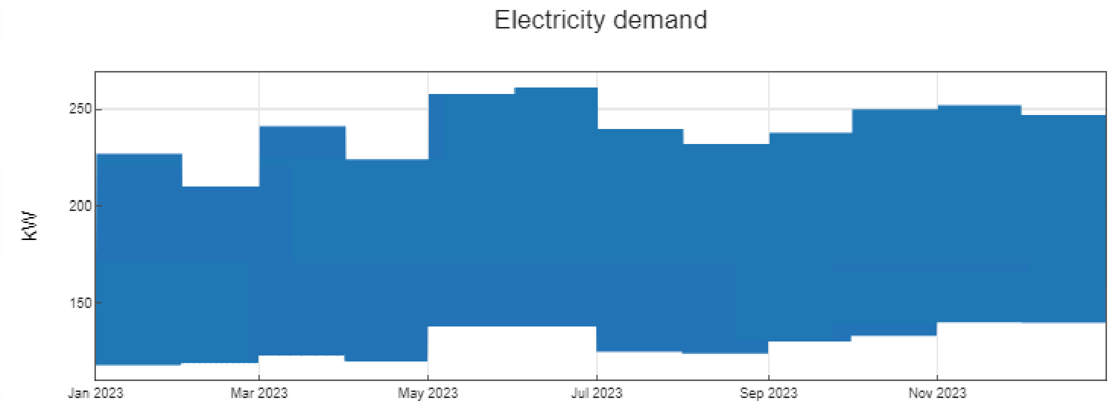


Figure 19: Annual load profile for Maripipi island.

7.3. Maripipi islands

Maripipi island is located in the Central-Eastern part of the Philippines, west of the larger islands of Samar and Leyte. The island is part of the province of Biliran (which is the next largest island) and part of the region of Eastern Visayas (Region VIII). NPC operates five diesel generators with a total installed capacity of 1,136 kW and a dependable capacity of 908 kW on the island. Power is distributed through the Maripipi Mulit-Purpose Electric Cooperative (MMPC) and provided for 24 hours per day. At the time of the study an installation of a combined solar PV (150 kW) and battery storage (150 kWh) plant was under discussion as well as a submarine power cable interconnection to neighbouring Biliran. More than 93% of consumers and customers are residential, 2% commercial customers and the remaining power is supplied to public building and street lights. For Maripipi island no sensitivity analysis was conducted due to the similarity in resource availability and consumption profile to Lubang.

Electricity demand and Solar PV resources

The annual load profile (see Figure 19) was comprised from typical daily load profiles for each month, as provided by NPC. This means that for each month, the daily load profile is assumed to be the same. No demand increase was considered due to the large uncertainty of the potential demand increase. The main characteristics of the annual load profile are as follows (Table 13):

Table 13: Key consumption characteristics for Maripipi.

Parameter	Unit	Value
Peak demand	kW	261
Mean demand	kW	165
Annual consumption	MWh	1,448
Peak month	-	June
Diesel capacity	kW	1,136

Figure 20 illustrates the specific PV potential over the course of a year; the annual potential is high at 1,600 kWh/kWp/a (compare Berlin 1,068 kWh/kWp/a). Seasonality can be observed from the feed-in curve, with the highest generation occurring from February to May.

Simulation results

Generally, the findings for Maripipi show similar patterns than compared to Lubang – as a comparison of Table 14 and Table 15 shows. Given the higher diesel fuel costs the BAU scenario is even more costly. As a consequence, the saving potential in the 100% RE scenarios is higher (apart from 100% RE with battery) and the RE share in the cost optimized scenarios is higher.

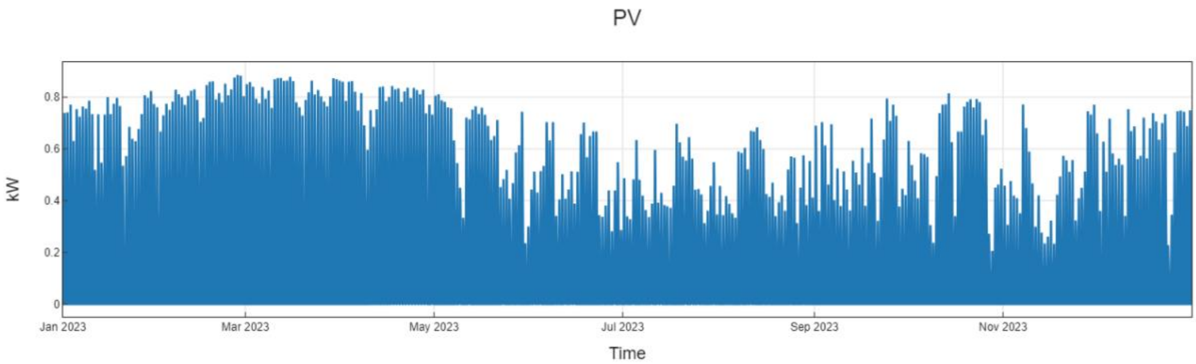


Figure 20: Solar yield curve in kW/kWp for Maripipi island.

Table 14: Economic simulation results for Maripipi.

Sc.	Name	LCOE (€/ kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Annuity O&M (€/year)	Excess Elec. (MWh)
1	Business-as-usual (100% diesel)	0.495	29.7	0	718.214	0	684,262	0
2	100% RE (H_2)	0.396	23.76	100	574,485	4,396,690	75,405	1,088
3	95% RE (H_2)	0.359	21.54	95	520,948	3,742,126	95,283	949
4	100% RE (battery)	0.514	30.84	100	745,649	5,356,801	91,323	3,351
5	Cost-optimization (technology agnostic)	0.310	18.6	73	449,154	2,394,048	157,086	149
6	Cost-optimization (H_2)	0.323	19.38	69	468,674	2,318,679	202,001	177

Table 15: Technical simulation results for Maripipi island.

Sc.	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	PV (kW)	Electo -lyzer (kW)	Fuel Cell (kW)	H_2 Strage (kgH_2)	Batt. Stor. (kWh)	Diesel (kW)
1	Business-as-usual (100% diesel)	0.495	29.7	0	0	0	0	0	0	1,136
2	100% RE (H_2)	0.396	23.76	100	2,710	1,164	261	1,365	0	0
3	95% RE (H_2)	0.359	21.54	95	2,489	1,054	228	333	0	68
4	100% RE (battery)	0.514	30.84	100	3,227	0	0	0	5,754	0
5	Cost-optimization (technology agnostic)	0.310	18.6	73	1,256	364	81	69	2,005	98
6	Cost-optimization (H_2)	0.323	19.38	69	1,475	706	160	122	0	126

Business-as-usual (100% diesel)

Due to the high diesel costs the LCOE are very high in the BAU scenario with 0.49 EUR/kWh. Since the real costs are probably even higher (due to maintenance costs and operation in part load) – this highlights again the economic rationale for investing in RE apart from emission savings.

100% RE (H_2)

A full RE supply with hydrogen reduces the current costs by 0.06 EUR/kWh or 10 PHP/kWh. The cost-optimized system would require 2.7 MW of solar PV combined with 1.1 MW electrolyzer capacity, 261 kW fuel cell capacity and a H_2 storage of 1.3 t. However, an initial investment of more than 4.3 million is required.

95% RE (H_2)

Similar to the analysis of Lubang, we find that a slightly lower RE share of 95% leads to a significant cost reduction basically through less PV and battery investments required.

100% RE (battery)

Similar as for the Lubang case study, achieving 100% RE with battery storage is the most expensive power system studied with LCOE of 0.51 EUR/kWh even exceeding the costs of pure diesel generation. High costs are a result of the seasonality of solar resources, which requires the installation of large capacities only to cater few periods of the year. In addition, a large amount of electricity is not used.

Cost-optimization (technology agnostic)

The cost optimization scenario reveals that an energy system based on PV and battery storage with H_2 and diesel generator as back-up is the most affordable system with 0.31 €/kWh (18.6 PHP/kWh) (saving of 0.18 €/kWh vs BAU). Under these system configurations, a relatively high RE share of 73% is achieved. However, an upfront investment of 2.4 million € (146 million PHP) required

Cost-optimization (H_2)

A cost optimization considering solar PV in combination with hydrogen components leads to slightly higher LCOE of 0.32 EUR/kWh and a smaller RE share of 69%.

7.4. Calayan island

Calayan island is located at the northern tip of the Philippines. It is part of the Babuyan island group, which is the second most northern island group after the Batanes island group. Administratively Calayan island is part of Cagayan Province and the Cagayan Value Region (Region II). Currently, NPC operates six diesel generator units with an installed capacity of 1,436 kW and a dependable capacity of 1,240 kW. Due to remoteness of the island and the difficulty to reach the island, the fuel costs are very high (33.7 PHP/kWh or 0.56 EUR/kWh).

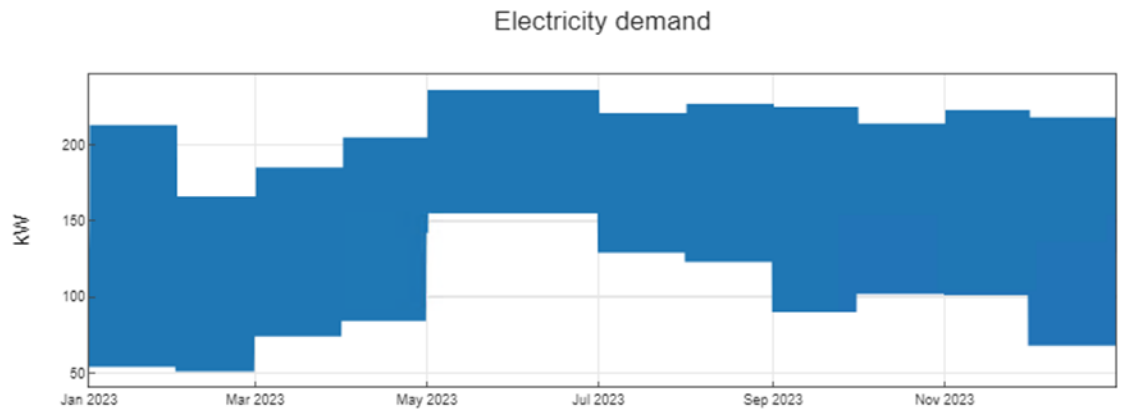


Figure 21: Annual load profile for Calayan island.

Electricity demand and Wind resources

The annual load profile (see Figure 21) was constructed using the same method as the other case studies – using typical daily load profiles for each month to create a profile for the year. Demand increases were also left out of the model due to large uncertainty regarding the potential for increase. The main characteristics of the annual load profile are as follows (Table 16):

Table 16: Key consumption characteristics for Calayan.

Parameter	Unit	Value
Peak demand	kW	236
Mean demand	kW	150
Annual consumption	MWh	1,310
Peak month	-	May/June

The specific wind resource potential is high at 2,987 kWh/kW/a. The wind resources are consistent throughout the year and are not restricted to daylight availability. Figure 22 shows the wind resource potential over the course of a year. There is no real observable seasonality, but the lowest production period is approximately May to July.

Simulation results

The results for all scenarios are summarised below. Table 17 summarises the possible technologies and their total capacities for each scenario, and Table 18 presents the KPIs for each scenario. For definitions of each KPI, refer to the methodology section. The business-as-usual scenario with only diesel (scenario 1) is expensive with LCOE of 0.604 €/kWh, and cost savings can be achieved for all system designs other than 100% renewable with battery storage. The cheapest energy system (scenarios 6 and 7) is designed with a combination of wind, hydrogen components and a back-up diesel generator to achieve a 70% renewable share.

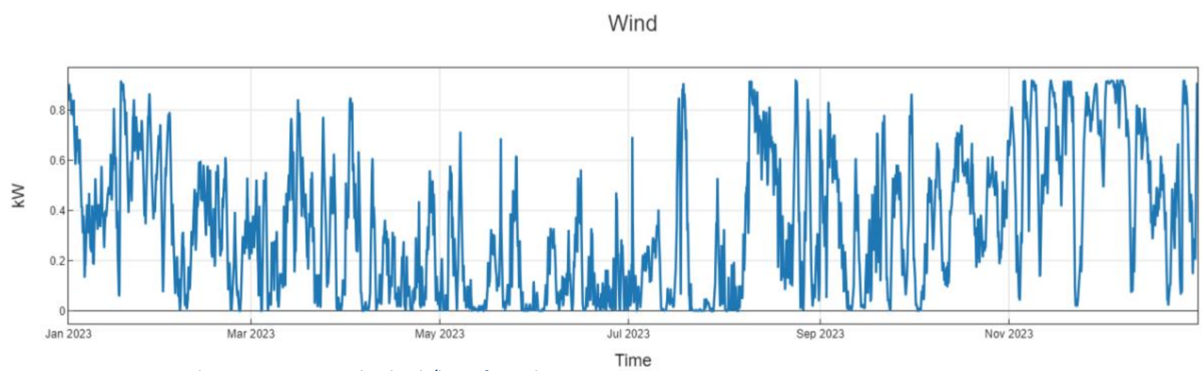


Figure 22: Wind resource potential in kWh/kWp for Calayan.

Table 17: Technical simulation results for Calayan.

Sc.	Name	Wind (kW)	Electro-lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kg H_2)	Battery storage (kWh)	Diesel (kW)
1	Business-as-usual (100% diesel)	0	0	0	0	0	1,436
2	100% RE share	2,466	757	236	2,063	0	0
3	95% RE share (H_2)	1,820	387	156	703	0	107
4	100% RE share + battery storage	7,201	0	0	0	35,617	0
5	Cost-optimization (technology agnostic)	738	131	68	218	0	170
6	Cost-optimization H_2	738	131	68	218	0	170

Business-as-usual (100% diesel)

Due to particularly high diesel fuel prices of 1.73 EUR/L, the LCOE of the BAU case is resultantly high at 0.604 EUR/kWh (36.2 PHP/kWh). Approximately 420,000 litres of diesel fuel are required to supply the annual load, which equates to annual expenses of 725,000 EUR for the fuel alone. The annual emissions in this case are 1.1 million kg CO2 equivalent. The results for the BAU are assumptions because factors such as price increases/fluctuations, load growth and variable diesel generator efficiency have not been considered in the model. This means that the costs are even an underestimation of the costs in reality.

100% RE (H_2)

Under the applied assumptions, a 100% renewable scenario with hydrogen has an LCOE of 0.447 EUR/kWh (26.8 PHP/kWh). This is 26% savings compared to the BAU, and a reduction of 0.15 EUR/kWh. The energy system is completely autonomous from fuel imports and therefore resilient to energy price fluctuations, and is considered to be zero emissions (only direct emissions included). However, it should be taken into account that such a design would require approximately 3.8 million EUR (228 million PHP) in upfront investment costs for the deployment of almost 2.5 MW wind, 757 kW electrolyzer, 236 kW fuel cell, and over two tonnes H_2 storage capacity. However, the annual operation and maintenance (O&M) costs are low (132,000 EUR/year). Also, there is a high proportion of excess electricity generation, which is over four times the annual consumption. This can potentially be monetarized if H_2 trade is possible – there is the potential to export 63.5 tonnes of H_2 annually given the 757 kW electrolyzer capacity.

95% RE (H_2)

Reducing the renewable share by 5% results in LCOE of 0.336 EUR/kWh, which reflects a 25% monetary savings (LCOE / kWh) compared to the 100% RE H_2 scenario. There is a significant reduction in the required RE technology capacities with the inclusion of a 107 kW diesel generator to cover the periods of high demand and low renewable generation. Because a smaller wind energy capacity is required, this leads to a 31% reduction in excess electricity generation compared to scenario 2.

100% RE (battery)

The 100% RE scenario with battery storage has a significantly high LCOE of 2.298 EUR/kWh (138 PHP/kWh). In this case, 7.2 MW wind is needed alongside a 35.6 MWh battery storage. This is a result of extended periods of time with no wind potential and only the battery storage to rely on for power. This configuration is infeasible due to obtaining the highest costs and requiring an unrealistic amount of land space relative to the system size.

Cost-optimization (technology agnostic)

The most affordable system has an LCOE of 0.260 EUR/kWh (16 PHP/kWh), resulting in 57% savings compared to the business-as-usual scenario. A renewable share of 70% is achieved, with the rest of the supply being covered by a 170 kW diesel generator. This energy system is based on wind with hydrogen technologies as a means of electricity storage – no battery storage is chosen here. The upfront investment costs amount to only a quarter of costs compared to the 100% renewable scenario as a result of less renewable technology requirements.

Cost-optimization (H_2)

This is the same as the cost-optimization case because no battery storage was selected anyway.

Table 18: Economic results for Calayan.

Sc.	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Annuity O&M (€/year)	Excess Elec. (MWh)
1	Business-as-usual (100% diesel)	0.604	36.24	0	791,437	0	748,518	0
2	100% RE (H_2)	0.447	26.82	100	585,068	3,855,655	132,185	5,605
3	95% RE (H_2)	0.336	20.16	95	440,126	2,508,438	142,279	3,892
4	100% RE (battery)	2.298	137.88	100	3,010,448	18,384,994	567,646	20,160
5	Cost-optimization (technology agnostic)	0.260	15.6	70	340,144	1,065,485	209,927	1,050
6	Cost-optimization (H_2)	0.260	15.6	70	340,144	1,065,485	209,927	1,050

Sensitivity analyses – interest rates

The first sensitivity analysis studied was regarding the capital interest rates, and the scenarios considered were the 100% RE H_2 scenario (Sc. 2) and the cost-optimisation scenario (Sc. 5). It is important to see the effects of a decrease of capital interest rates. This is because the capital costs have a significant impact on the feasibility of RE and green hydrogen projects given the necessity of large initial investments in contrast to comparable low operational costs with increasing RE shares. Therefore, we have studied the effect of a decrease of the capital interest rates to 7% and 4%.

Table 19 and 20 present the energy system designs and KPIs for changing capital interest rates for the 100% RE H_2 scenario (Sc. 2). In this case, a lower interest rate favours less investments in wind energy and slightly larger investments in electrolyzer and H_2 storage. However, the impacts are minimal due to the constraint of being a 100% renewable solution. The LCOE is impacted though, with potential savings of 15% (for 7% interest rate) and 29% (for 4% interest rate).

Table 19: Sensitivity analysis for capital costs on Calayan 100% RE H2 scenario scenario – economic KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Excess Elec. (MWh)
10	**100% renewable (H_2)**	0.447	26.82	100	585,068	3,855,655	5,605
7	**100% renewable (H_2)**	0.379	22.74	100	496,130	3,855,778	5,600
4	**100% renewable (H_2)**	0.317	19.02	100	415,877	3,856,435	5,577

Table 20: Sensitivity analysis for capital costs on Calayan 100% RE H2 scenario scenario – technical KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Wind (kW)	Electro-lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kG H_2)	Battery storage (kWh)	Diesel (kW)
10	**100% renewable (H_2)**	0.447	26.82	100	2,466	757	236	2,063	0	0
7	**100% renewable (H_2)**	0.379	22.74	100	2,465	760	236	2,063	0	0
4	**100% renewable (H_2)**	0.317	19.02	100	2,457	772	236	2,064	0	0

Table 21 and Table 22 present the energy system designs and KPIs for changing capital interest rates for the cost-optimisation scenario (scenario 5). In this case, the reduction of interest rates leads to both larger wind and hydrogen technology capacities and lower diesel generator capacities. There is the potential for the RE share to increase from 70% to 74% (7% interest rate) up to 77% (4% interest rate). Lower interest rates favour higher renewable scenarios.

Table 21: Sensitivity analysis for capital costs on Calayan cost-optimized scenario – economic KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Excess Elec. (MWh)
10	**Cost-optimization (technology agnostic)**	0.260	15.6	70	340,144	1,065,485	1,050
7	**Cost-optimization (technology agnostic)**	0.240	14.4	74	314,526	1,185,438	1,188
4	**Cost-optimization (technology agnostic)**	0.221	13.26	77	496,130	1,289,631	1,344

Table 22: Sensitivity analysis for capital costs on Calayan cost-optimized scenario – technical KPIs.

Int. rate	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Wind (kW)	Electro-lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kGH2)	Battery storage (kWh)	Diesel (kW)
10	**Cost-optimization (technology agnostic)**	0.260	15.6	70	738	131	68	218	0	170
7	**Cost-optimization (technology agnostic)**	0.240	14.4	74	804	154	90	289	0	163
4	**Cost-optimization (technology agnostic)**	0.221	13.26	77	869	165	108	348	0	157

Sensitivity analyses system components

The results from the energy system simulations and optimizations are heavily dependent on the selected input parameters, so investigating the effect of key costs is crucial to understand the robustness of the results. The parameters chosen for investigation were specifically selected based on their respective contributions to the total annuity of the cost-optimization scenario.

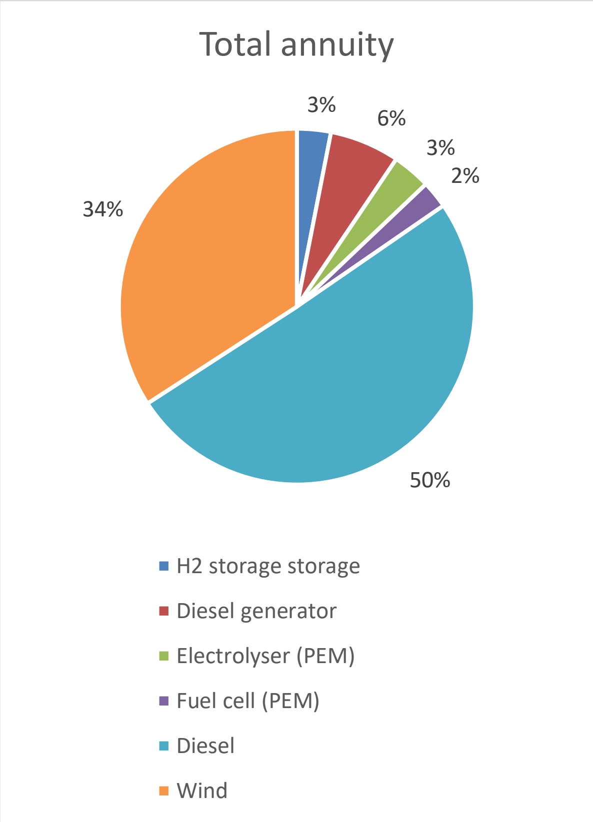


Figure 23: Share of system components to total annuity - Calayan.

For Calayan, diesel fuel (50%) and wind power (34%) are the largest contributors to the total annuity. Sensitivity analyses are therefore chosen for the wind CAPEX and diesel fuel price, with a range of -25% to +25% of the assumed costs (Table 23).

Table 23: Overview about applied scenario inputs for Calayan.

Sensitivity scenario	Wind CAPEX (EUR/kWp)	Diesel Fuel price (EUR/liter)
-25%	750	1.29
Base scenario	1,000	1.72
+25%	1,250	2.15

An increase in wind CAPEX results in less investments into wind, but more into hydrogen components and diesel. It can be observed that if the wind CAPEX is reduced by -25% of the assumed costs, the wind capacity increases and the H_2 storage capacity also increases to store more excess generation, despite a smaller electrolyzer capacity. If the wind CAPEX is increased by +25% of the assumed costs, the H_2 storage capacity increases because the wind capacity is lower and more H_2 needs to be stored through a larger electrolyzer capacity. In all cases, hydrogen as a means of electricity storage is still chosen over battery storage. A +25% increase in wind CAPEX results in a 6% increase of LCOE, and a -25% decrease in wind CAPEX results in a 7% decrease in LCOE. The renewable share varies by 8 percentage points between the lowest and highest wind CAPEX.

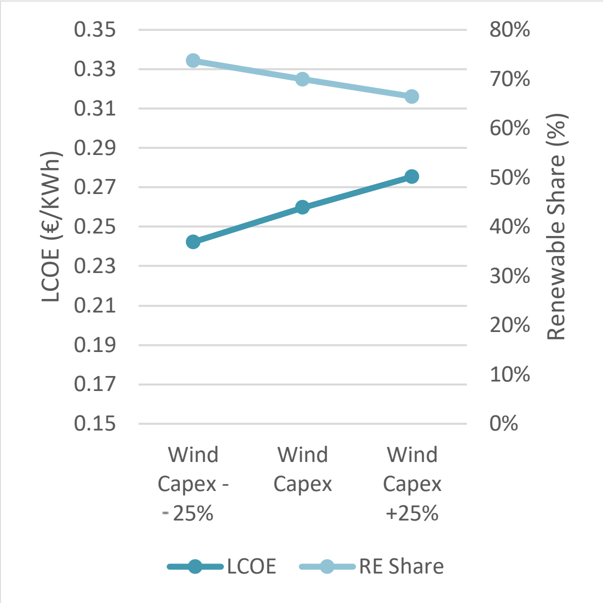


Figure 24: Effect of Wind CAPEX on LCOE and RE share.

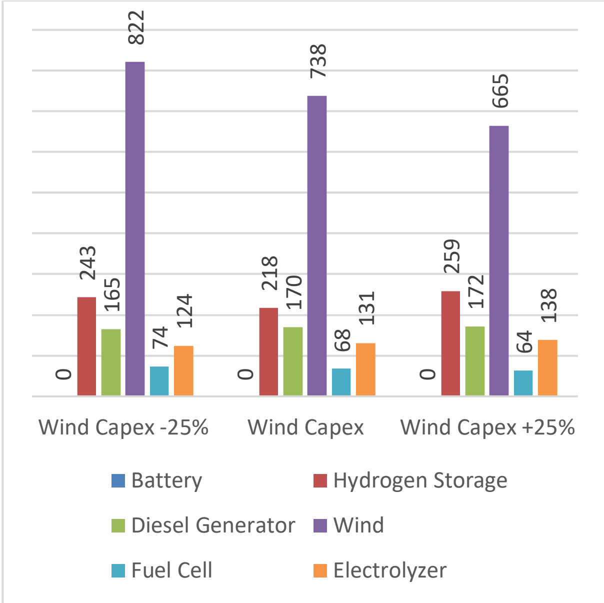


Figure 25: Effect of Wind CAPEX on system components

In all sensitivity cases with varying diesel fuel price, hydrogen technologies remain in the proposed energy system. When the diesel price is reduced by -25%, a 13 kW battery storage enters the system. This is because more diesel in the system enables handling prolonged periods of low wind generation with reduced reliance on hydrogen, and so employing battery storage for short-term requirements. Wind capacity is the most affected component in response to fluctuations in diesel price. As diesel prices fluctuate, the RE share experiences a notable increase of 12 percentage points from the lowest to the highest diesel fuel price levels. The LCOE increases by 12% if the diesel fuel price increases by 25%, and decreases by 14% if the fuel price decreases by 25%. The diesel fuel price therefore has a fairly large impact on the system results, but wind with H_2 remains in all scenarios.

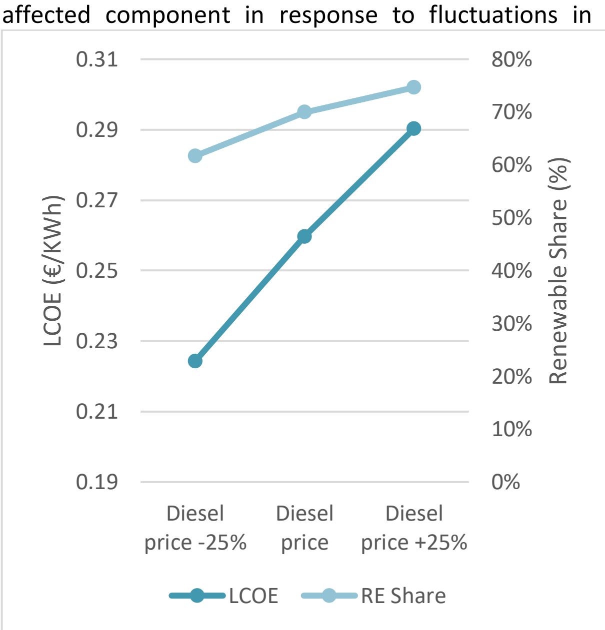


Figure 26: Effect of diesel price on LCOE and RE share.

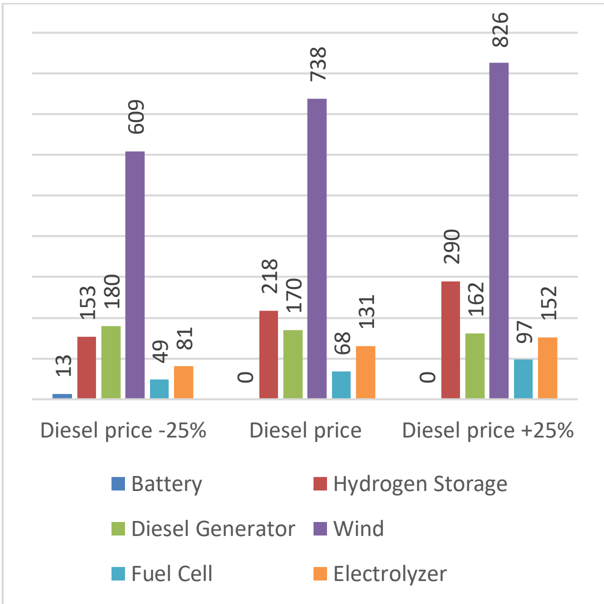


Figure 27: Effect of diesel price on system components

Figure 29: Annual load profile isolated island resort.

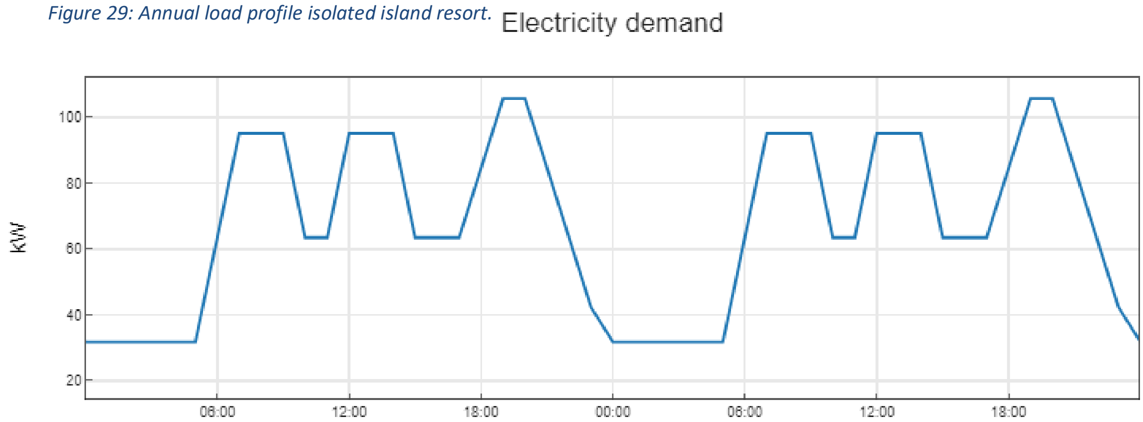
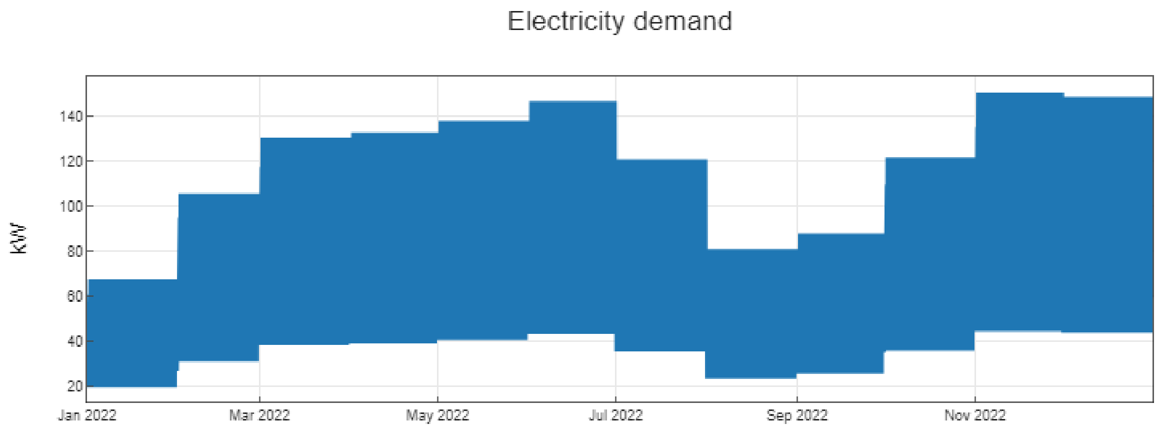


Figure 28: Daily load profile for isolated island resort.



7.5. Isolated island resort

Finally, an isolated island resort in northern Palawan was examined. The island resort pursues and eco-branding strategy, and is looking to install an energy system based on RE. The island has been analyzed to find points of similarities and difference compared to islands run by NPC. Resort islands tend to have different load profiles and electricity demands.

Currently, diesel generators are applied to ensure electricity supply in the resort. A total capacity of 413 kW is installed on site. Since most of the generators were installed in recent years, the generator efficiency is higher compared to the aforementioned case studies with a consumption of 0.317 l/kWh. The island operators revealed that their diesel costs are around 1.27 EUR/liter (78 PHP/liter).

Electricity demand and Solar PV resources

The resort operators were not able to provide a site-specific load profile. Therefore, a generic load profile from a resort case study was applied which is characterized by typical peaks during breakfast, lunch time and in the evening (see Figure 28). The resort operators provided monthly consumption patterns (see Figure 29), low demands can be observed in August and September. The main characteristics of the annual load profile are as follows (Table 24):

Table 24: Key consumption characteristics for isolated island resort.

Parameter	Unit	Value
Peak demand	kW	150
Mean demand	kW	76.5
Annual consumption	MWh	670
Peak month	-	June & November

Figure 29 illustrates the specific PV potential over the course of a year; the annual potential is high at 1,630 kWh/kWp/a (compare Berlin 1,068 kWh/kWp/a). Seasonality can be observed from the feed-in curve, with the highest generation occurring from February to May.

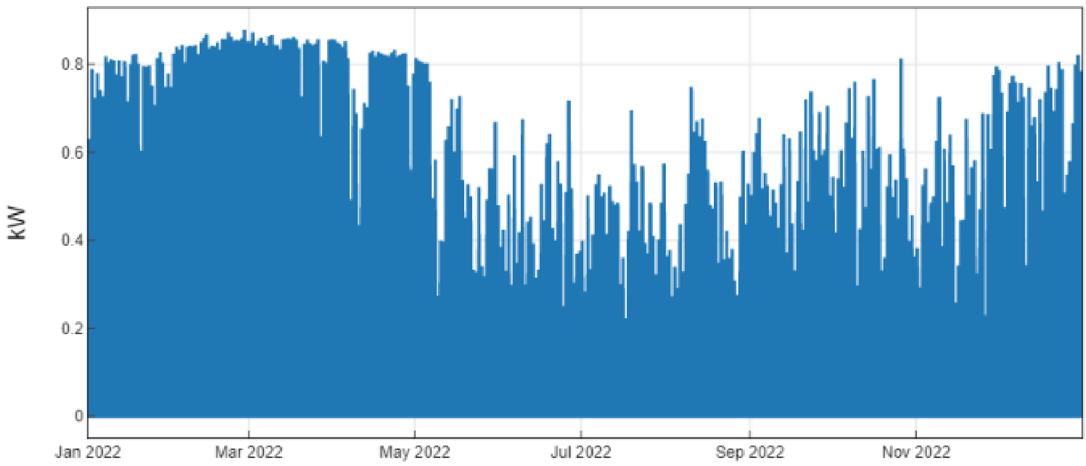


Figure 30: Solar yield curve in kW/kWp for isolated island resort.

Simulation results

The simulation results (Table 25 and Table 26) for the isolated island resort underline the high potential for RE on small islands in the Philippines. In addition to the business-as-usual scenario, only a 100% supply of renewable energies with H_2 and cost optimization were examined. This simplification was carried out in consultation with the research institute and in accordance with the objectives of the resort operator in order to reduce complexity. The transferability of the findings to comparable applications remains unrestricted. A 100% RE based power supply leads to lower costs per kWh than the power supply. Additionally, no emissions at all are generated. However, the cost optimization scenario leads to the lowest costs with an already significant RE share of 68%. The limited availability of space due to the island's mountainous topography could be a limiting factor for all scenarios, and further investigation in this regard would be necessary.

Table 25: Economic simulation results for isolated island resort.

Sc.	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	Annuity (€/year)	Upfront invest (€)	Annuity O&M (€/year)	Excess Elec. (MWh)
1	**Business-as-usual (100% diesel)**	0.453	27.18	0	303,866	0	291,523	0*
2	**100% RE share**	0.378	22.68	100	254,029	1,944,201	33,244	593
3	**Cost-optimization (technology agnostic)**	0.279	16.74	68	187,595	955,558	73,111	101

Table 26: Technical simulation results for isolated island resort.

Sc.	Name	LCOE (€/kWh)	LCOE (PHP/ kWh)	RE share (%)	PV (kW)	Electro-lyzer (kW)	Fuel Cell (kW)	H_2 Storage (kG H_2)	Battery storage (kWh)	Diesel (kW)
1	**Business-as-usual (100% diesel)**	0.453	27.18	0	0	0	0	0	0	413
2	**100% RE share**	0.378	22.68	100	1,184	452	150	671	0	0
3	**Cost-optimization (technology agnostic)**	0.279	16.74	68	558	164	33	31	529	53

Business-as-usual (100% diesel)

In the BAU scenario, the power generation costs are high with 0.453 EUR/kWh (27.2 PHP/kWh), due to high diesel fuel prices of 1.27 EUR/L. Approximately 223,000 liters of diesel fuel are required to supply the annual load, which equates to annual expenses of approximately 283,000 EUR for only the fuel. At the same time, more than 593,000 kg CO_2eq are emitted annually. Both high costs and high emissions are unattractive for the resort's goals of minimizing costs and becoming more sustainable.

100% RE (H_2)

Under the applied assumptions, for the resort to become fully renewable with the use of hydrogen as a means of energy storage, the power generation costs are 0.378 EUR/kWh (22.7 PHP/kWh). Not only will this scenario significantly reduce emissions for the resort (it is considered as zero emissions), but it will also increase the resilience of the energy system by being independent on energy price changes/increases. Compared to the BAU case, the power generation costs are reduced by approximately 0.7 Eurocent/kWh and the annual annuity costs are reduced by approximately 50,000 EUR. To invest in this fully RE system, the resort will need approximately 1.9 million EUR in upfront investments costs to install 1.2 MW solar PV, 452 kW electrolyzer, 150 kW fuel cell and 671 kg H2 storage. As well as the high upfront cost requirements, space requirements should also be further considered. It was understood by the stakeholder interviews that space is a major issue on the small island resort. The question is if a total of 1.2 MW solar PV can feasibly be installed.

Cost-optimization (technology agnostic)

The cost-optimization scenario would lead to the highest cost reduction with more than 0.17 EUR/kWh (38%) as compared to the BAU. A RE share of 68% is achieved which reduces emissions significantly compared to a fully diesel dependent system. The energy system consists of a PV system in combination with battery storage and hydrogen storage, and a 53 kW diesel generator which is utilized in times of particularly low renewable generation and/or particularly high demand. With this configuration, the upfront investment costs are reduced by approximately one million EUR compared to the 100% renewable scenario and excess generation is reduced by 83% as a result of smaller solar PV capacity.

7.6. Main findings and recommendations

Overall, the findings reveal a high economic potential for implementing RE into the energy supply systems of off-grid islands in the Philippines. For all case studies, the current costs of diesel power generation (BAU) are higher compared to a renewable integration (cost-optimized scenarios). For the cases of Maripipi and Calayan the BAU scenario costs even exceed all other energy system configuration scenarios with the only exemption of the 100% RE share + battery storage scenario. Under the applied investment cost assumptions the cost-optimized RE shares (cost-optimized scenarios) are in a range of 60-70% with still relatively high costs between 0.26 to 0.3 EUR/kWh. For the cases of Lubang and Maripipi solar PV in combination with both battery storage and hydrogen storage provided the most cost-effective results, however for Calayan the combination of wind with hydrogen storage is more cost advantageous. Additionally, for all case studies the 100% RE scenarios with hydrogen storage outperformed the 100% RE scenarios with battery storage. This highlights the advantage of hydrogen storage components over battery storage in case of more fluctuating and seasonal renewable sources (e.g. wind) and for achieving high RE shares. Hydrogen components can be more adequately designed for the two cases and require less costs for storage capacities.

The implementation of RE technology required large upfront investments although operational costs are low compared to the BAU. The sensitivity analyses for capital costs showed that low capital costs are key and enable lower power generation costs and higher RE shares. Further for the case of Lubang it was revealed through sensitivity analysis that a slight increase in battery storage costs (390 EUR/kWh) significantly increases the viability of hydrogen storage. Other technology CAPEX (solar PV and wind) had a less significant impact on LCOE and RE share which highlights the robustness of the viability of RE implementation. Diesel fuel costs and development need to be considered for the RE integration. For the case of Lubang it was revealed that lower diesel fuel costs of 25% (0.9EUR/kwh) decrease the economic competitiveness of RE significantly. It needs to be mentioned that this scenario is rather unlikely and lower diesel costs had less impact in the sensitivity analysis for Calayan where fuel costs are already on a higher level.

Recommendation for Lubang

Lubang is the case study with the largest demand and lowest diesel fuel costs considered. Therefore, it is recommended to stepwise increase solar PV capacities. In a first step, the direct utilization of solar power during the day could avoid substantial diesel fuel consumption. In a second step, the solar PV capacities could be increased either in combination with battery storage (scenario 5) or hydrogen components (scenario 6) as both scenarios deliver comparable costs.

Recommendation for Calayan

A 100% renewable system with wind and hydrogen is competitive compared to an only diesel scenario (BAU). However, the most cost-effective strategy entails investment in wind, hydrogen, and a small backup diesel generator, resulting in 57% savings compared to the BAU while still achieving a 70% renewable share. For Calayan, battery storage emerges as a less favorable option compared to hydrogen storage. This preference is attributed to prolonged periods of low or no wind generation, making seasonal storage capabilities more crucial. In such scenarios, hydrogen storage offers enhanced viability for ensuring reliable energy supply during extended periods of renewable resource variability.

Recommendation for Maripipi

A combination of solar PV with battery storage, a small hydrogen system for seasonal storage and small diesel back-up generator would lead to lowest LCOE of 0.31 EUR/kWh with a RE share of 73% (scenario 6). However, for Maripipi it could be considered to implement a 95% RE system with solar PV capacity (scenario 3) in combination with H_2 system with slightly higher LCOE of 0.36 EUR/kWh but almost independent and emission free power supply.

8. Conclusion

8.1. Future research and limitations

Key limitations of this study are the uncertainty of cost assumptions, which were addressed with sensitivity analyses. Nevertheless, more detailed information would improve the overall results. Especially more accurate and detailed costs of the current diesel-based power supply would be required. Furthermore, a more detailed engineering of suggested energy systems (e.g. hydrogen components) would add to the knowledge base but were out of scope for this study. Further questions and research needs arise with regard to the results of the feasibility study. A more detailed elaboration of the simulated energy systems and examination of the cost assumptions would be needed for the implementation of a possible demonstration project. The consideration of load growth and suppressed demand in island systems would help to gauge the future energy needs. This would also include an analysis of the technical and economic potential for local trading of hydrogen or derivatives.

Lastly, the disaster resilience for RE and hydrogen system has to be examined, given the high vulnerability of climate change related disasters in the Philippines.

8.2 SWOT-analysis

The SWOT analysis summarizes the strengths and weaknesses inherent within a hybrid system of RE sources and hydrogen components, considering factors such as technological expertise, infrastructure readiness, and financial resources. Furthermore, we will evaluate external opportunities and threats arising from market dynamics and regulatory frameworks, to develop a comprehensive understanding of the potential for success in the evolving energy landscape in remote areas of the Philippines.

Strength	Weaknesses
• Low OPEX costs for H_2 technology compared to diesel generators • Feasibility study shows H_2 technology can be cheaper than diesel generators over a 20-year period • Hydrogen Framework of the Ministry of Energy shows acknowledgment and government support through Tax and duty exemption relief planned for hydrogen projects	• High CAPEX costs for H_2 technology • Lack of clear financing options • Level of knowledge regarding H_2 for maintenance and installation • Limited financing and funding options
Opportunities	**Threats**
• High fuel and transport costs for diesel and maintenance effort for diesel generators and susceptibility to breakdowns • Pressure for sustainable energy supply and cost savings from the Ministry of Energy • Strong network of the AHK Philippines in the energy and hydrogen sector	• Pilot character of hydrogen technology • Hesitant acceptance of new technologies without local reference projects • Complex framework conditions for project realization • Extreme weather events

Table 27: SWOT-analysis

8.3 Next steps

The completion of the feasibility study paves the way for different potential follow-up projects and activities. These include political and advocacy work, knowledge building activities and a pilot demonstration system.

Political and advocacy work

Further awareness-raising and "policy advice" to create a good framework and funding opportunities for green hydrogen in the Philippines is necessary. The feasibility study has shown, that capital costs are a decisive factor for the financial viability of H_2- and RE projects. Therefore building public support and advocacy work for risk-sharing and insurance programs can help in the development of H_2-projects.

Further a market exploration trip for pilot projects in the Southeast Asia region and/or Germany could also stimulate interest and acceptance for hydrogen technology. It could also include the cooperation with a German technology partner with interest in the Philippine market for a pilot showcase project.

Knowledge building activities

During the project, it became apparent that the expertise on hydrogen technology in the Philippines is very limited. There is a lack of qualified personnel to operate and maintain the systems in off-grid areas - training and further education of personnel would therefore be a prerequisite for successful long-term applications. Knowledge building workshops for Philippine stakeholders in the energy and hydrogen sector on green hydrogen are a possible starting point, followed by a more in-depth training program to qualify and educate personnel for the maintenance and operation of a hydrogen system. This could also be realised at a demonstration pilot plant.

Pilot demonstration project

The feasibility study lays the foundation for further collaboration with NPC, private power cooperatives, and/or off-grid hotel resorts for the establishment of a pilot hydrogen technology demonstration plant.

- A further cooperation with the National Power Corporation would benefit from the committed and technology-interested management team at NPC, and the clear target from the DOE to reduce fuel costs at the public utility. NPC’s administration would require support to access capital and financing options, as well as the expansion of existing RE facilities with a connected hydrogen plant. Limited financial resources of NPC would requirement the procurement of external funding would could complicate and slow down a pilot project.

- Cooperation with an electric cooperative would be another avenue for a pilot demonstration project. Some cooperatives have extensive existing RE-installations as well as better access to capital. Faster decision making processes could also facilitate a project.
- A private hotel resort is another possible pathway to establish a pilot showcase project. These are often catering to the luxury market and are run by big conglomerates who are able to access capital to invest in a RE and energy storage technology. A reputational gain for eco-branding through the switch to RE is also a motivational driver for resorts. Further a private project partner could allow for faster decision making and project realization.

At the same time, the implementation of hydrogen projects in off-grid areas in the Philippines is not easy. So far, only a few and only small-scale RE systems have been installed in NPC, though some private electricity cooperatives and remote hotel resorts already have larger existing plants.

Further activities by GPCCI

GPCCI continues to monitor market developments in the Philippines, also with regard to possible follow-up projects. The existing network of stakeholders and contacts established during the conference with NPC, DOE and private electricity cooperatives are potential starting points for a pilot showcase project. Together with RLI, GPCCI aims to present the feasibility study and promote green hydrogen as part of the Asian Development Bank's (ADB) Clean Energy Forum. A cooperation with ADB to provide information on financing options is also pursued. Meetings with the European Investment Bank and NPC were also supported by GPCCI.

Another potential partner is the German Agency for International Cooperation (GIZ) Their H2Uppp funding program of the German Federal Ministry for Economic Affairs and Climate Protection accompanies and supports the market ramp-up of green hydrogen (H2) and Power-to-X (PtX) applications in South East Asia. Through GIZ further studies or a demonstration pilot project could be financially and logistically supported.

A pilot showcase project would promote knowledge transfer and modernization opportunities and show how clean and affordable energy can be achieved economically. It would also promote sustainable economic development in off-grid areas and, thus, contribute to climate-friendly development that improves the living conditions of Filipinas and Filipinos in line with the BMUV's program Export Initiative Environmental Protection (EXI).

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