Hybridization of Islands, Thailand

FEASIBILITY STUDY
KOH BULON DON

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1 EXECUTIVE SUMMARY

The project site is located in the Andaman Sea in Southern Thailand. The current electricity supply relies mainly on diesel generators, which supply either individual households or small grids of up to 10 households. The objective of this project is to upgrade the conventional electrical generation system into a modern, renewable-conventional hybrid system. A secure 24 hour electrical supply shall be provided by implementing a hybrid system consisting of diesel generator, photovoltaics (PV) and battery.

1.1 Site Visit

A site visit has been carried out in March 2017. During the site visit, ILF Consulting Engineers (ILF or the Consultant) focused especially on technical aspects such as the locally available generators and grid infrastructure, while GIZ conducted a socio-economic assessment. Moreover, the Consultant reviewed the possible areas for the PV and battery installation in terms of suitability. To determine an energy demand and load profile of the island, the Consultant installed an energy measurement device to record the power output of the generator over the course of 1 month. In addition the infrastructure and logistics were reviewed to ensure a successful project implementation and to identify potential risks and limitations.

1.2 Energy Demand Analysis

Based on the recorded energy data as well as the findings during the site visit, the Consultant analysed the data to determine the current energy demand on the island. Taking further assumptions, such as socio-economic factors and future appliances into account, a future energy demand and load profile has been developed and optimized. The forecast was performed for the period 2018-2027. The estimated future annual amount of gross generated energy by the hybrid power plant has been calculated and amounts:

- In year 2018 : 66.10 MWh
- In year 2022 : 91.11 MWh
- In year 2027 : 106.26 MWh

Furthermore, the related monthly load profiles were developed. The load profiles formed the basis for system design and were implemented in the system simulation.

1.3 Hybrid System Design and Energetic Simulation

The parameters of the future hybrid system were sized and optimized. The optimized system parameters were simulated to:

- Total capacity diesel generators : 3 x 15 kW (3 x 18.75 kVA)
- Total installed PV capacity : 52.14 kW_p
- Total installed battery capacity : 100 kWh

For comparison, a reference scenario, assuming 100% diesel, was also simulated.

Based on the mentioned results, a total renewable fraction of 62% in the first year of operation (2018) could be achieved by implementing the hybrid system. This means, compared to the reference scenario, a significant saving of diesel fuel (18,003 litres in 2018) could be achieved. Moreover, the emission of CO_2 could be reduced significantly by almost 66%.

1.4 Calculation of Levelised Cost of Electricity

The Consultant calculated the future levelised cost of electricity (LCOE) for both, the hybrid system and the reference scenario (100% diesel). Therefore, the capital expenditure (CAPEX) and operational expenditure (OPEX) were estimated. Furthermore, several assumptions such as inflation rate, fuel price escalation, discount rate, and basic financial input parameters were defined and considered in the calculation. It shall be noted that especially the future estimated escalation of fuel price shows the dominant influence on the estimated LCOE. The calculated LCOE for 10, 20 and 30 year project lifetimes:

- Reference scenario with 100% Diesel :
  - 10-year project lifetime 0.545 USD/kWh (18.55 THB/kWh)
  - 20-year project lifetime 0.594 USD/kWh (20.22 THB/kWh)
  - 30-year project lifetime 0.662 USD/kWh (22.53 THB/kWh)
- Diesel/PV/Battery hybrid system :
  - 10-year project lifetime 0.535 USD/kWh (18.21 THB/kWh)
  - 20-year project lifetime 0.474 USD/kWh (16.13 THB/kWh)
  - 30-year project lifetime 0.483 USD/kWh (16.44 THB/kWh)

The results show that the LCOE of Diesel/PV/Battery hybrid system, compared to the calculated reference scenario with 100% Diesel, are reduced by approx. 1.83%, 20.20% and 27.04% for 10, 20 and 30year project lifetime respectively.

In addition to the LCOE calculation, the Consultant also calculated the real annual generation costs for the 10, 20 and 30 year scenarios. The calculated real generation costs in the first year of operation (2018) are:

- Reference scenario with 100% Diesel :
  - 10-year project lifetime 0.481 USD/kWh (16.37 THB/kWh)
  - 20-year project lifetime 0.450 USD/kWh (15.32 THB/kWh)
  - 30-year project lifetime 0.440 USD/kWh (14.98 THB/kWh)
- Diesel/PV/Battery hybrid system :
  - 10-year project lifetime 0.460 USD/kWh (15.66 THB/kWh)
  - 20-year project lifetime 0.331 USD/kWh (11.27 THB/kWh)
  - 30-year project lifetime 0.296 USD/kWh (10.08 THB/kWh)

Same as for the LCOE, the results of the real annual generation costs confirm the attractiveness of the Diesel/PV/Battery hybrid system. Compared to the reference scenario, the generation costs could be already reduced in the first year of the operation.

1.5 Summary results table

Table 1: Summary results of 100% diesel scenario

Reference scenario: 100% Diesel	Unit	2018	2022	2027
System parameters				
Total capacity diesel generators	kW	45 (3x15 kW)		
Number of diesel generators	Unit	3		
Homer simulation output				
Total energy production (demand)	kWh/a	66,072	91,067	106,219
Total diesel consumption	l/a	27,463	35,953	41,616
Specific diesel consumption	l/MWh	416	395	392
Total diesel operating hours	hr/a	8,782	9,630	10,783
Operation hours below 50%	%/a	50.83	21.78	13.53
CO_2 emission	t/a	73	95	110
Financial parameters				
Willingness to pay	Residential type **I** : 14.69 – 29.38 USD/month (500 - 1,000 THB/month) Residential type **II** : 8.81 – 44.07 USD/month (300 – 1,500 THB/month)			
Current electricity expenses	Residential type **I** : 12.78 – 42.30 USD/month (435 – 1,440 THB/month) Residential type **II** : 12.78 – 63.45 USD/month (435 – 2,160 THB/month)			
LCOE (10-year project lifetime scenario)	0.545 USD/kWh (18.55 THB/kWh)			
LCOE (20-year project lifetime scenario)	0.594 USD/kWh (20.22 THB/kWh)			
LCOE (30-year project lifetime scenario)	0.662 USD/kWh (22.53 THB/kWh)			

Table 2: Summary results of PV/Diesel/Battery hybrid system

PV / Diesel / Battery Hybrid System	Unit	2018	2022	2027
System parameters				
Total capacity diesel generators	kW	45 (3x15 kW)		
Number of diesel generators	Unit	3		
Total PV capacity	kW_p	52.14		
Total PV inverter	kW_{AC}	46		
Total battery capacity	kWh	100		
Usable total battery capacity (SOC_{min} 10%)	kWh	90		
Battery inverter capacity	kW	27.3		
Homer simulation output				
Total energy production (demand)	kWh/a	66,072	91,067	106,219
Share Diesel	kWh/a	24,940	42,077	55,933
Share PV and battery	kWh/a	41,132	48,990	50,286
Excess PV energy	kWh/a	23,369	12,113	8,732
Total diesel consumption	l/a	9,460	15,795	20,944
Reduction of diesel consumption (compared to diesel reference scenario)	l/a	18,003	20,158	20,672
Specific diesel consumption	l/MWh	379	375	374
Renewable fraction (PV and battery)	%	62	54	47
Excess PV energy	%	34	18	14
Total diesel operating hours	hr/a	2,047	3,193	4,162
Operation hours below 50%	%/a	6.37	0.28	0.04
CO_2 emission	t/a	25	42	55
Reduction of CO_2 emission (compared to diesel reference scenario)	t/a	48	53	55
Financial parameters				
Willingness to pay	Residential type I : 14.69 – 29.38 USD/month (500 - 1,000 THB/month) Residential type II : 8.81 – 44.07 USD/month (300 – 1,500 THB/month)			
Current electricity expenses	Residential type I : 12.78 – 42.30 USD/month (435 – 1,440 THB/month) Residential type II : 12.78 – 63.45 USD/month (435 – 2,160 THB/month)			
LCOE (10-year project lifetime scenario)	0.535 USD/kWh (18.21 THB/kWh)			
LCOE (20-year project lifetime scenario)	0.474 USD/kWh (16.13 THB/kWh)			
LCOE (30-year project lifetime scenario)	0.483 USD/kWh (16.44 THB/kWh)			

2 INTRODUCTION

Bulon Don Island is located in Southern Thailand. The current power generation of Bulon Don relies mainly on diesel generators, which supply either individual households or small grids of up to 10 households.

The Consultant has produced a technical and financial pre-feasibility study to determine a suitable hybrid system utilising diesel generators, PV and batteries which will provide 24-hour coverage of electricity for 10 years based on forecasted power consumption.

The Consultant conducted a site visit to examine and evaluate the existing system, quality of electricity supply, island's socio-economics and to forecast future demand for the island.

2.1 Project Location and Description

The island is located in the Andaman Sea in the Satun province of the Kingdom of Thailand, shown in Figure 1. It is located approx. 22 km West of Pak Bara pier. Approximately 300 local inhabitants are living on the island in a total of 81 households.

All of the households are clustered towards the South-East of the island. There are three public buildings, namely the health centre, school and mosque. The island is part of the Mu Koh Phetra National Park.

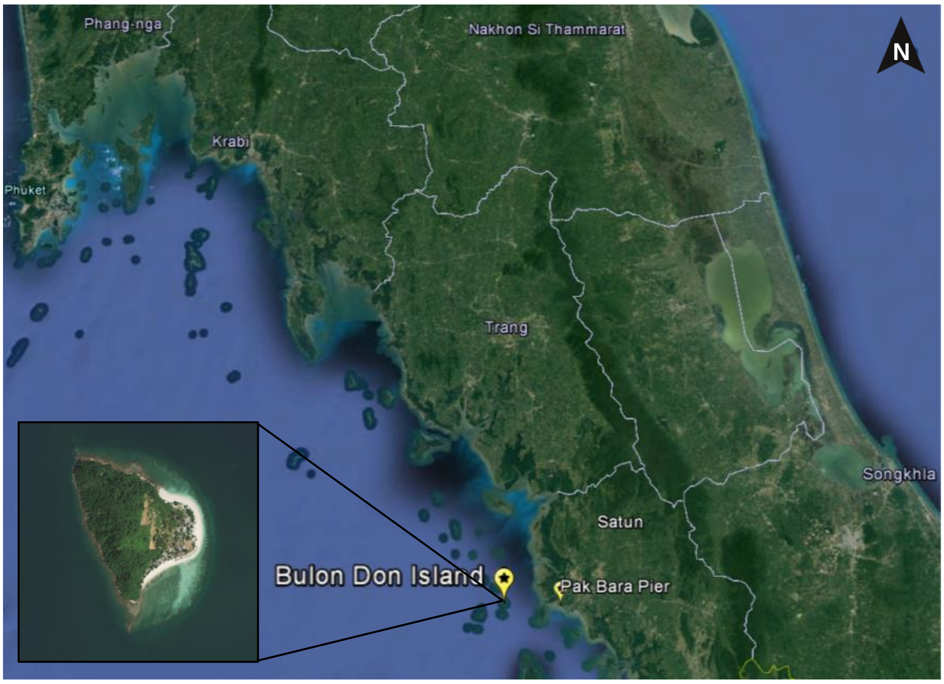


Figure 1: Project location

The island used to be electrified by the island's community generator. Approx. 1 year ago, the generator broke down after just 2 years of operation and might be replaced by a new 50 kW generator (provided by SAO) within the next months. Currently, the locals revert back to individual diesel generators to supply power, which they used to operate before the central generator was commissioned (and eventually failed). Usually, up to 10 households are connected to each generator, forming small informal micro grids. The current price of electricity for the locals then depends on their diesel consumption. Which amounts to roughly 1.87 USD/kWh (63.69 THB/kWh).

2.2 Methodology and Background Information

2.2.1 Current Situation on the Island

Koh Bulon Don used to have a central diesel generator that provided electricity to local. This generator broke down end of 2016. Currently, electricity is available for approximately 4-5 hours per day in the evening supplied by individual diesel generators connecting up to 10 houses.

The vision and target is to upgrade the very basic, low-tech and manually managed system to a modern grid system providing up to 24 hours electrical supply by implementing a hybrid system consisting of diesel, PV and batteries.

2.2.2 Socio-Economic Background

Most electrical demand originates from residential buildings on the island. To understand the actual condition on the island, to project a load profile and to conduct a load forecast, the Consultant and GIZ studied the socio-economic situation of the island. A survey of several households, listing electrical appliances, income and other factors have been conducted during the site visit and further used to predict the load forecast.

The results showed that a standard household is equipped with lights, electrical fans, mobile chargers and TV.

The average income covers the wide range from 132.20 USD/month (4,500 THB/month) to 1,321.97 USD/month (45,000 THB/month). The main income source appears to be from fisheries and farming (chicken and goats).

2.2.3 Load Measurement, Forecasting and Load Assumptions

To model and deploy a hybrid system, a load profile needs to be generated. No load/energy demand information was available on the island and so the Consultant installed a measurement device to record the power demand for 1 month. As of the number of small grids on the island, it was difficult to record the power demand of all households on the island. Therefore, one of the largest grids in terms of number of connected households was chosen to install the measurement device.

The Consultant analysed the recorded data and determined the load profile of all households on the island. The profile was projected from approx. 4 hours to 24 hours.

Taking seasonality effects into account, the profile was estimated over 12 months and further expanded into a profile for a 10 year period.

Typically a load forecast is carried out to cover a period of 10 years. Such period is then used for the simulation and design of the system, ensuring sufficient reserves and sizing of the system.

To simulate the load profile and expand it from 4 hours to a 24-hour load profile, the socio-economic data on the island and the experience of the Consultant were applied.

2.2.4 Hybrid System Simulation

The simulation was carried out using HOMER Pro 3.9.1 software ("HOMER"). The target of the simulation was twofold:

1. To simulate various technical viable scenarios to determine the optimum size of each involved technology and simulate the sensitivity of the results by re-analysing the system
2. To financially optimize the system to obtain the best LCOE for each scenario.

Hourly load profile of year 2018-2027 served as input-data as shown in Chapter 4. Results of the solar PVsyst simulation and financial parameters as observed in the market with standard market prices complemented the inputs. As a summary, simulation inputs consisted of:

- Load profile over the period (hourly resolution)
- Selected technologies and their technical parameters
- Weather data set
- Fuel consumption curves of the generators
- Battery technologies and parameters
- Costs of each system component
- Financial parameters of each technology such as CAPEX, OPEX, replacement costs and lifetime.

The overall target of the simulation was to achieve a system that:

- Has a high renewable energy share
- Ensures reliable and sustainable energy supply
- Is optimized technically and economically according to the LCOE
- Provides sustainable electricity over 24 hours and 7 days a week
- Is capable and sized sufficiently for at least 10 years

To achieve this aim, two possible scenarios were simulated and the corresponding LCOE was calculated as

- Reference scenario with 100% diesel
- Diesel/PV/Battery hybrid system

3 SITE VISIT

During the site visit of Bulon Don Island, the Consultant focused on several aspects to develop a hybrid system. In particular the current situation of socio-economic factors, grid infrastructure, electrical generation, and possible areas for the solar PV and battery installation were evaluated and reviewed. The load over the course of 1 month was also measured with a 1 minute resolution to determine a load profile of the island. Beyond the technical aspects, the Consultant reviewed the infrastructure and logistics. Furthermore the Consultant and GIZ studied the socio-economics of the island to ensure major impacts on electrical load forecasting have been identified and can be addressed accordingly.

3.1 Socio-economic of Bulon Don Island

3.1.1 Education

There is a combined elementary (1st to 6th grade) and secondary (7th to 9th grade) school on Bulon Don Island, currently educating 72 students. After elementary school the students go to the mainland for higher education (30%, mostly children with relatives on the mainland), visit the island's secondary school (40%) or stop institutional education, joining the family fishery or gastronomy business (30%).

9 teachers are currently working and living on the island. Next to the school is a building to host them, but it is lacking sufficient capacity (the building was planned to host 5 teachers). At this time, the remaining 4 teachers are staying at the library building. The community is currently constructing a second teacher's building next to the mosque.

3.1.2 Occupation, Local Business and Economic Situation

The main income source is fishery. Some residents are running a small restaurant or shop. The average income of the population is widely spread, ranging from approx. 132.20 USD/month (4,500 THB/month) to 1,321.97 USD/month (45,000 THB/month), averaging around 235.02 USD/month (8,000 THB/month) in mode average. As a fisher´s island, the generated income always depends on the day-to-day results and seasonal condition of the ocean as people stated in the survey.

3.1.3 Typical Appliances

The Socio-Economic Survey on Bulon Don Island provided by GIZ ("GIZ Survey") showed that a typical household on the islands has 2-4 light bulbs, 1-2 mobile phones, 1-2 fans and mostly a TV (around 60%). A few households also own a washing machine (around 7%). The three public buildings (school, health centre, and mosque) have more electric appliances installed (additional light bulbs, fans, TVs as well as speakers, fridge etc.).

3.1.4 Community Spirit

The overall impression of the community spirit on Bulon Don was positive. People were organized, well informed and very keen on providing all necessary data and information. The site assessment was originally scheduled on 28th February 2017 and people gathered on the island instead of leaving for fishery to welcome the team and contribute to the community meeting. Due to bad sea conditions, the team was not able to visit the island as scheduled and had to postpone for one day. The willingness to conduct telephone interviews on 28th February 2017 indicated their commitment.

The idea to reactivate the centralized community grid and include high shares of renewable energy was received positively.

However, one local stated that a centralized system would only work sustainably if it is operated and maintained by an external party. From her experience, previous projects weren't successful because the locals did not care about maintenance for long term operation as they were lacking knowledge on long term effects. Special training courses and other capacity building measures might help to improve the situation and are part of the Project.

3.1.5 Local Resources

It has to be mentioned that the island is frequently facing fresh water shortages so that the locals are saving water as much as possible.

The availability of local building materials is limited due to the national park restrictions.

Currently a lot of locals are operating and maintaining their own diesel generators, which means they have a certain technical know-how which the Project can build upon. Most houses are also constructed by the locals which may provide support in construction work of the Project.

3.2 Existing Grid Infrastructure

There is currently 1 central grid, which is not in use, and 11 small grids for household supply observed during the site visit. Table 3 presents these grids' information on the island.

Table 3: Overview of existing grid infrastructure

Item	Central grid	Private generator's small grids
Frequency	50 Hz	50 Hz
Voltage level	400/230 Volt, 3-phase 4-wire	220 Volt
Transmission length	350 meters approximately	Varied in each small grid
Cable specification	THW-A 50 sq.mm TIS 2541	VAF 2x1.5 sq.mm TIS 2531

<u>Existing central grid transmission line (currently not in use)</u>

There is an existing central grid transmission line, which used to connect all households, shown as black line in Figure 2. The grid was fed by a community generator. Since the generator is non-operational, the grid is not in use and so small private grids have been implemented. The existing powerhouse in Figure 2 might be relocated as informed by the local during a site visit.

Figure 2: Existing central grid transmission line

Private generator's small grids (currently in use)

11 small grids were observed during the site visit consisting of 2x1.5 sq.mm VAF cables. There is currently no interconnection between small grids and the central grid.

Figure 3: Private generators and small grids of the households

3.3 Existing Diesel Generator

A community generator was installed approx. 3 years ago, however, the generator failed after 2 years of operation. Therefore, the people currently rely on their private generators. During the site visit, the Consultant observed 14 private generators of the households supplying the electricity for 1-10 households, shops and a restaurant as shown in Figure 3. The detailed information of each generator is described in the site visit report (N048-ILF-AD-0002_Site_Visit Report_Bulon_Don).

Figure 4: Examples of private generators forming small grids

3.4 Existing Photovoltaics Systems

PV systems and solar home systems were observed during the site visit. The detailed information of each system is described in the site visit report (N048-ILF-AD-0002_Site_Visit_Report_Bulon_Don).

Figure 5: Examples of solar home systems on the island

Figure 6: Examples of PV systems on the island

3.5 Areas for PV Hybrid System Installation

According to the site visit report, there are 4 preferred areas to install the PV power plant of the hybrid system which were selected in Chapter 5.2.2. Two preferred locations have been identified to install the generators and batteries marked as no. 5 and no. 6 in Figure 7.

1) Blue school building roof
2) Gray school building roof
3) Green school building roof
4) Replacement of the school's PV system
5) Battery-inverter building of school's PV system
6) Replacement of broken PV system

Figure 7: Overview of possible areas of the hybrid system installation

Pros and cons of these 2 locations for the generators and batteries installed are described in the following table.

Table 4: Pros and cons of the 2 locations for the generators and batteries installation

Area	Pros	Cons
No. 5	▪ Close to the central grid ▪ Existing building ▪ Less distribution losses	▪ Close to the residential households resulting in noise pollution

Area	Pros	Cons
No. 6	▪ Far from the residential area (low noise pollution)	▪ Far from the central grid ▪ Difficult transportation of the components during construction (steep access road) and for diesel during operation

3.6 Transport and Logistics

The population lives densely towards the South-East of the island within a radius of 200 m. All transportation is conveniently done by foot. There are no roads on the island, only dirt tracks.

The transport of the hybrid system components can be performed by boat, however, the cargo needs to be distributed to a small boat/long-tail boat at the mainland pier, i.e. at Pak Bara Pier, because there is no pier on the island. The regular ferry or cargo ship cannot dock or approach the island.

Furthermore, it has to be noted that for the execution of the project, there is neither heavy machinery (excavator, crane, truck, etc.) nor a petrol station available on the island. Therefore, all steps of the construction may be executed manually.

4 ENERGY DEMAND ANALYSIS

An energy demand analysis presents the current and future estimation of energy demand on Bulon Don Island. The current energy demand of Bulon Don Island shall be analysed. The results of the current energy demand analysis shall be used as a basis to develop future load profiles of Bulon Don Island.

4.1 Load Measurement

Since there is no data logger or recorded energy data on the island, the Consultant installed one load measurement device (Eco Sense 3) on 1st March 2017 to measure the energy consumption of the connected generator loads in March until 1st April 2017. The device measures relevant grid parameters like voltage, current, active and reactive power and frequency for each phase separately.

The measurement device was connected to Generator #37 (5 kW diesel generator), which supplies electricity to 9 residential households, including 2 shops. Based on GIZ Survey the shops have similar loads to residential households. The Consultant thus assumes the measured data of shop's load similar to that of a residential household's load.

The main data input for the study comprises of daily power consumption recorded on-site and the GIZ Survey. The main data, information and inputs have been used as a basis for the energy demand and load profile analysis of Bulon Don Island. The main inputs and data are presented in the following table.

Table 5: Main input data for energy demand and load profile analysis

Data	Content	Source
Daily Power Consumption	Daily power consumption of a 5-kW generator providing the electricity for 9 residential households, 1 minute recording interval	Measurement on-site
Socio-economic survey	Detailed information of each household: ▪ Type of consumer ▪ Current electrical appliances ▪ Monthly income ▪ Current source of the electricity ▪ Current electricity expenses ▪ Ability to pay for the electricity from the hybrid system in the future ▪ Future electrical appliances	Survey prepared by GIZ

4.2 Current Energy Demand and Load Profile Analysis

4.2.1 Measurement Data

At the time of measurement, the power is supplied by the decentralized generator to the end-users. The power consumption measurement is conducted at the generator, where after the energy demand and load profile have been analyzed.

The load measurement device has measured the data of the mentioned 9 residential households, which comprise of:

- Residential Type I:
  5 households having light, fan, mobile phone, and no TV
- Residential Type II:
  4 households having light, fan, mobile phone and TV.

According to the information received during the site visit and GIZ Survey, the following electrical devices are generally available or installed in the households, which are considered as the basis for the load profile analysis, as presented in the following table:

Table 6: Appliances of Residential type I and II

Appliances	Power [W]	Number of appliances	
		Residential type I	Residential type II
Light bulbs	12	4	4
3-level Fan	50	1	1
Mobile Phone	7.5	2	2
TV 19” CRT	80	0	1

In general, the daily operation duration of power generator is approximately 4.5 hours, between 18:30 to 23:00.

4.2.2 Load Profile Analysis of Measured Data

The measured data was qualitatively analyzed. The following outliers were excluded from the analysis:

- 2nd of March: Extended periods of under voltage (≈110V), matched with low consumption (<100W), which likely prevent the device to start. Further to that, out of range readings across all variables (Voltage, Amps, Watts, etc.) occurred prior to shut down.
- 3rd, 5th, 6th, 8th, 10th, 15th and 16th of March: All days experienced short operational periods varying from 17 to 113 minutes which is not considered as ‘typical’ for daily profiling. Additionally the 6th of March experienced a period of under voltage (≈110V). All days experienced some out of range readings prior to shut down.

- 11th of March: Out of range readings occurred for a prolonged period.
- 28th of March: Zero power production recorded due to technical fault in the measurement device power supply.

The days listed above have not been included to determine the daily load profile as they do not represent a typical day. With a stable and safe power supply these events shall unlikely occur.

In addition, the Consultant understands that the power generator usually switches on between 18:30-19:00, and presumes that the power consumption behavior is similar on a regular daily basis. Therefore, the filtered measurement data has been shifted for the starting time to be 18:30 for the load profile analysis in order to avoid the averaging overlapping time and leading to under- or overestimation.

It should be noted that the Consultant considers daylight saving time programmed in the measuring device influencing the readings during 26th-31st March 2017, when the recorded time has been delayed for an hour. Therefore, the starting recording time of time saving period was adjusted to be at 18:30 for the load profile analysis.

The average daily load profile based on on-site measurement (9 residential households), together with 7th, 17th, 29th load profiles, is presented in the following graph. It can be seen from the average load profile that it decreases gradually after 22:30 because of an average of the daily load profiles, in other words, it's not because appliances are switched off. The daily load profiles show that the power drops dramatically when the generator is switched off.

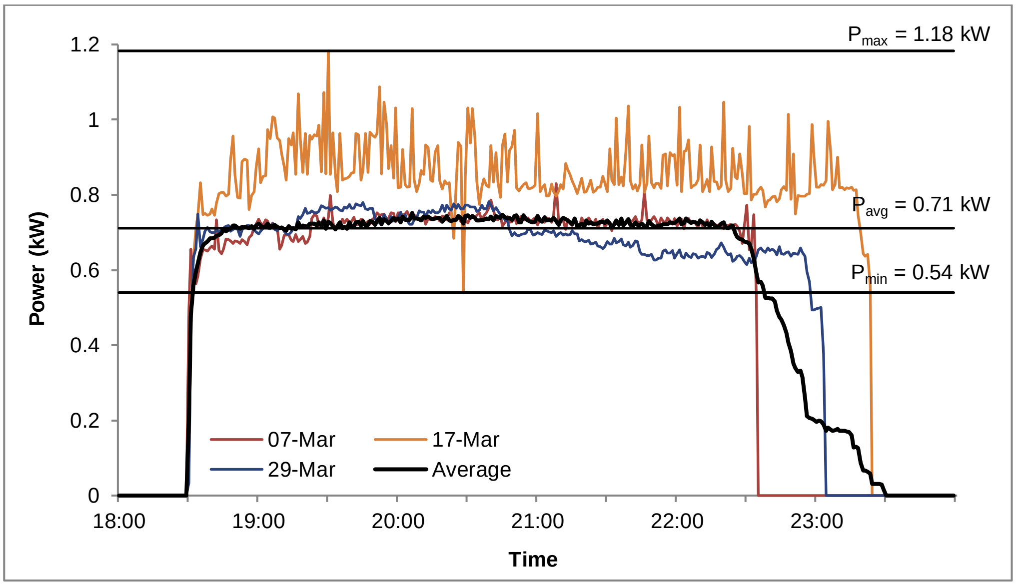


Figure 8: Average daily load profile of on-site measurement including 7th, 17th, 29th load profiles

The results of current energy demand of on-site measurement are presented in the following table.

Table 7: Results of current energy demand of on-site measurement

Item	Value
Number of residential type I	5 households
Number of residential type II	4 households
Maximum power	1.18 kW
Minimum power[1]	0.54 kW
Average power	0.71 kW
Total average daily energy demand	3.14 kWh/d
Average operation duration	4.42 hrs

Interpreting the on-site measurement data, the following appliances are estimated to be in operation at the same time and categorized in Residential type I and II, and this combination shows a good fit with the on-site measurement:

- TV : 75% of total available quantity running at the same time;
- Light Bulb : 50% of total available quantity running at the same time; and
- Fan : 80% of total available quantity running at the same time, switching on at level 2 (i.e. 35 W).

The load profiles of Residential type I and Residential type II are estimated, as presented in the following figure.

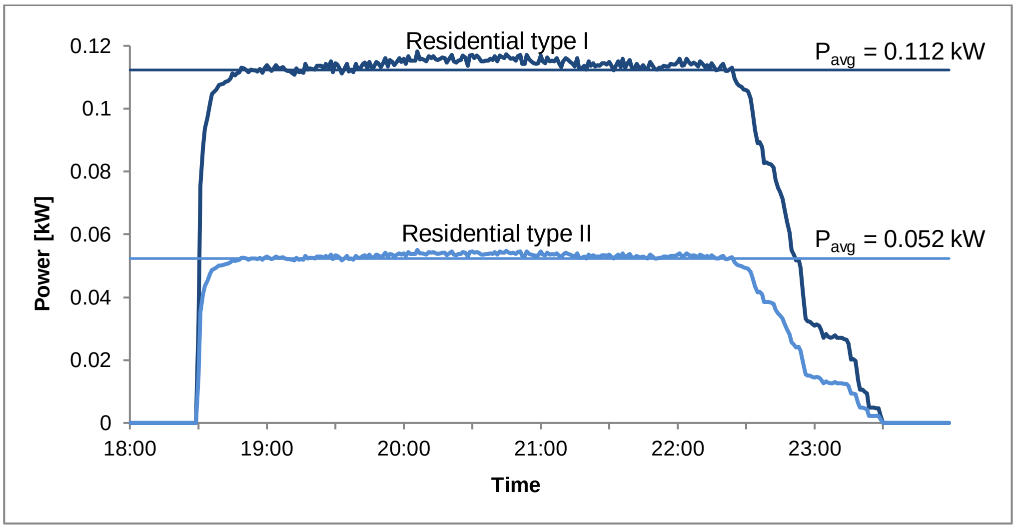


Figure 9: Load profile of Residential type I and Residential type II

[1] This minimum power is considered during the operating period (not in the beginning/end of the operation).

The results of estimated energy demand of residential type I and type II are summarized in the following table. The estimated total energy demand of approximately 3.15 kWh/d is in line with the actual energy demand of the measured data in Table 7, i.e. 3.14 kWh/d.

Table 8: Estimated energy demand of residential type I and type II

Item	Average power	Average daily energy demand (1 household)	Qty.	Average daily energy demand
Residential type I	0.052 kW	0.23 kWh/d	5	1.15 kWh/d
Residential type II	0.112 kW	0.50 kWh/d	4	2.0 kWh/d
Total	-	-	-	3.15 kWh/d

4.3 Load Profile Estimation of Bulon Don Island

The power consumption deceived from the on-site measurements is indicating a ratio of 55.6% of Residential type I and 44.4% of Residential type II. According to GIZ Survey, the residential types recorded by GIZ are presented in the following table.

Table 9: Residential type record of GIZ Survey in Bulon Don Island

Item	No. (from GIZ survey)	Percentage	All Household (extrapolated)
Residential type I	22	37.9%	31
Residential type II	36	62.1%	50
Total	58	100%	81

The Consultant considers the household distribution (Residential type I and Residential type II) on the island according to the survey conducted by GIZ applicable to the entire island. As the total number of households in Bulon Don Island is 81, therefore, the number of households of Residential type I and Residential type II are extrapolated to be 31 and 50, respectively.

The above assumptions is used for energy demand extrapolation and load profile simulation for the whole island.

Based on the combination of on-site measurement results, GIZ survey, and assumptions made by the Consultant, the estimated load profile of Bulon Don Island is shown as Figure 10.

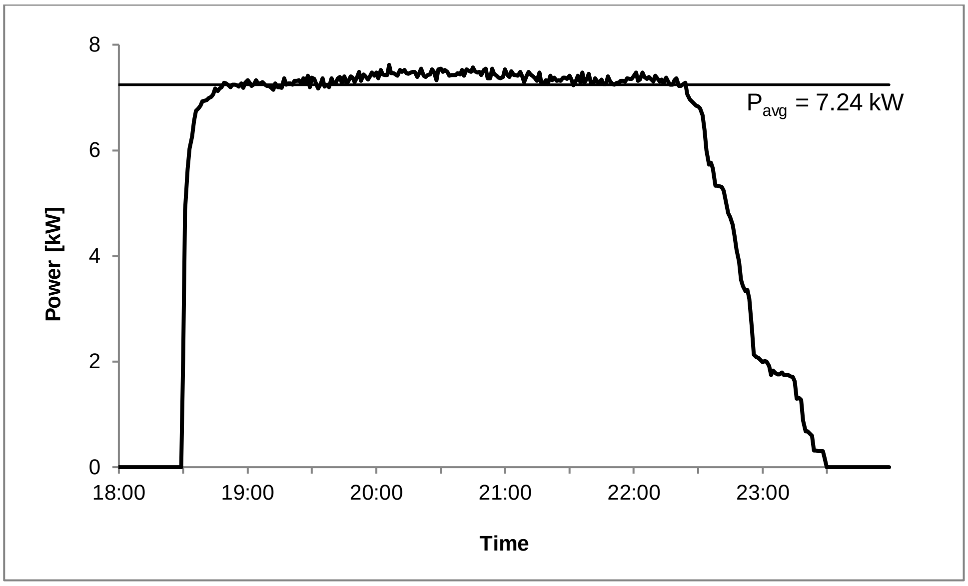


Figure 10: Load profile of Bulon Don Island

The estimated energy demand and power consumption are presented in the following table.

Table 10: Estimated energy demand and power consumption of Bulon Don Island

Item	Value
Average power	7.24 kW
Total average daily energy demand	32.01 kWh/d
Average operation duration	4.42 hrs

4.4 24-hour Load Profile of Bulon Don Island Anticipation

To derive a suitable and plausible future 24-hour load profile local behavior was observed and matched with the Consultants experiences. The assumptions and methodology are described in following section.

4.4.1 Anticipated residential 24-hour Load Profile

The Consultant appraises the behaviors and characteristics of local people living on Bulon Don Island based on the Deputy Head of Village interview carried out by GIZ on May 9th as well as the information taken from the GIZ Survey. This information is crucial input to anticipate the 24-hour load profile.

Fishermen regularly leave Bulon Don Island in the early morning around 06:00 and return around 09:00. In the afternoon, some fishermen leave the island again around 16:00 for squid fishing and they return to the island around 21:00-22:00. For approximately 5-6 days a month the island experiences low tides which prevent the fisherman from leaving according to their regular schedule (06:00). Instead they depart later between to 08:00 to 09:00 and return at around 12:00.

The appliances are turned on as much as possible during the daytime in households equipped with Solar Home Systems (SHS) for as long as sunlight can produce electricity. This can be interpreted that the local people will tend to utilize more electricity, if there is supply.

The assumptions for a regular 24-hour load profile have been made according to the acquired information, perceiving an electricity-supply for 24 hours, as presented below:

- Men go to work offshore while women and children stay home during day time. This forms a day time base load which is formulated based on their energy consumption.
- Students leave in the morning and come back home in the late afternoon. Demand for electricity prior to leaving their homes and after returning home is expected to increase.
- Fishermen returning home at noon time will impact and hence increase electrical demand. Fishermen returning to work in the afternoon will coincide with students returning home, thus the fishermen's demand will reduce but students will increase at similar times.
- Tendency to utilize more if electricity is able to be supplied; and
- Low tidal influences are not considered under the typical load profile estimation. However, the sensitivity analysis shall address this to cover low tidal influence.

It is expected that the increased availability of electricity will go along with more demand for power, as well as demand for new appliances. According to the GIZ Survey and experience of the consultant this could include appliances, such as washing machines, rice cookers, computers, and fridges. The Consultant assumes the following characteristics and sizes of these new appliances to anticipate the 24-hour load profile of Bulon Don Island:

- Washing machine (8 kg) approx. average power of 100 W;
- Rice Cooker (1.8 l) approx. average power of 650 W;
- Fridge (80-200 l) approx. average power of 176.66 kWh/year for 24/7 usage.
- Computer laptop (50 W) and desktop computer (300 W).

It shall be noted that boat repairing is an on-going activity on the island. Considering boat repairing activities, the Consultant understands that one generator (650 W) is dedicated for this particular activity. There is no detail regarding boat repair power tools provided in the GIZ Survey. Therefore, the Consultant assumes conservatively that boat repair power tools require peak power equal to generator power output in this analysis.

Based on the above assumptions, the Consultant assumes the followings behaviors for anticipated 24-hour Residential load profile of Bulon Don Island. The main assumptions are the followings:

- TVs will partly switch on in early morning and during the day, especially when fishermen come back home at noon for lunch and rest. Moreover, TVs will mainly turn on in the afternoon (students are back home after school) and night time;
- Half of the residential area’s light bulbs are expected to be turned on. During the site visit, light switches were observed in households and light bulbs were installed inside and outside a household. Therefore, the lighting is assumed to be switched on when it is necessary during the night-time;
- Compact fans are mainly utilized for the whole night. Considering daytime, the high operation rate of compact fan is expected when fishermen come back home at noon and early afternoon, however, it is assumed to be on partly during the rest of the day time;
- Washing machines are expected to be in operation late morning and in the evening;
- Rice cookers are assumed to be utilized in early morning and in the evening;
- Boat repairing tools are assumed to be utilized for a certain time in late morning and in the afternoon; and
- Computers will be expected to be mainly switched on in the evening but partly in the morning as well. During the end-of-semester period, however, computer could be in use during daytime as kids will be staying at home.
- Refrigerators will expected to be switched on all day
- At least 1 mobile phone charger will expected to be utilized all day in each household

In addition, the specific usages of each appliance are summarized in Appendix 1. Since the load profile is estimated for 2018 in this stage, the number of additional appliances, i.e. washing machines, rice cookers, fridges, computers, shall be assumed according to Table 14. Therefore, the number of washing machines, rice cookers, fridges and computers in 2018 will be 5, 3, 4 and 5 respectively. Based on the assumptions above, the load profiles of each additional appliance are shown in Figure 11.

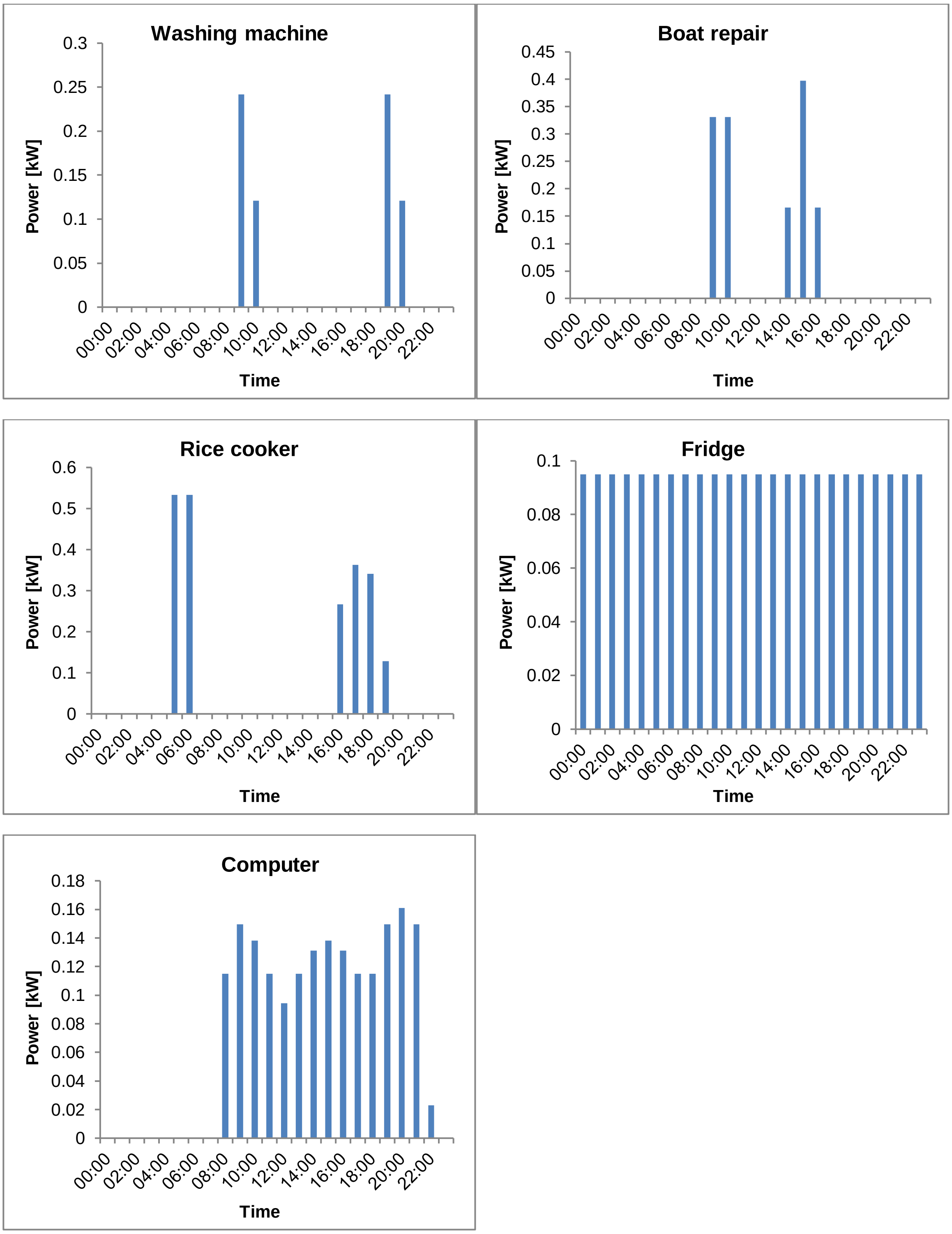


Figure 11: Anticipated load profiles for additional appliances (washing machine, boat repair, rice cooker, fridge and computer)

Based on the above assumptions, the 24-hour load profile of Residential type I, type II together with all additional appliances as described above for the month of March is presented in the following figure.

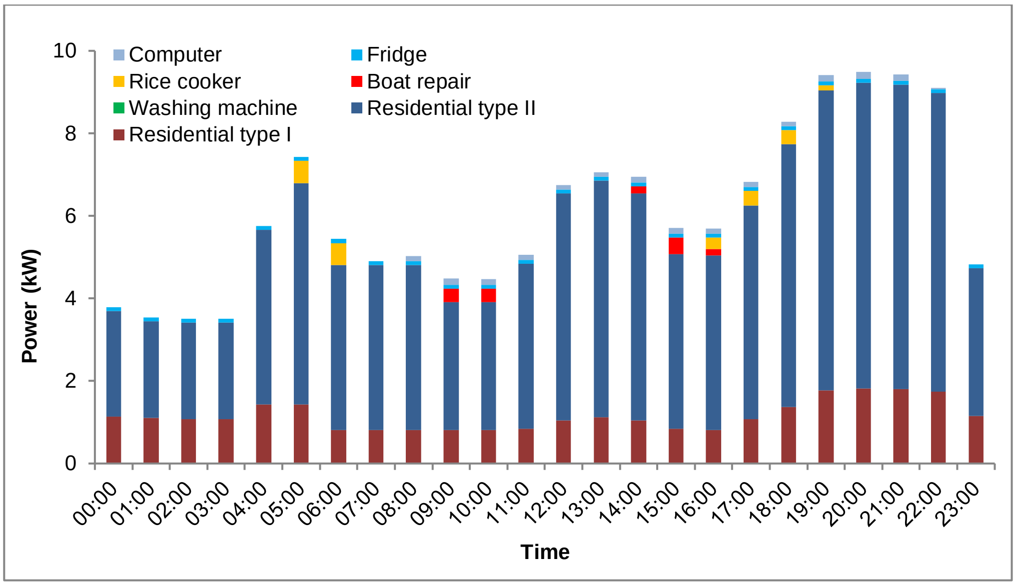


Figure 12: Anticipated 24-hour load profile for residential households of Bulon Don Island in the month of March

Based on the 24-hour load profile for residential households in Bulon Don Island simulation, the estimated energy demand and power of all residential households for 24 hours scenario results in the typical month of March are presented in the following table.

Table 11: Estimated 24-hour energy demand and power of all residential households

Item	Value
Maximum power	9.65 kW
Minimum power	3.51 kW
Average power	6.13 kW
Total average daily energy demand for 24-hour electricity	147.12 kWh/d
Average daily energy demand for 24-hour electricity (1 household)	1.79 kWh/d

The seasonality influences will be taken into account and described in more detail in the following sections.

4.4.2 Anticipated 24-hour Load Profile of Other Clusters

Besides residential area in Bulon Don Island, there are several other clusters on the island, which are listed as the following:

- School
- Mosque
- Health Centre
- Street Lights

- Battery Storage Room

The current appliances and their anticipated behavior will be described and used as a basis to simulate a 24-hour load profile for each cluster.

School

As the on-site measurement did not apply to the school, the Consultant assumes the most likely behavior on summer semester as a basis, based on the available information and assessment of ILF.

According to GIZ Survey, the school has 72 students and 9 teachers in total. Most of the students are under grade 6, and the highest level of education at this school is level 9. Some of the students may leave school after level 6 graduation and start working (fishery) right away. Teachers live on the school's premises.

It is also noted that the new building in the school is under construction with 5 rooms, which will become the teachers' housing.

The current school's appliances are listed below. However, the power of each appliance is not indicated in the GIZ Survey and no information was received during the site visit. The power consumption of these devices will be assumed and are written with the quantities of the devices below:

- 5 TV (80 W)
- 17 Light Bulbs (22 W)
- 18 Fans (50 W)
- 1 Fridge (80-200 L) approx. required average energy of 176.66 kWh/year[1] for 24/7 usage.
- 4 Computers, 5 in total but 1 is currently broken (300 W)
- 1 Water Pump (150 W)
- 1 Network System (50 W)

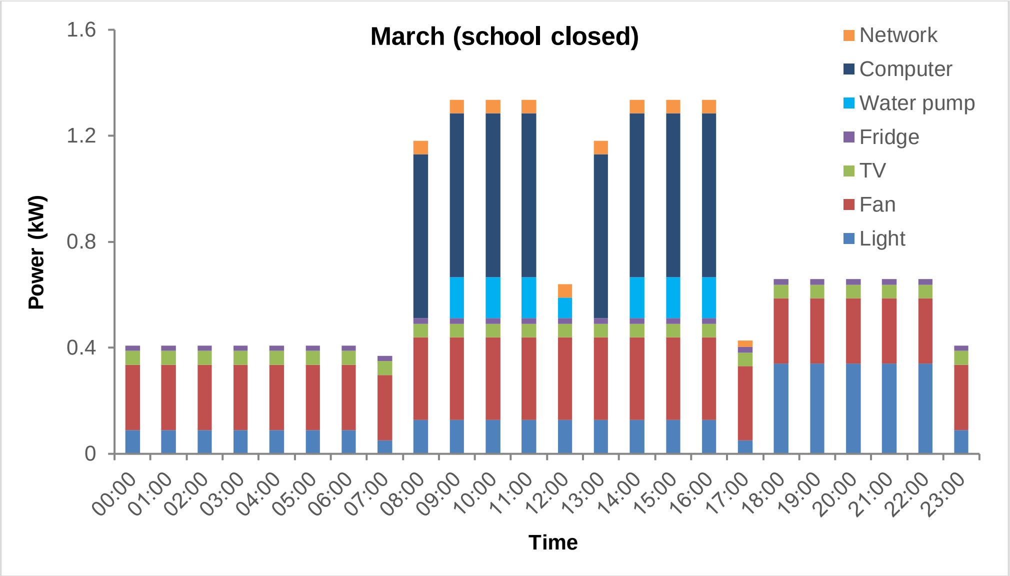
During school hours it is assumed that appliances used for education (fans, computers, network system, lighting, TV and the water pump) are switched on for classes between 08:00-11:00 and 12:00-16:00, where 11:00-12:00 is the lunch break.

As teaching staffs reside at the school it is assumed that they will use TV, lighting and fans at night time. The refrigerator is assumed to be switched on 24 hours every day.

The specific usages of each appliance are summarized in Appendix 1.

[1] This average energy demand is derived from EGAT energy consumption survey data.

Based on the above assumptions, 24-hour load profile of school is simulated, as presented in the following figure.



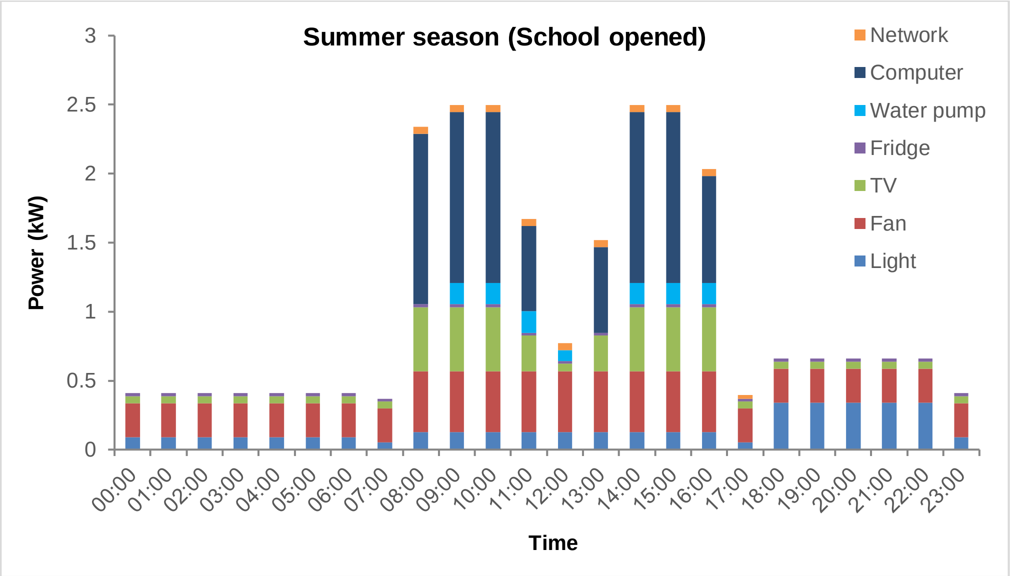


Figure 13: Anticipated 24-hour load profile for school of Bulon Don Island

The school vacation and seasonality influences will be taken into account and described in more detail in the following chapter.

The Consultant estimates that the school in March (school closed) and during summer semester (school opened) requires approx. 18.38 kWh/d and 25.64 kWh/d respectively.

It has to be noted that there is tsunami warning tower nearby the school area powered by two PV panels. The Consultant assumed it will remain isolated. However, if it will be connected with the hybrid system in the future, the system can serve the load because the power consumption of the tower is insignificant.

Mosque

As the on-site measurement did not apply to the mosque, the Consultant assumes the most likely behavior in March as a basis, based on the available information and assessment of ILF.

Based on GIZ Survey, the quantity of appliances is provided but wattage information of each appliance is not provided, they shall be assumed as shown below. The current mosque's appliances are listed below:

- 2 Light Bulbs (12 W)
- 2 Fans (50 W)
- 1 Speaker (22.5 W)

According to the information provided by GIZ on 15th May 2017, the averaging praying times in Bulon Don Island are provided and it is assumed that appliances will be utilized during praying times only, as listed below:

- Fajr (early morning, before sunrise) 04:30-05:00
- Dhuhr (mid-day) 12:00-12:45
- Asr (afternoon) 15:15-15:45
- Maghrib (after sunset) 18:15-18:30
- Isha'a (night time) 19:00-19:30

Each prayer time is estimated around 15-30 minutes. Additionally, people usually stay at the mosque after Maghrib till Isha'a.

The specific usages of each appliance are summarized in Appendix 1.

Based on the above assumptions, 24-hour load profile of mosque in March is simulated, as presented in the following figure.

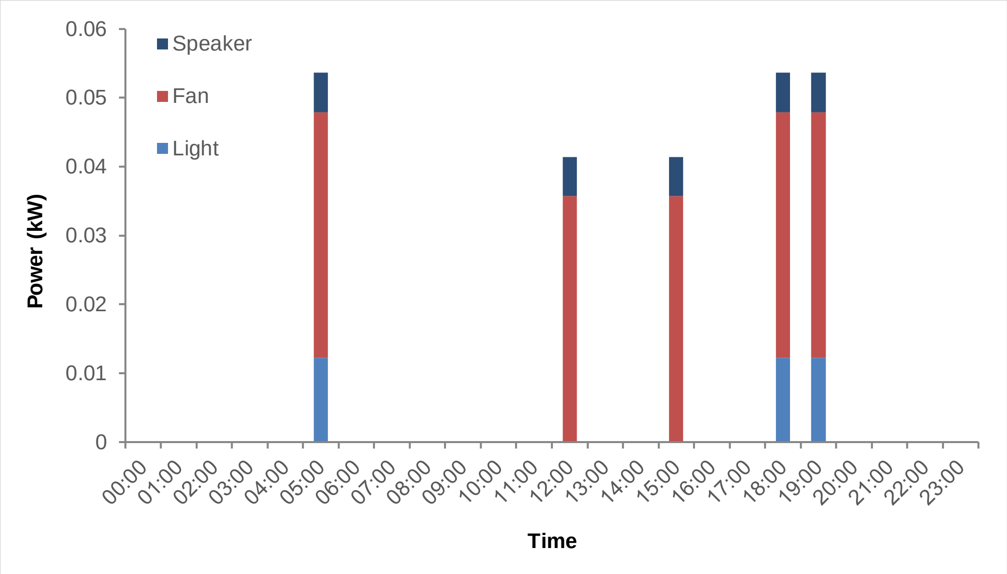


Figure 14: Anticipated 24-hour load profile for mosque of Bulon Don Island in March

The Ramadan period and seasonality influences will be taken into account and described more detail in the following sections.

The Consultant estimates that the mosque requires energy approx. 0.24 kWh/d in March.

Health Centre

As the on-site measurement did not apply to the health centre, the Consultant assumes the most likely scenario based on the available information and assessment of ILF.

Based on information received during the site visit, only one doctor is stationed at the health centre but the health centre is currently not operating because the ceiling is broken. However, based on information provided by GIZ on 15th March 2017, the health centre is planned to reactivate after the ceiling is repaired. Therefore, the 24-hour load profile of health centre is estimated considering existing appliances recorded in GIZ Survey when ready for utilization.

Based on GIZ Survey, the health centre's quantity of appliances and power of some appliances are provided. However, the power of remaining appliances that are not indicated in the GIZ Survey or received any information during the site visit shall be assumed. The current health centre's appliances are listed below:

- 5 Light Bulbs (20 W);
- 2 Fans (50 W);
- 1 Communication System (150 W); and
- 1 Oxygen Concentrator (350 W).

The GIZ Survey records a radio as one of the appliances in health centre, which the Consultant understands is a communication system (radio, transmitter, speaker, microphone, etc.) based on observation during the site visit.

Since the oxygen concentrator could be used in an emergency case at any time. The system shall therefore be able to serve the equipment at any time. In a worst-case scenario, it might be utilized during the peak power period, specifically 19:00-20:00. The Consultant then assumed the oxygen concentrator to be used 30 minutes a day during the peak power. The communication system is considered to be in standby mode, 10% rated capacity, for the entire day. Lightings are utilized more in the night-time and less in daytime but fan is vice versa.

The specific usages of each appliance are summarized in Appendix 1.

Based on the above assumptions, 24-hour load profile of health centre in March is simulated, as presented in the following figure.

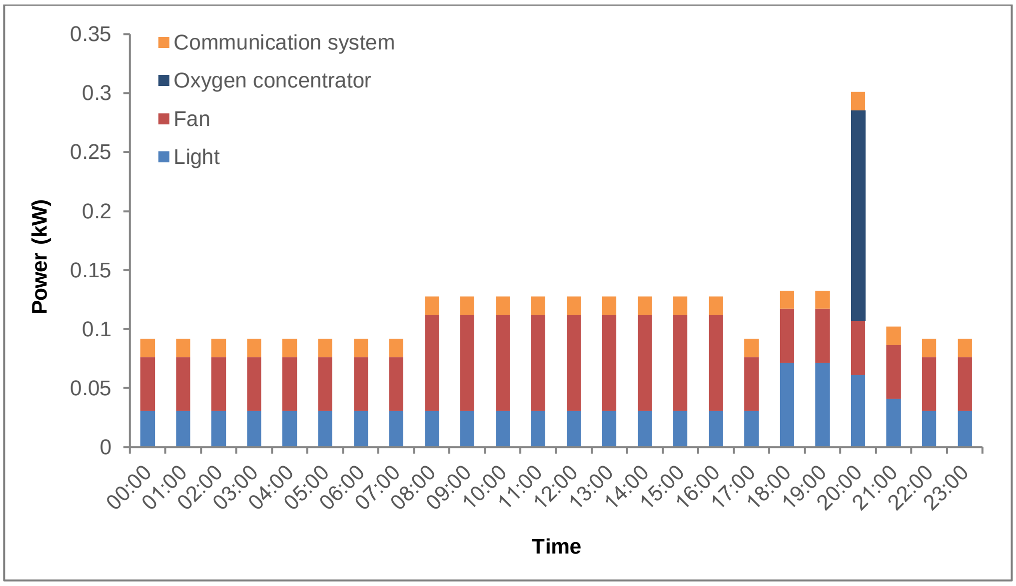


Figure 15: Anticipated 24-hour load profile for health centre of Bulon Don Island in March

The seasonality influences will be taken into account and described more detail in the following chapter.

The Consultant estimates that the health centre requires approx. 2.88 kWh/d in March.

Street Lighting

During the site visit, the Consultant has been informed that street lights have previously been installed. However, during the site visit, the street lights had been removed.

Therefore, the Consultant assumes that the street light will be reinstalled right after hybridization system installation. The quantity and power of light bulbs are assumed:

- 50 Light Bulbs (12 W).

The street lights are expected to be in operation only in the night time (18:00-06:00).

Based on the above assumptions, 24-hour load profile of street light in March is simulated, as presented in the following figure.

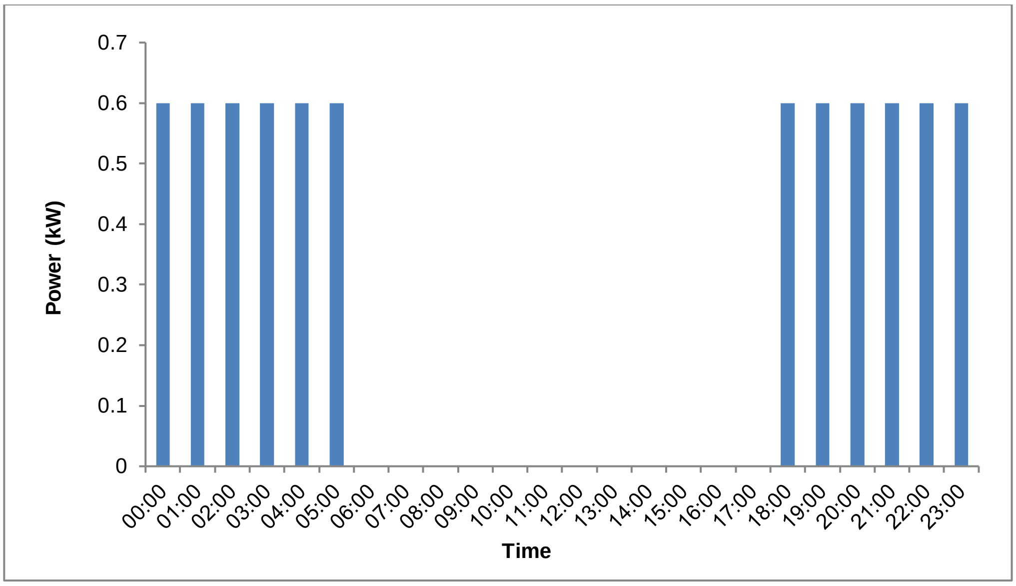


Figure 16: Anticipated 24-hour load profile for street lights of Bulon Don Island in March

The Consultant estimates that the street light requires approx. 7.2 kWh/d in March.

Battery Storage Room

Based on the area requirement for battery storage and PV-inverter, the room shall be approx. 9 sq. meter and requires a 9,000 BTU air conditioner for sufficient cooling. The air-conditioner load profile is specific to the surrounding climates conditions, which is complex to model accurately and requires a much higher resolution of 1 min for load profiling. As of this an average consumption per hour is assumed, in which day time day time cooling demand will be higher compared to the night time, shown in Figure 17. The average demand is approximately 1,700 kWh/year. Additionally the system is sufficiently designed to account for the in-rush current associated with the starting of the compressor.

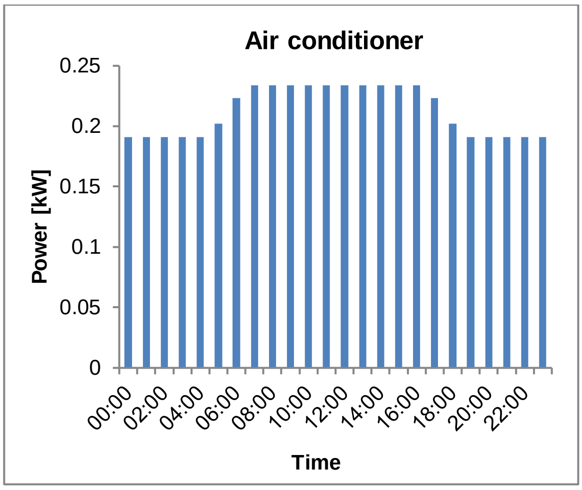


Figure 17: Anticipated load profile for A/C in battery storage room

4.4.3 Anticipated 24-hour Load Profile of the Bulon Don Island

The anticipated 24-hour load profile of Bulon Don Island is estimated based on the combination of the load profile of all clusters. The typical load profile of Bulon Don Island is assumed as 1) typical load profile of 82 households in March 2018, 2) during school semester, 3) Ramadan is not considered, 4) health centre has been reactivated, and 5) street light is reinstalled.

The anticipated 24-hour load profile of Bulon Don Island is presented in Figure 18.

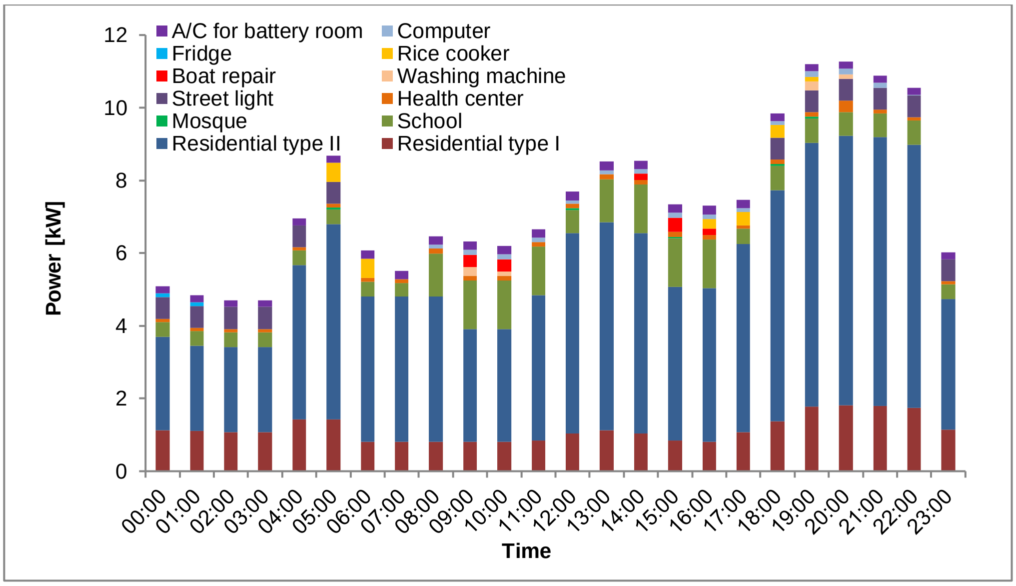


Figure 18: Anticipated 24-hour load profile of Bulon Don Island in March

The energy demand of Bulon Don Island incorporated all clusters in March is presented in the following table.

Table 12: Estimated energy demand of Bulon Don Island incorporated all clusters

Item	Value
Residential (82 households)	147.12 kWh/d
School	18.38 kWh/d
Mosque	0.24 kWh/d
Health centre	2.88 kWh/d
Street light	7.20 kWh/d
Air conditioner for battery storage room	4.66 kWh/d
Total	**180.48 kWh/d**

4.5 Influences of the Seasonality on Energy Demand

To develop the energy demand and load profiles over the 12 months, the Consultant takes the seasonality effect into consideration.

According to the Thai Meteorological Department (TMD) weather data, the weather on the island can be divided into 3 seasons as follows:

1. Summer season : Jan, Feb, Mar, Apr, Nov, Dec
2. Rainy season : May, Jun, Jul, Aug
3. Monsoon season : Sep, Oct

The seasonal effects on the island have influence on the locals' behaviour directly as assumptions below:

In rainy season,

1. The temperature will be lower than in the summer. Fans will therefore switch on at level 1 instead of level 2 in the summer season, (the power consumption of the fan at level 1 is approx. 20W). The power consumption of the fridge in the rainy season is also less than in the summer season.
2. The daylight hours will be less than the summer season and the number of cloudy and dark days will increase. The number of light bulbs switching on during the daytime will increase by approx. 20%.
3. Due to the turbulent waves, the fishermen cannot go out for the fishing, which could lead to approx. 10% more TVs being switched on during rainy season in comparison to summer season as mentioned in Chapter 4.4.1.

In monsoon season,

1. The effect is similar to rainy season but increased. The number of fans switching on at the same time will be reduced by approx. 20% less than in the rainy season. The number of light bulbs switching on during the daytime will be

increased by approx. 15%. The number of TVs switching on during the normal fishing time will be increased 10% more than in the rainy season.

Furthermore, the school also has the seasonality effect from the end-of-semester period which is in Mar, Apr, May and Oct. Therefore, the power consumption of the school will be less during the end of semester. The following assumptions apply:

1. The power consumption of the appliances related to the classroom during the end of semester, which are fans, light bulbs, computers and TVs, will be significantly reduced.
2. The season on the island described above also has influence on the school's load profile.

Since most of the locals are Muslims, Ramadan period[1] also has influence on the locals' behaviour as follows:

1. For the breakfast, the locals must finish breakfast before the sunrise, therefore, they have to wake up very early in the morning. The energy demand of light bulbs, fans, rice cookers and TVs shall be shifted to the early morning.
2. For the dinner, they must have dinner after the sunset. The energy demand of the appliances shall be shifted to the late evening.

4.6 Peak Load Analysis

Based on the on-site measurement data, the daily peak loads during the measurement period were analysed. Subject of the analysis is the specific P90 power which covers 90% of the annual measured peaks. In other words, 90% of the total amount of measured values are below or equal to the P90 value. The results are outlined in Table 13.

Table 13: Measured daily peak load and P90

Period	P90	Highest measured peak
1st March 2017 to 1st April 2017	0.80 kW	1.18 kW

The distribution of daily peak load is showed in Figure 19. It should be noted that the outliers are excluded from the peak load analysis.

[1] Ramadan period depends on Islamic calendar which is changed every year. The developed load profiles in this study are considered Ramadan period in July only.

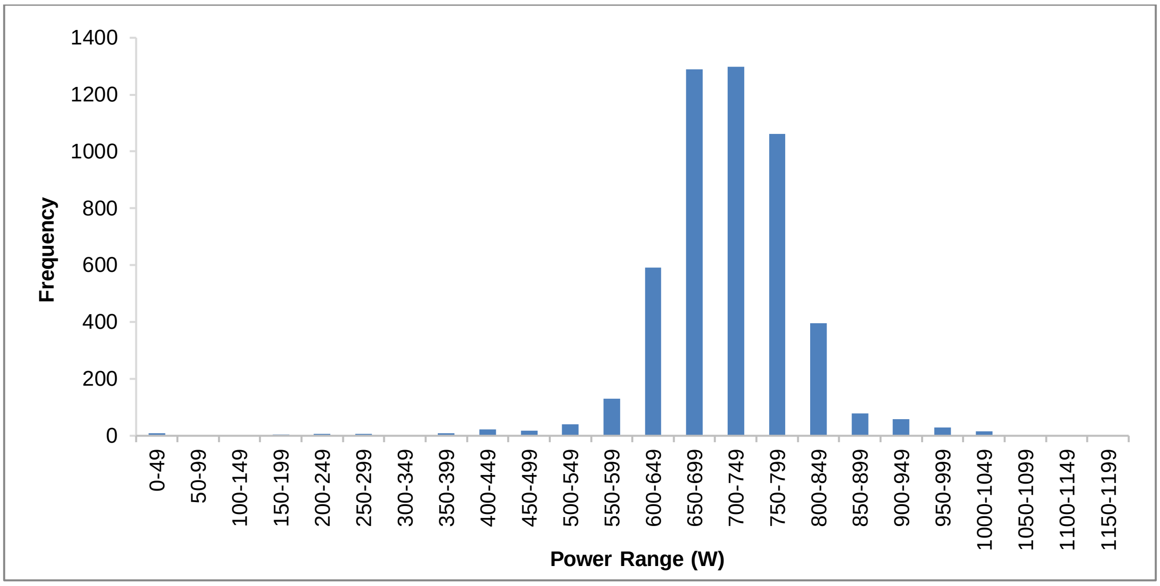


Figure 19: Distribution of measured daily peak load

As the total energy daily consumption is scaled up based on the on-site measurement data. Therefore, P90 of Bulon Don Island is estimated to increase by the same proportion as the average power. The P90 is approximately 8.10 kW.

4.7 Forecast Future Energy Demand and Load Profile

4.7.1 General Assumptions

The Consultant estimated the future energy demands and developed the corresponding future load profiles based on the assumptions for energy demand forecast and additional appliances as shown in Table 14. The assumptions can be divided into 3 parts which are:

1. Residential household growth
2. Specific appliance growth (quantity growth)
3. Power consumption growth

It has to be noted that all of the growth assumptions are cumulative calculation.

Table 14: Assumptions for energy demand forecast

Item	Growth description	Y1-Y5	Y6-Y10
Residential household growth			
Household growth	Additional new household	1 p.a.	1 p.a.

Item	Growth description	Y1-Y5	Y6-Y10
Residential type I (will buy new TV)[1]	% of Residential type I in previous year	20% p.a.	10% p.a.
Specific appliance growth (quantity growth)			
Rice cooker	% of total residential households	4% p.a.	2.5% p.a.
Washing machine	additional amount per year	1 p.a.	0
Fridge	% of total residential households	4% p.a.	2% p.a.
Laptop and desktop computer	% of total residential households	5.5% p.a.	3% p.a.
Power consumption growth			
Fan power consumption	% of total residential households' fan power consumption	4% p.a.	2% p.a.
School	% power consumption	3% p.a.	
Health centre	% power consumption	2% p.a.	
Mosque	% power consumption	2% p.a.	
Street light	% power consumption	0.5% p.a.	
Boat repairing	% power consumption	2% p.a.	

Furthermore, Table 15 below shows the assumptions for future appliances during year 1-5 for school, health centre and mosque, which were made by GIZ to estimate the future demand to develop the corresponding load profiles.

Table 15: Future appliances assumptions for energy demand forecast during year 1-5 for school, health centre and mosque

Item	No. of future appliances (unit)		
	School	Health centre	Mosque
Lighting	12	2	5
Radio	1	0	0
Fan	5	2	2
Phone	3	1	0
TV	2	1	1
Rice Cooker	1	0	0
Computer	3	1	1

[1] This results in residential type I will be changed to type II, in other words, residential type II will increase 20% of residential type I in previous year (year 1 to 5) and 10% (year 6 to 10).

Item	No. of future appliances (unit)		
	School	Health centre	Mosque
Speaker	0	0	0
Fridge	1	1	0
Iron	1	0	0
Washing Machine	1	1	0

4.7.2 2018, 2022 and 2027 Results

Figure 20 shows the estimated values for the future energy demand. The values were estimated based on the assumptions which have been defined in Chapter 4.7.1.

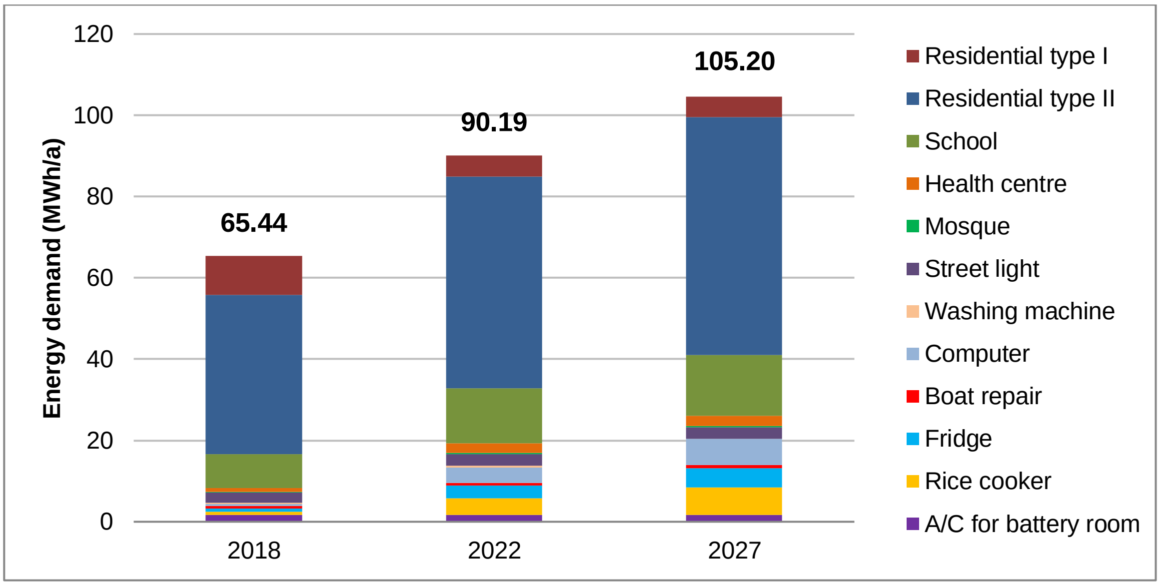


Figure 20: Future estimation of energy demand

Taking distribution losses of 1% into account, the future energy generation delivered by the hybrid power plant is summarized in Table 16.

Table 16: Future estimated amount of generated energy by hybrid power plant

Data	2018	2022	2027
Gross generation of hybrid power plant	66.10 MWh/a	91.11 MWh/a	106.26 MWh/a

4.7.3 Results of Peak Load Forecast

The Consultant takes the following daily peak load forecasts for the next ten years into account. The future load profiles were estimated based on monthly average values (see

Figure 21). To simulate more realistic values, the random variability inputs[1] of day-to-day approx. 15% and a time step of approx. 10% were assumed in HOMER simulation. The hourly load demand will be automatically generated by HOMER.

Based thereon, the resulting peak powers are listed in Table 17.

Table 17: Summary peak load forecast

Data	Average power (P_{avg})[2]	Peak power (P_{max})	P_{max}/P_{avg}	Peak power (used in HOMER simulation)
2017[3]	0.71 kW	1.18 kW	1.66	-
2018	10.81 kW	17.98 kW		18.06 kW
2022	15.26 kW	25.39 kW		25.72 kW
2027	17.83 kW	29.67 kW		29.94 kW

4.7.4 Developed Load Profiles in 2018, 2022 and 2027

The developed future load profiles are shown in Figure 21. The load profiles were implemented in the HOMER simulation considering the random variability as mentioned above.

[1] These values are added randomly to the load profile to make it more realistic. However, the total energy and average power are not modified.

[2] The average power is considered only in March, 18:00-22:00.

[3] The data in 2017 derived from measured data of 9 households in March.

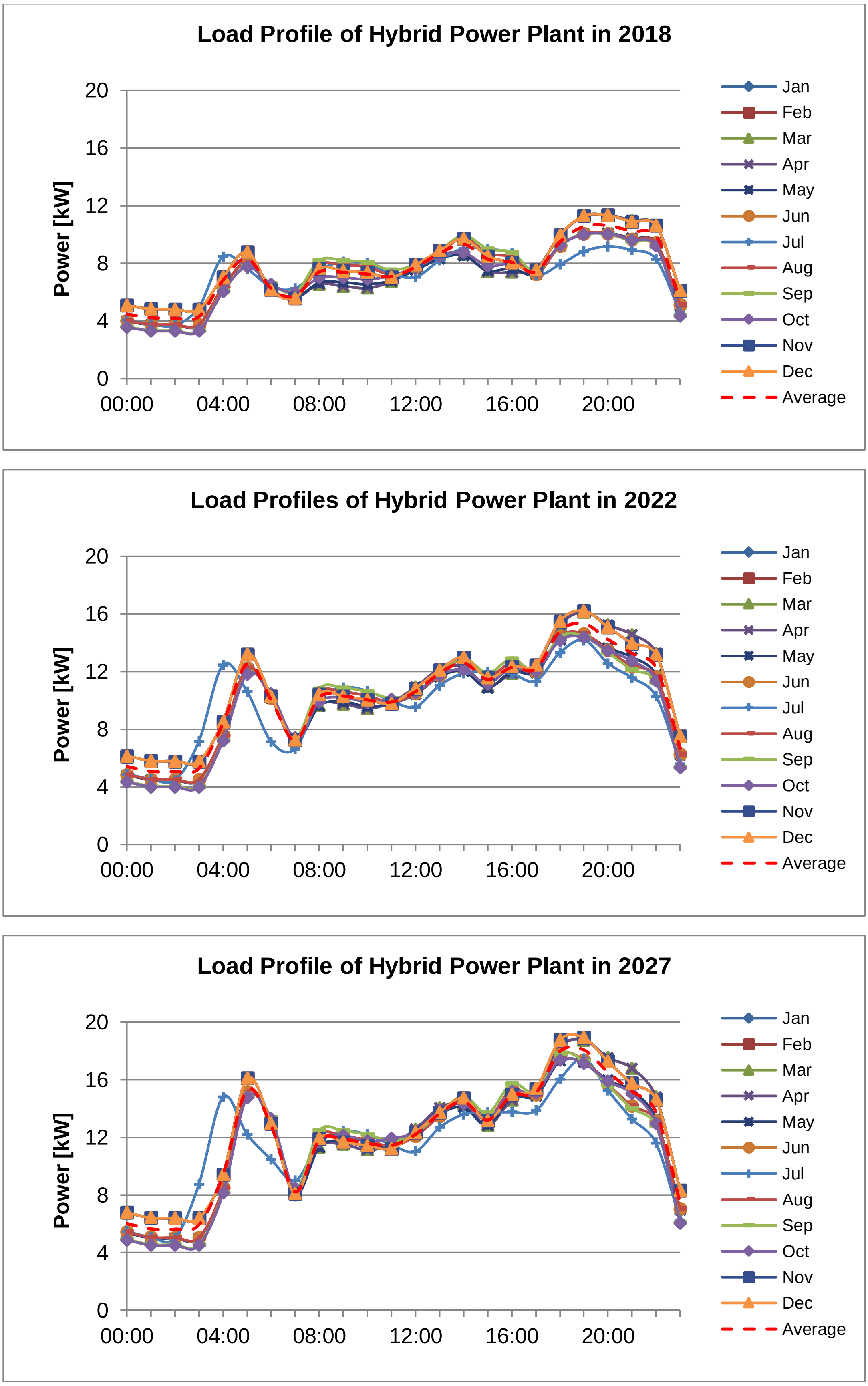


Figure 21: Developed load profiles in 2018, 2022 and 2027

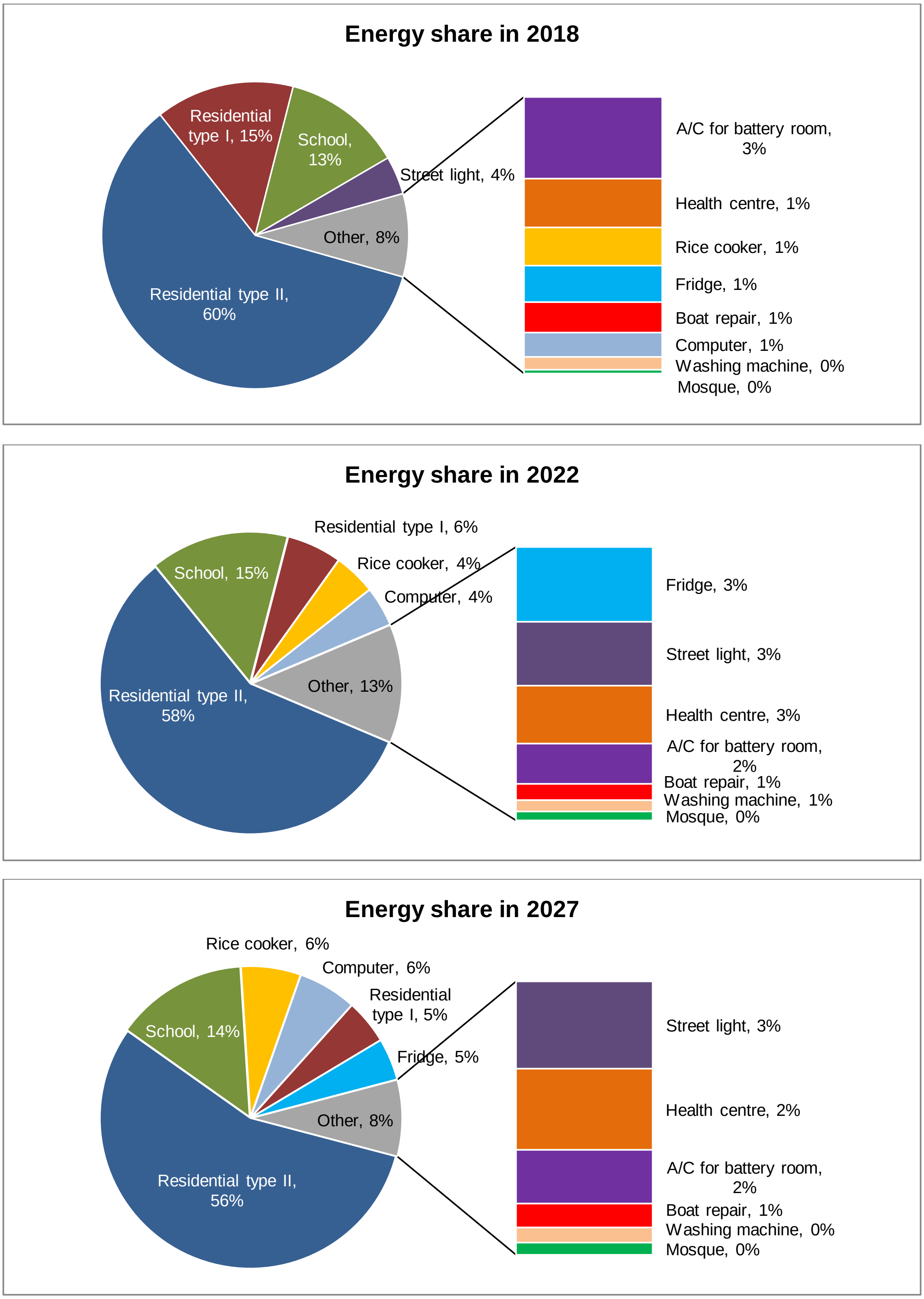


Figure 22: Energy share in 2018, 2022 and 2027

5 HYBRID SYSTEM DESIGN AND ENERGETIC SIMULATION

5.1 Sizing and Simulation Tools

To size, simulate and optimize the hybrid system of Bulon Don Island, the HOMER Pro® version 3.9.1 was used. HOMER (Hybrid Optimization Model for Multiple Energy Resources) is a commonly used simulation software to design renewable hybrid micro grids for on- and off-grid application. Also, the software initially will evaluate and optimize the technical and economic feasibility of a large number of technology options. For a more flexible and powerful economic optimization and financial calculation, the Consultant used an in-house developed Microsoft-Excel-based calculation tool.

5.2 System Architecture and Methodology of Operation

Figure 23 shows the schematic system architecture of future hybrid system of Bulon Don Island. The hybrid system consists mainly of the following components:

- Diesel Generators
- PV power plant including string inverters
- Battery storage system including grid forming battery inverters and hybrid system controller

The detailed arrangement of the components and its specific capacities are shown in the Single Line Diagram (SLD) in Appendix 6 and are further discussed in the following sections.

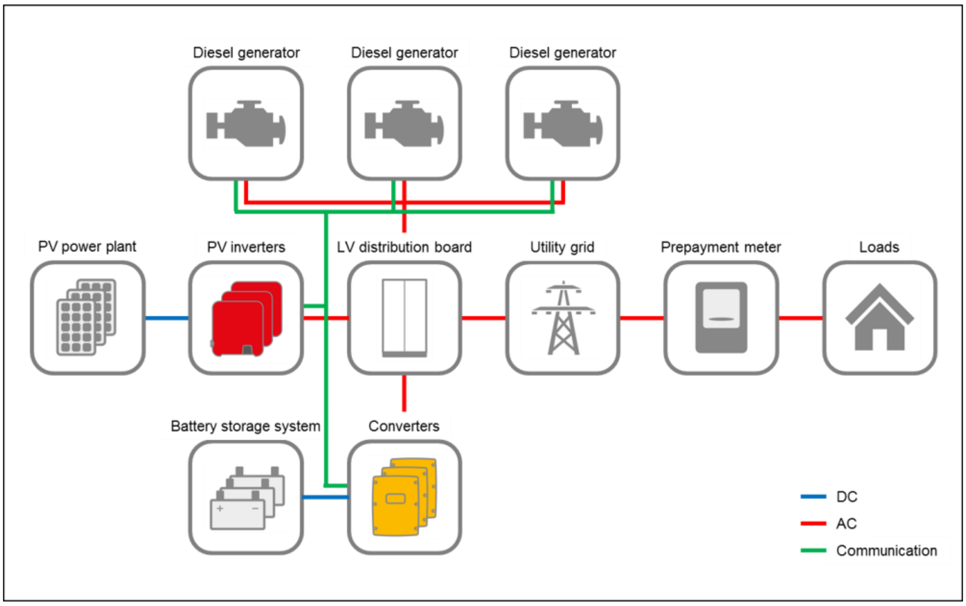


Figure 23: System architecture hybrid system the Island

Figure 24 illustrates the principle of operation of the hybrid system of the Island. During the day the output power of PV system covers the whole load and generates sufficient surplus energy to fully recharge the battery (SOC_{max} = 100%).

During the evening peak hours (~18:00-23:00), the diesel generators are forced to run, and the generator, when technical possible, runs at its rated capacity (load factor ~80%) as shown in Figure 35. This also generates surplus energy to charge the battery up to defined SOC. Furthermore, whenever the energy feeding from the PV system or the battery is not sufficient to cover the load, the diesel generators will be activated running at its rated capacity to cover the remaining load and create surplus energy to charge the battery.

This methodology is called Cycle Charging ("CC"). Benefit of CC operation method is to reduce the operating hours of diesel generators at low load factor (below 50%) significantly, as the generator is always running at its rated capacity. With CC, the shared generated energy by the diesel generator will increase and total renewable fraction consequently is lower.

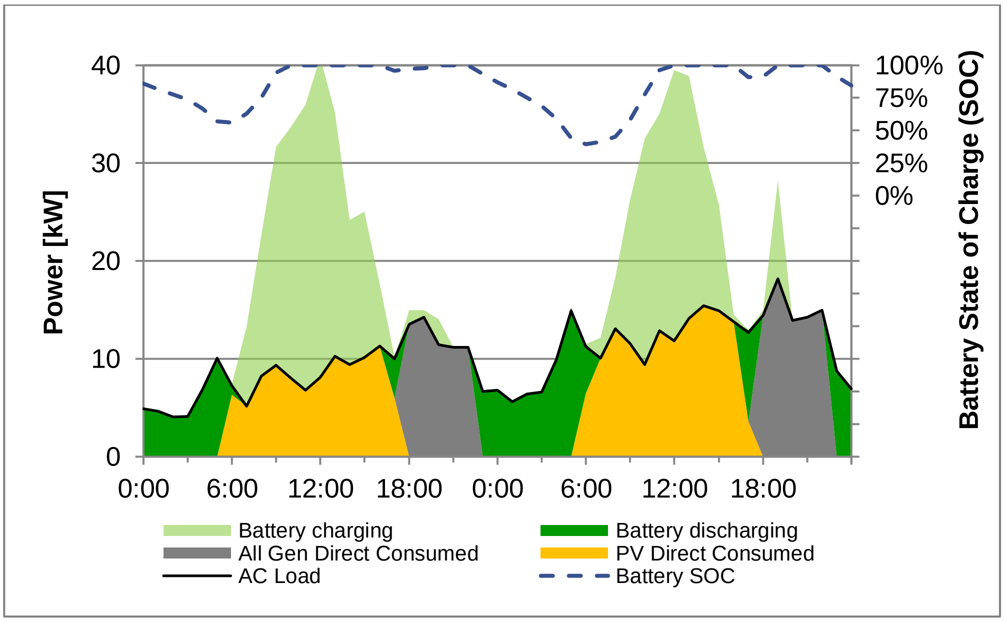


Figure 24: Operating methodology hybrid system

An alternative to CC approach is called "Load Following" (LF). This means, a generator produces only sufficient power to serve the load and does not charge a battery. As a result, the LF operation method provides a higher renewable fraction (lower demand of conventional fuel), which it is a benefit of this operation method. However, the operating hours of diesel generator at low load factor (below 40%), e.g. bad sunlight day, would be higher.

The Consultant has simulated both scenarios and recommends the operation methodology "Cycle Charging" for Bulon Don Island to achieve the lowest Levelised Cost of Electricity ("LCOE"). Bulon Don Island load is rather fluctuating, as it is a small island where only a few high wattage appliances could impact the peak load. Hence, higher generator operating duration at low load factor would be higher under LF operating method, which this could shorten the generator life time. It notes that the renewable fraction of both CC and LF are about equal.

To control the hybrid system, there are two common types of communication systems:

1. The heart of the hybrid system is the battery inverter together with the hybrid system controller. The battery inverter is the grid forming unit, providing frequency and voltage. The hybrid system controller communicates in a separate network (see Figure 23) and is generally responsible for the balance between the load and the hybrid system components and shall ensure grid stability even in critical situations. The controller communication is based on pre-defined and component specific set-points. For instance, the controller would switch on the diesel generators to provide the required power, once the PV system and battery outputs are no longer sufficient to supply the current energy demand.

2. Another way of communication between battery and PV system is the so-called "frequency droop control". This means, the battery inverters uses only the frequency as a communication medium to control the output power of the PV inverters. This solution avoids additional communication cables between battery inverter and PV inverter making the hybrid system controller, which it is less complex in terms of communication units.

The frequency droop control is usually used within smaller and less complex systems (PV system capacity below 300 kW_p) and this is recommended for Bulon Don Island.

5.2.1 Diesel Generator

The main objectives of sizing the diesel generator are:

- to select the right size which will be sufficient to provide the required power during the average peak load hours in the evening, and
- to limit the number of operating hours

Figure 25 shows the specific consumption curves for various diesel generators. The diesel generator operates ideally above 50% of its rated capacity, to reduce the specific diesel consumption per generated megawatt-hour. Frequent undercutting of this threshold value may impair the diesel generator and lead to higher maintenance effort and consequently to a limitation of its average operation lifetime. Therefore the aim during simulation and sizing was to increase the operating hours above 50% and to operate the diesel generator in an optimal range of above 50% as well.

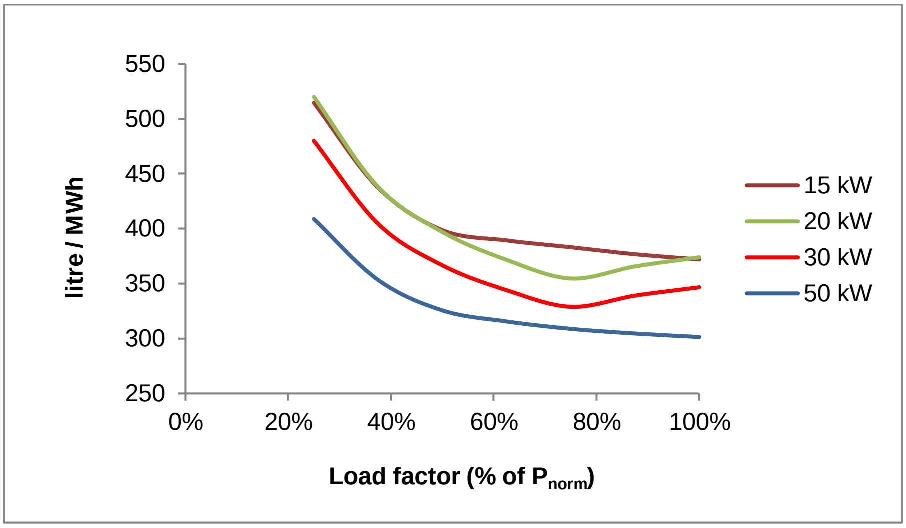


Figure 25: Specific consumption curve for different size of diesel generator[1]

The optimized diesel generator capacity, for the case of the island has been identified to be 15 kW (18.75 kVA) considering a power factor of 0.80. In the first year of operation, one generator should almost be sufficient to serve the load during the average peak load hours in the evening. In case the output power will be no longer sufficient, the second generator will be switched on and they share the load. In the later years, the load will increasingly require the second generator. It has to be noted that the third generator represents a backup, in case of a failure or maintenance demand.

Currently, the diesel generators were controlled manually by the locals. In the future hybrid system, an automatic mode will be implemented to ensure the required grid stability.

The main characteristics are summarized in Table 18. Most of the parameters were implemented and considered in the HOMER simulation. But it needs to be mentioned, that it is not possible to define the power factor or the overload capacity in HOMER itself.

Table 18: Main characteristics of the diesel generator

Parameter	Value
Number of generators	3
Application class (according to ISO-8528-1)	Prime Power (PRP)
Operation strategy	Load sharing (if necessary during peak load hours)
Generator size	15 kW (18.75 kVA)
Power factor (cosφ)	0.8
Minimum load ratio	30%
Possible (short-term) overload capacity	10%

[1] Source: Generac diesel generator datasheet

Parameter	Value
Lifetime (operating hours) before general revision or replacement	20,000 hrs
CO_2 emission (diesel fuel)	2.64 kg/l

5.2.2 PV/Battery Sizing Optimization

The size of the PV power plant was optimized according to the following criteria:

- The output power during an average day with average solar irradiation must be enough to cover the daytime load and further to create sufficient surplus energy to fully recharge the batteries
- PV system excess energy should not exceed 40%

For the battery, the Consultant considered Li-ion technology and took no further technology such as lead-acid based battery into consideration. The capacity of the Li-ion based battery was optimized according to the following criteria:

- The amount of energy is usually necessary to cover the load during the night and early morning hours,
- In combination with the daily direct consumption of PV energy, the hybrid system shall achieve an annual renewable fraction of more than 60% considering the future estimated energy demand in 2018, and
- The hours of the battery operating at SOC more than 20% shall be increased to extend the battery's lifetime

To achieve the above criteria the range of PV capacity, 40-70 kWp, and battery capacity, 90-130 kWh, has been simulated by HOMER to show the sensitivity of the LCOE compared to installed capacity. Figure 26 shows the LCOE of the hybrid system in various sizing's of PV/Battery capacity compared with the lowest LCOE scenarios, the optimum LCOE vales for PV/Battery are 45 kWp / 90 kWh, 60kWp / 90kWh and 70kWp / 110kWh for 10, 20 and 30 year project life time's respectively.

While a financial optimum appears at these levels, there are technical issues surrounding a battery capacity of 90kWh which become increasingly apparent from year 5 onwards. The issue is that the battery bank becomes increasingly unable to serve the morning load, before the PV can provide sufficient power. As of this the generator is required to start and the frequency of the start-stop operation of the generators increases. To avoid any damage from start-stop operation of the generators the Consultant recommends to increase the battery bank capacity by 10 kWh. The LCOE varies only slightly from the optimum while mitigating any damage that could be incurred from stop-start operation.

The PV capacity is a function of the demand, as the project lifetime increases, so does the required capacity. In this scenario, as the project lifetime increases so does the unpredictability of forecast demand. As solar can be considered modular the Consultant recommends and installed capacity of 50 kWp to be installed. Similarly to batteries, the LCOE only varies marginally from the optimum in the 10 and 20 year scenarios while mitigating risks associated with a higher CAPEX in year 1.

At year 10 a design review should be triggered to assess the actual trends in load profile to expand the system size to maintain the lowest LCOE while at safe and stable operation.

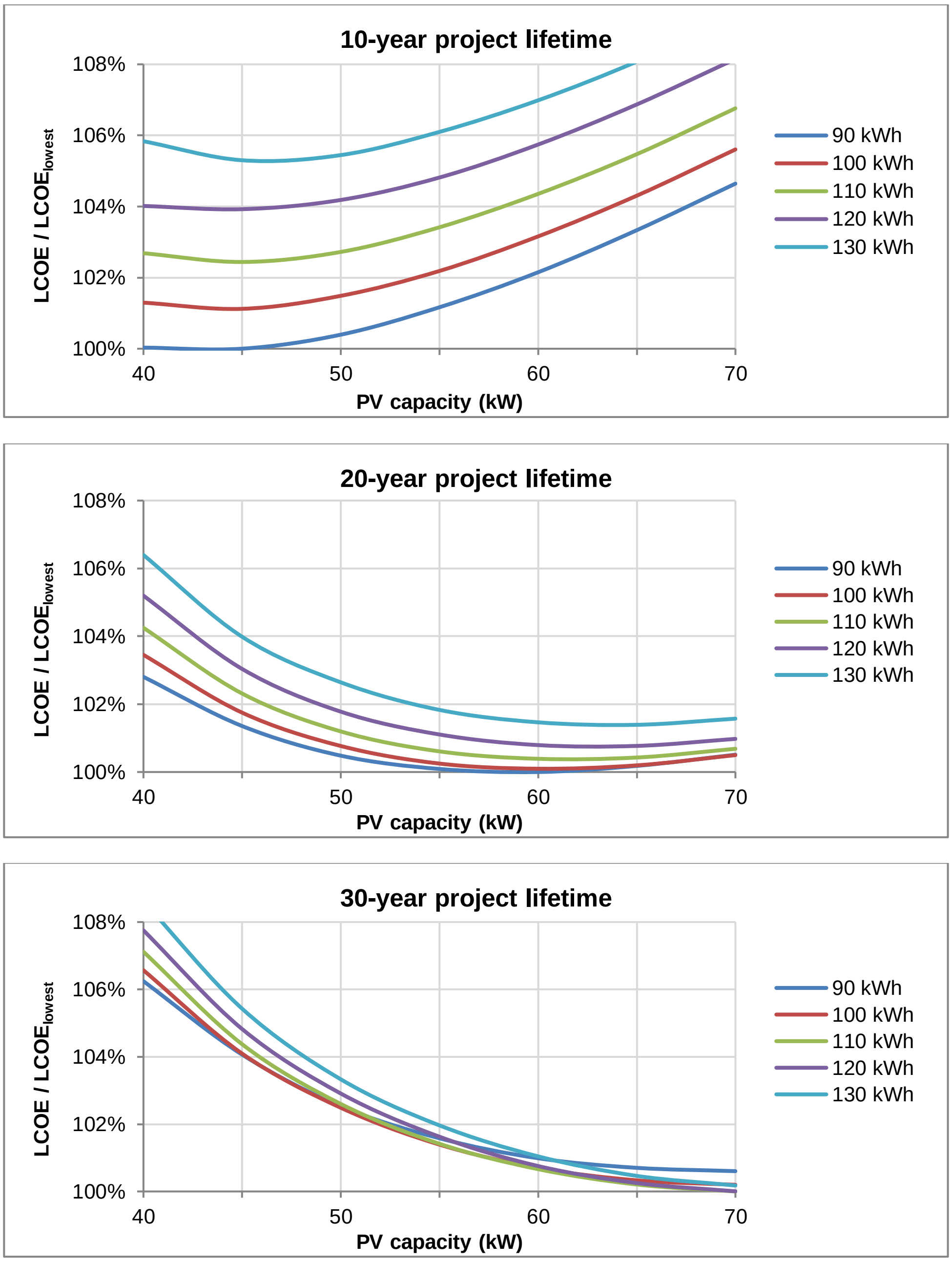


Figure 26: LCOE / LCOE$_{lowest}$ of various sizing of the PV/Battery capacity for 10-, 20- and 30-year project life time

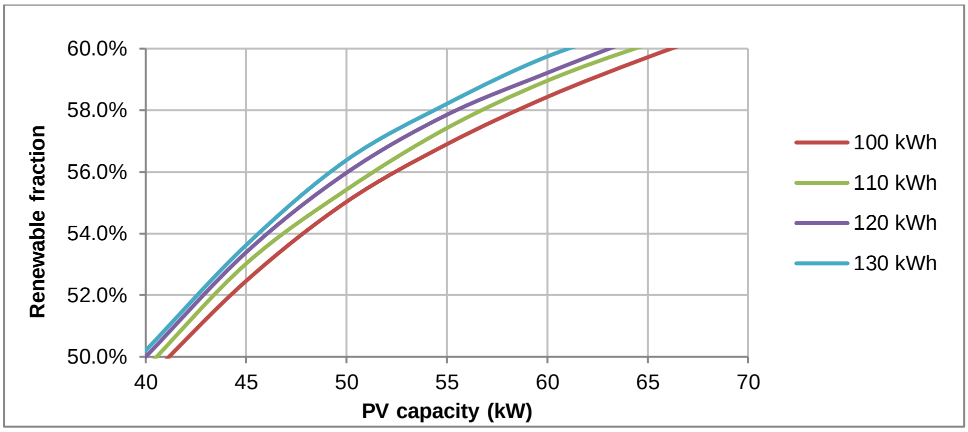


Figure 27: Renewable fraction of various sizing of the PV/Battery capacity in year 2022

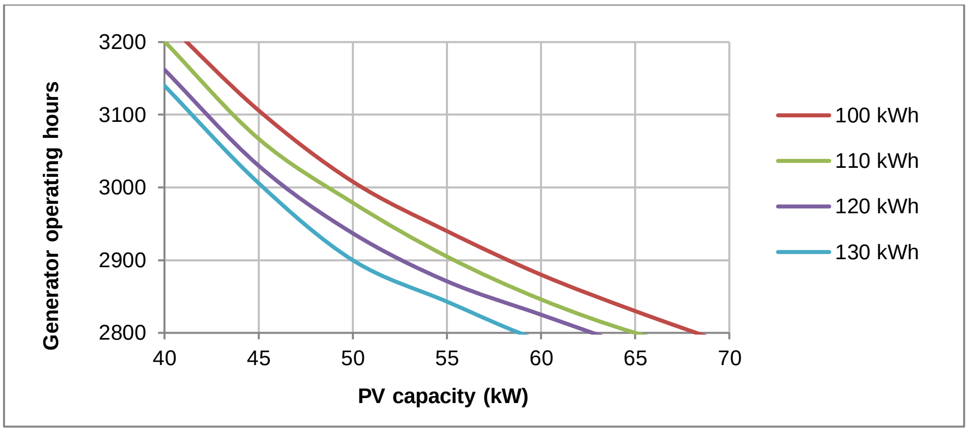


Figure 28: Total generator operating hours in year 2022

To minimise the amount of installed capacity on the ground the Consultant assessed the rooftops at the school for installation. To use all available space on the rooftops, 10.56kWp (32 modules) must be mounted on the ground. As of the sub-optimal orientations of the roof from varying orientations and increased heat losses, the installed capacity must increase to 52.14 kWp. This arrangement will output the same power as the 50 kWp scenario used in HOMER, which was a south facing and ground mounted arrangement. In Figure 29, the Consultant has drafted the layout for the solar modules on the island: Approx. 27.7 kWp may be placed on the rooftop of the grey-roof classroom building, the remaining approx. 27.7 kWp shall be ground mounted in two rows onto the land next to the green-roof school building, replacing the existing solar modules at that location.

Table 19 summarizes the main parameters of the PV power plant. As described in Chapter 3.5, the PV power plant shall be installed within the school area. Figure 29 shows an overview of the designed PV power plant. Power station building for batteries and diesel generators is also included in the Figure 29. Alternatively, the power station building could be constructed on the hillside as shown as No. 6 in the Figure 7.

More information is stated in Appendix 6 (Single line diagram of the hybrid system), Appendix 7 (PV power plant layout) and Appendix 8 (Alternative location of power station).

Table 19: Main characteristics of PV power plant

Parameter	Value
Total PV capacity (DC, STC)	52.14 kWp
Total inverter capacity (AC)	46 kW_{AC}
DC/AC ratio	1.13
Power factor (cosφ)	0.8

Figure 29: PV power plant layout (see Appendix 3 and Appendix 4)

Table 20 summarizes the main parameters of the battery storage system.

Table 20: Main characteristics of battery storage system

Parameter	Value
Technology	Li-ion
Total battery capacity	100 kWh
Battery inverter capacity	27.3 kW
Roundtrip efficiency	~90%
Maximum C-Rate (charge/discharge)	1.0C / 1.0C
Maximum DOD (SOC_{min})	90% (10%)
Estimated shelf lifetime (according to manufacturer information)	30 years (Performance Warranty 10 years and Product Warranty 5 years)
Number of cycles @ DOD 100% EOL 70%	~6,000 cycles
Estimated lifetime throughput	~600,000 kWh
Room conditions for battery storage	▪ An air-condition system must be installed in the battery storage room to prolong the battery lifetime ▪ Battery storages shall be housed in specially made cabinet rated for salt mist protection.

5.2.3 Prepayment Energy Meter

The Consultant proposes the usage of prepayment energy meter on the island due to its benefits for the customers and electricity suppliers. A prepayment meter is a special type of energy meter that can be installed in domestic properties. With a prepayment, or 'pay as you go' tariff, customers pay for their energy before they consume. Users can monitor their usage unit of electricity and also control their usage against their budget.

The payment method is flexible for users. The supplier will receive payment regularly. There is no need to send a person to check on energy meter and to collect the payment from users. This also prevents human error from meter reading.

<u>Prepayment process</u>

Each household is encouraged to register at the electricity supplier spot; the electricity supplier shall install prepayment energy meters for each household. Meters shall be installed visibly to avoid any fraud, i.e. bypass. The electricity supplier shall install a central recharging unit to top-up and provide an energy credit. A user can then use an electricity until a warning signal appears at the energy meter to buy more energy credit.

<u>System Setup</u>

The Consultant recommends to install a prepayment energy meter in outdoor area because this will avoid bypassing the meter. With regard to the safety, a fuse, residual-current device (RCD), surge arrestor, shall comprise a high level of safety and installation quality according to international installation standards.

System Main Functions

- Anti-tampering functions against reverse connection, magnetic and meter/terminal cover open detection
- Emergency credit management
- Two-way communication
- Internal relay for load control
- Max demand management
- Event recording including programming, reverse connection, power failure and tampering
- Import and export active / reactive energy measurement optional
- LCD display item configurable
- Backup battery for energy display when powered off

5.2.4 Transmission line Recommendations for the Hybrid System

To implement the hybrid system on the island, the grid transmission line shall be upgraded. During a site visit, the Consultant observed the cables of the existing central grid transmission are in good condition as mentioned in Chapter 3.2. However, the poles shall be upgraded with a minimum height of 2.5 meters according to the Thai standard. The Consultant recommends the new poles shall be made of concrete. Furthermore, the transmission line shall be extended to cover all households. Therefore, a length of approx. 150 meters as indicated by the red solid line in Figure 30 is deemed necessary. The extended line shall be three-phase line (4-wire cables) same as the existing line.

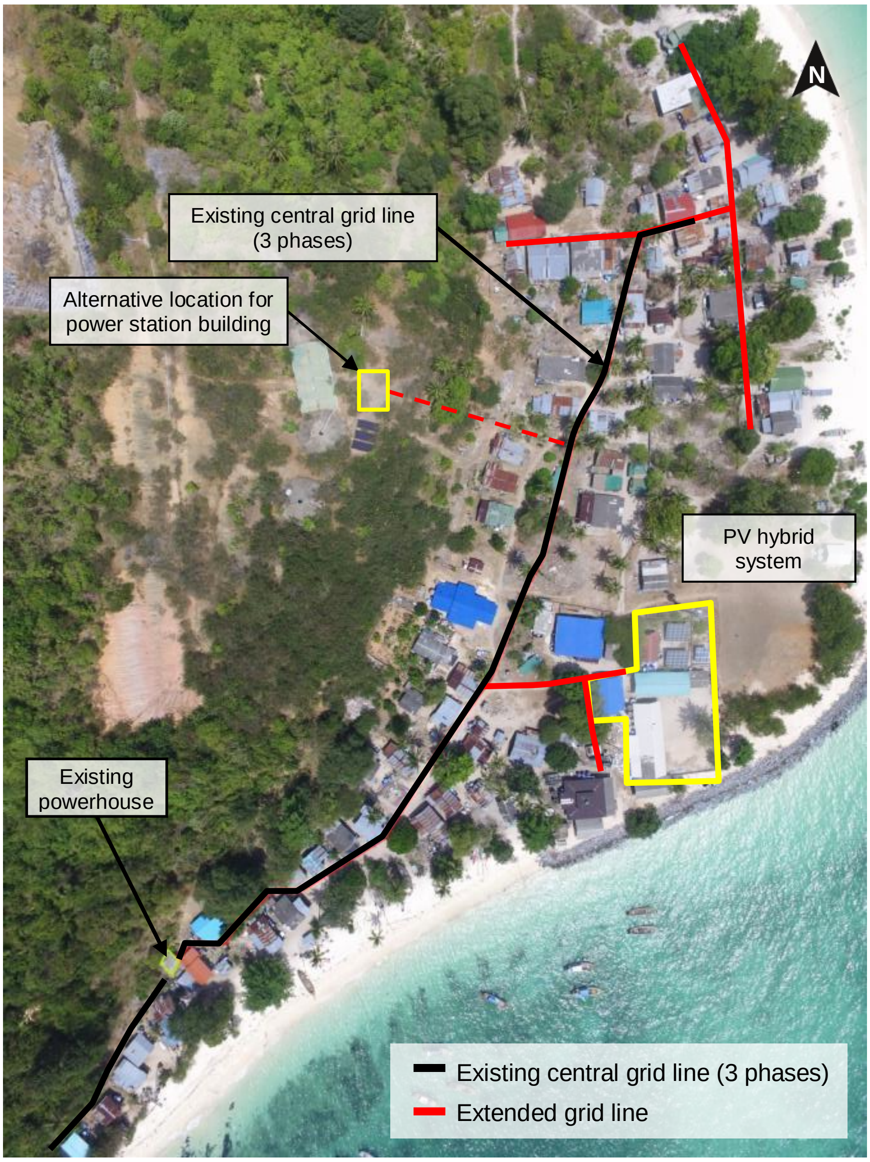


Figure 30: Proposed transmission line on Bulon Don Island

5.3 Other Inputs used in HOMER simulation

It shall be noted that the specifications for the inputs for HOMER simulation are presented in Appendix 2.

5.3.1 Meteorological Data

For the calculation of the expected annual PV yield, the Consultant used the weather data set of Meteonorm 7. The data is shown in the following graph. It shows the monthly average values of Global Horizontal Irradiation (GHI), diffuse irradiation (DHI), ambient temperature.

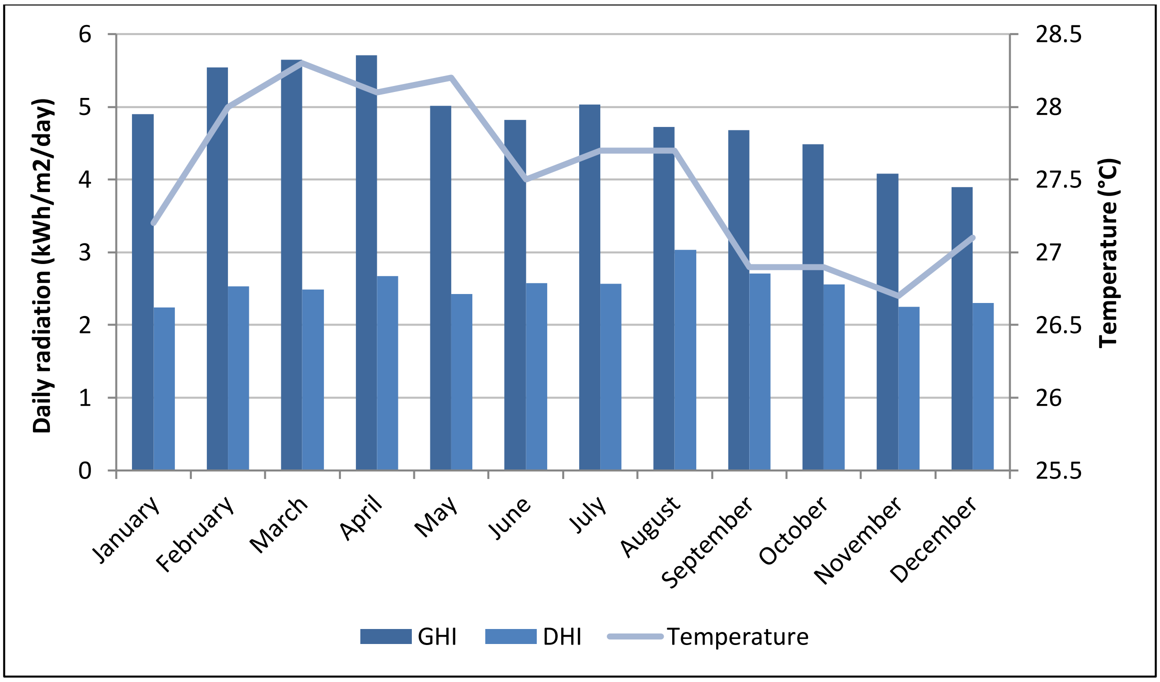


Figure 31: Meteorological data for HOMER and PVsyst simulation

5.3.2 Load Profiles

The load profiles used in HOMER are according to Chapter 4.7.4.

5.4 Interpretation of Simulation Results

The following chapter presents the energetic results of the HOMER simulation. To compare the result with the conventional power generation, a 100% diesel generator scenario was simulated. Therefore, two scenarios were simulated considering in total three different load profiles (2018, 2022 and 2027).

5.4.1 Simulation Summary: Reference scenario with 100% diesel

Table 21: Summary of simulation results reference scenario with 100% diesel

Reference scenario: 100% Diesel	Unit	2018	2022	2027
System parameters				
Total capacity diesel generators	kW	45 (3x15 kW)		
Number of diesel generators	Unit	3		
Homer simulation output				
Total energy production (demand)	kWh/a	66,072	91,067	106,219
Total diesel consumption	l/a	27,463	35,953	41,616
Specific diesel consumption	l/MWh	416	395	392
Total diesel operating hours	hr/a	8,782	9,630	10,783
Operation hours below 50%	%/a	50.83	21.78	13.53
CO_2 emission	t/a	73	95	110

5.4.2 Simulation Summary: Diesel/PV/Battery Hybrid System

The main energetic simulation results of the Diesel/PV/Battery hybrid system are summarized in Table 22. In first year of operation (2018), a renewable energy share of 62% could be achieved. Due to the increasing load over several years, this value will be reduced to approximately 47% within the next ten years (2027). Compared to the 100% diesel reference scenario in Table 21, the diesel consumption as well as the diesel operating hours can be reduced. Moreover, due to the limitation of diesel operating hours below 50%, the specific consumption of the diesel generators in the hybrid system is acceptable. Harmful annual CO_2 emission could be also reduced.

Table 22: Summary of simulation results Diesel/PV/Battery hybrid system

PV / Diesel / Battery Hybrid System	Unit	2018	2022	2027
System parameters				
Total capacity diesel generators	kW	45 (3x15 kW)		
Number of diesel generators	Unit	3		
Total PV capacity	kW_p	52.14		
Total PV inverter	kW_{AC}	46		
Total battery capacity	kWh	100		
Usable total battery capacity (SOC_{min} 10%)	kWh	90		
Battery inverter capacity	kW	27.3		
Homer simulation output				
Total energy production (demand)	kWh/a	66,072	91,067	106,219
Share Diesel	kWh/a	24,940	42,077	55,933
Share PV and battery	kWh/a	41,132	48,990	50,286
Excess PV energy	kWh/a	25,096	14,417	11,250
Total diesel consumption	l/a	9,460	15,795	20,944
Reduction of diesel consumption (compared to diesel reference scenario)	l/a	18,003	20,158	20,672
Specific diesel consumption	l/MWh	379	375	374
Renewable fraction (PV and battery)	%	62	54	47
Excess PV energy	%	37	22	18
Total diesel operating hours	hr/a	2,047	3,193	4,162
Operation hours below 50%	%/a	6.37	0.28	0.04
CO_2 emission	t/a	25	42	55
Reduction of CO_2 emission (compared to diesel reference scenario)	t/a	48	53	55

5.4.3 Energy Distribution 2018-2047

Figure 32 shows the energy distribution curve over the whole project lifetime. Due to the increasing energy demand from 2018-2027 and considering an annual PV degradation of 0.5%, the renewable share is decreasing compared to the total energy production. After 2027, the annual energy demand was estimated as constant and the renewable share is reduced annually by 0.6% in average. However, there is an increase on renewable share on 2034 because of the replacement of the battery storage.

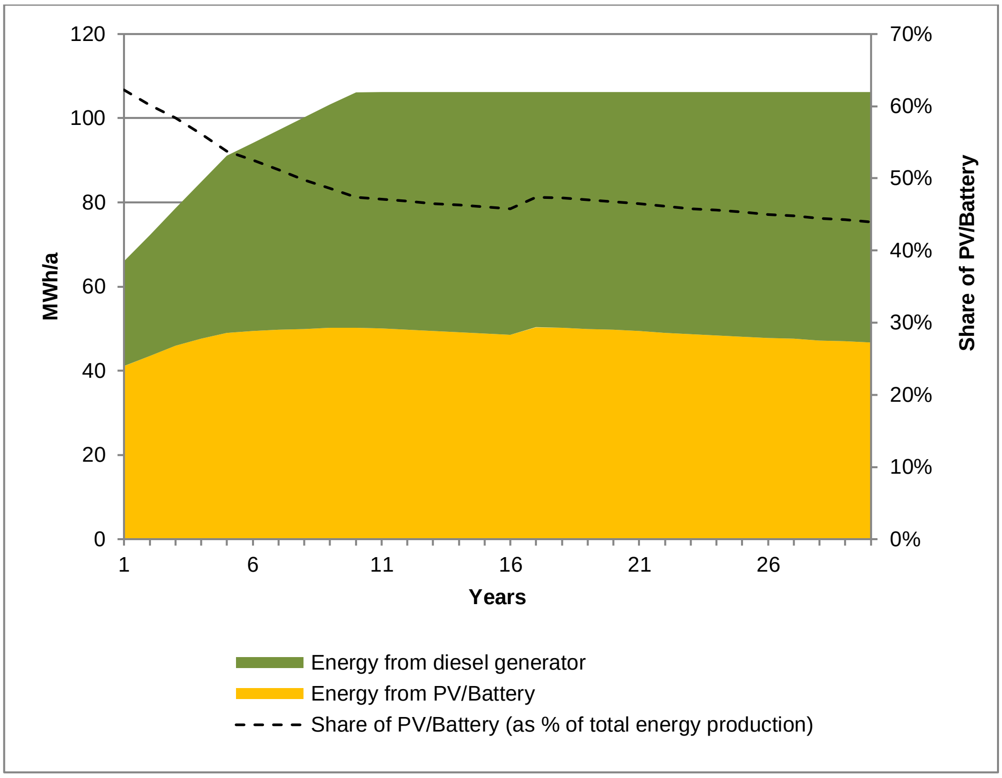


Figure 32: Energy generation and distribution curve 2018-2047

5.4.4 Energy Generation and Consumption Curve for a Typical Week 2018, 2022 and 2027

Figure 33 shows the energy generation and consumption curve for a typical week in 2018, 2022 and 2027. Furthermore, the related curve of battery's SOC is shown in the upper part of each figure.

During a "perfect" day (see in Figure 33: day 1, 2, 3, 4, and 5), the daily energy demand is covered by the PV power plant. The created surplus energy charges the battery during the daytime. The diesel generators generate the required energy during the peak load hours in the evening. In the night and the early morning hours, the battery is discharging.

During a "bad" day (see in Figure 33: day 6 and 7) with less solar irradiation, the produced energy from the PV power plant is not sufficient to serve the daily load and to recharge the battery. Therefore whenever required, the diesel generators are forced to run and to generate the missing energy. The operation hours during the "bad" days lead to the amount of operating hours in the early morning time, which could practically not be avoided.

Due to the increased energy demand in year 2027 (see in Figure 33: typical week 2027), the battery is no longer able to store enough energy during the day and to cover the whole load during the night or the early morning hours. As a result, the diesel generators are forced to generate the missing energy. As stated previously, at this point a design review is necessary to consider expansion of the renewable systems capacity.

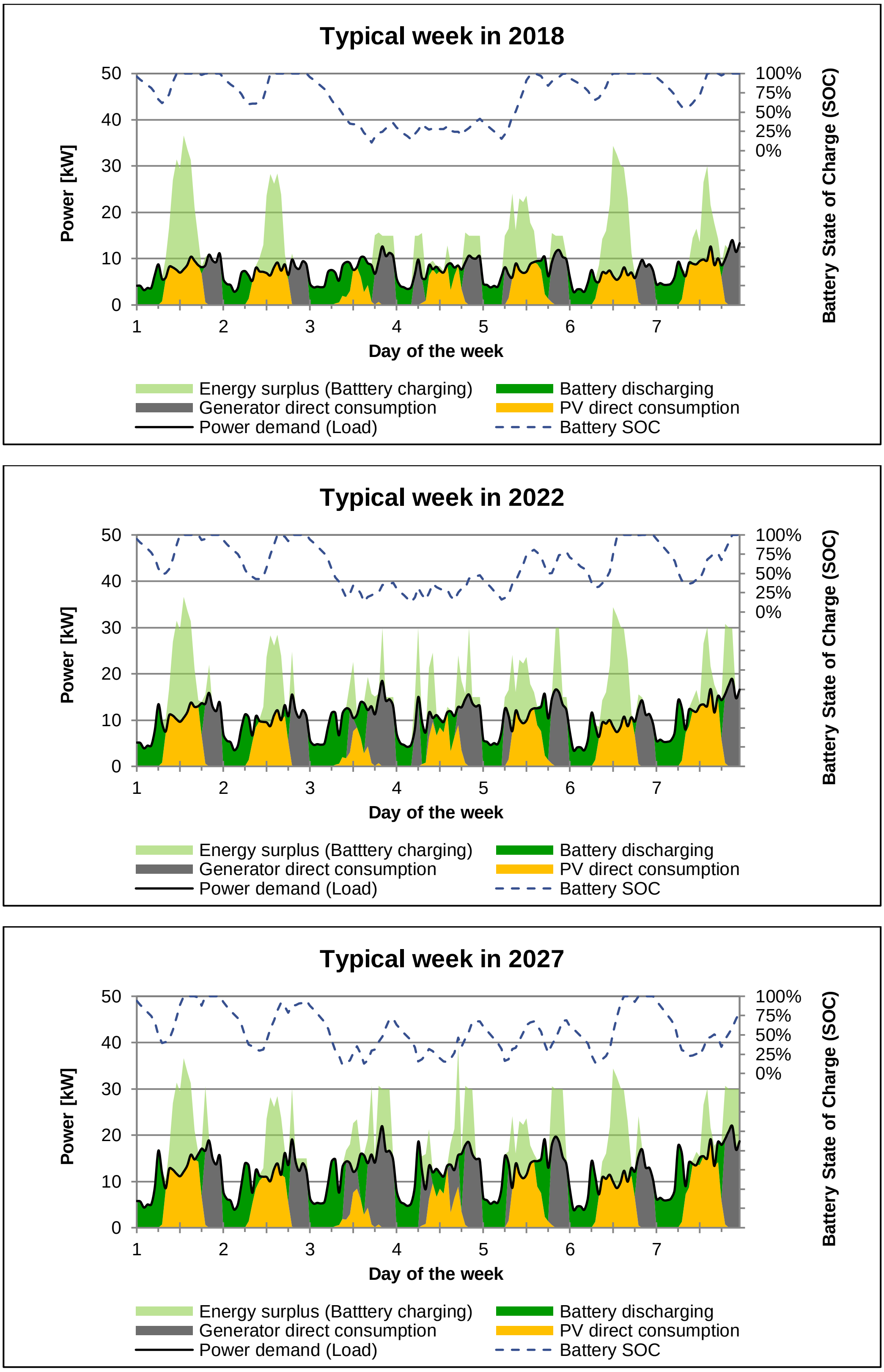
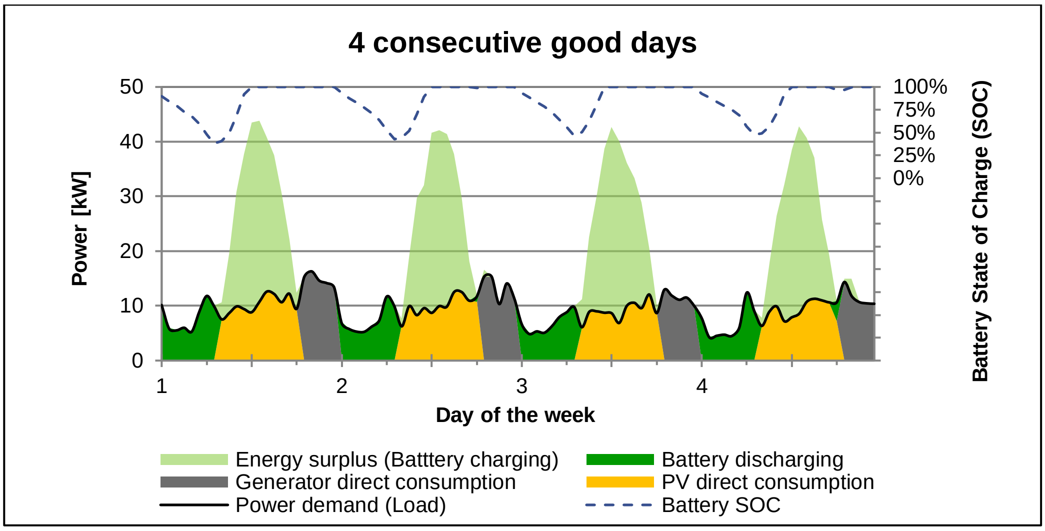


Figure 33: Energy generation and consumption curve for a typical week in 2018, 2022 and 2027



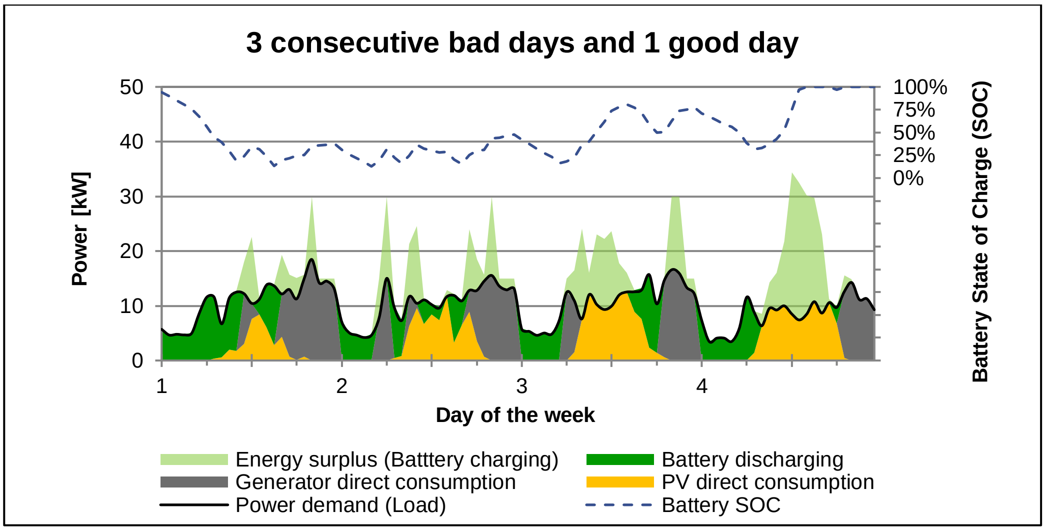


Figure 34: Energy generation and consumption curve for consecutive good days and bad days

5.4.5 Load Factor Curve 2018, 2022 and 2027

Figure 35 shows number of operating hours running at each load factor (% of its rated capacity). It is shown that the generators run at their rated capacity for most of the operating hours. The advantage for the operation methodology of CC is described in more detail in Chapter 5.2, the operating hours at low load factor (below 50%) are significantly reduced. The specific figures are summarized in the following table.

Table 23: Summary of generator operating hours below 50%

Parameter	Number of hours operating below 50%		
	2018	2022	2027
Operating Hours	129	7	1
Percentage	6.37%	0.28%	0.04%

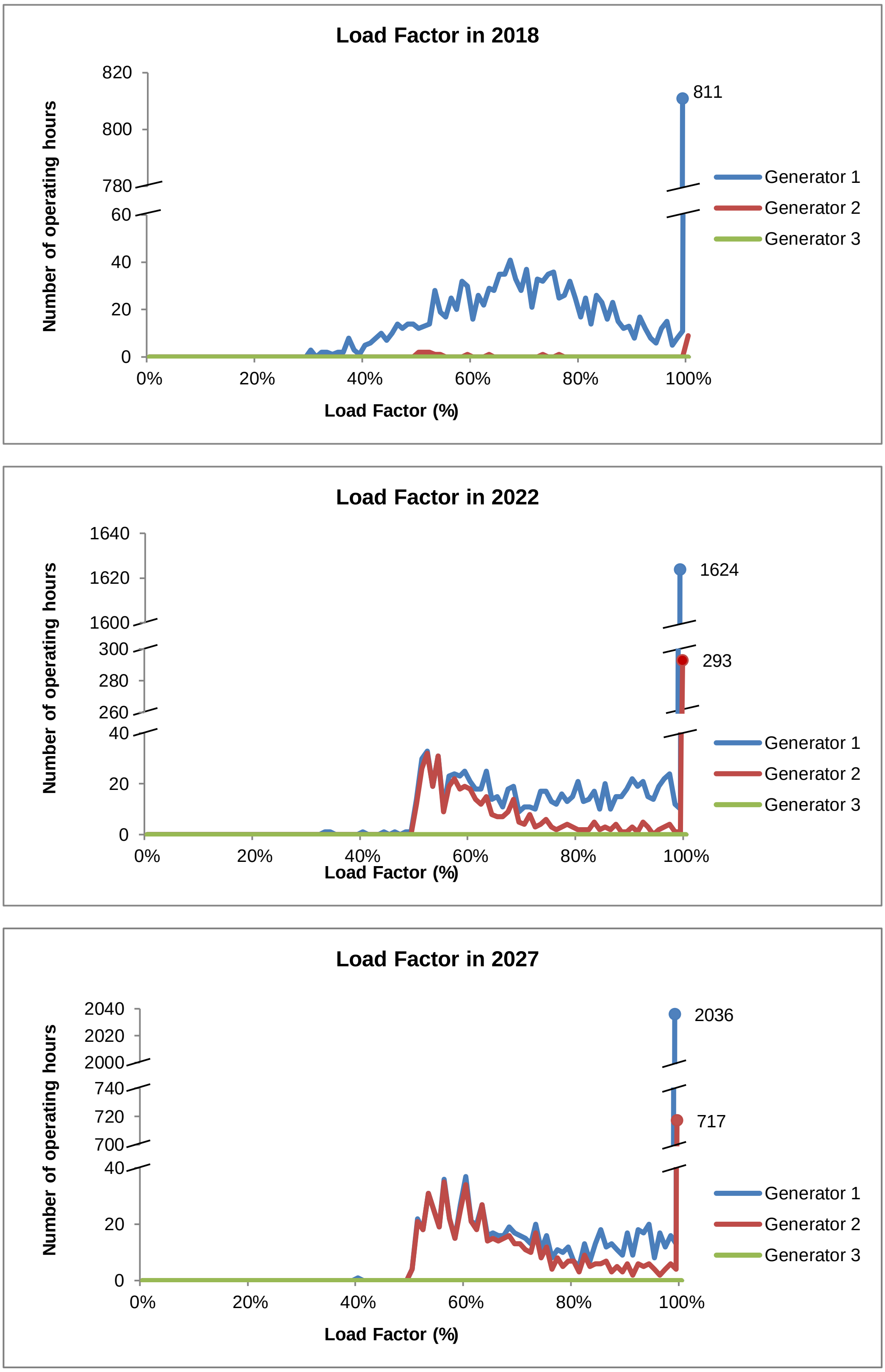


Figure 35: Load factor curve generators in 2018, 2022 and 2027

6 CALCULATION OF LEVELISED COST OF ELECTRICITY

This chapter presents the calculation of the Levelised Cost of Electricity ("LCOE") for each investigated scenario. The two scenarios are:

- Reference scenario with 100% diesel
- Diesel/PV/Battery hybrid system

The initial investment costs and the required costs for operation as well as maintenance were estimated for each system on a pre-feasibility level and may have a typical error-margin in solar-PV of -15% to +20%. The cost estimation presents the input for the subsequent LCOE calculation.

6.1 Calculation Formula

The calculation of the LCOE is based on the following formula:

$$LCOE = \frac{\sum_{n=1}^{N} \frac{I_n + F_n + O\&M_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$

- I_n Investment or Capital Expenditure in year n
- F_n Financing costs in year n
- $O\&M_n$ Operating & Maintenance costs or Operating Expenditure in year n
- Q_n Net electricity production in year n
- d Discount rate of 6 %
- n Analysis period in years has been taken into consideration

6.2 Main Inputs and Assumptions

The most relevant inputs and assumptions which are used for the LCOE calculation are presented in this section.

6.2.1 Economic Project Lifetime

The Consultant considers 3 scenarios with an economic project lifetime of 10, 20 and 30 years. The calculation starts in year 2018 and ends in 2047.

6.2.2 Exchange Rate

All prices are stated in Thai Baht (THB) or in United States Dollar (USD). The considered exchange rate in the study was taken on 8th June 2017: 34.04 THB/USD (source: www.bot.or.th).

6.2.3 Inflation Rate

The inflation rate is assumed to be 2.0%, which is the mean of Thailand inflation rate of the last 10 years (source: https://tradingeconomics.com/thailand/inflation-cpi).

6.2.4 Diesel Escalation Rate

The Consultant used an initial price and annual growth rates to calculate the impact of the diesel fuel price on the LCOE. The diesel price in Thailand was approximately 0.72 USD/litre (24.59 THB/litre) based on price structure of petroleum product dated 8th June 2017 provided by Energy Policy and Planning Office (EPPO). The price consists of the refinery price plus handling, marketing, tax as well as oil fund costs. The refinery price was 0.42 USD/litre (14.41 THB/litre) and presents the basis for the future escalation. The costs for handling, marketing, tax and oil fund were approximately 0.30 USD/litre (10.18 THB/litre) and were assumed as constant, subject to inflation (source: www.eppo.go.th). During the site visit, the Consultant was informed by the locals with respect to the diesel delivery cost of approx. 0.0059 USD/litre (0.2 THB/litre).

To define the annual growth rate, forecasts of the crude oil price (COP) were applied. In the last ten years the correlation coefficient of diesel and crude oil (petroleum) price was 0.927, indicating that the diesel price strongly depends on COP and the application of COP forecasts to project diesel prices is valid (source: www.indexmundi.com).

World Bank, Economic Intelligence Unit (EIU) and International Monetary Fund (IMF) projected crude oil prices in 2017. World Bank forecasted a COP annual growth of approximately 2.9% within the next 10 years, and EIU predicted a COP annual growth of approximately 3.3% within the next 5 years. However, IMF forecasted no growth of COP till year 2022. The following table provides a brief overview of projected COP annual growth rates and projection periods.

Table 24: Overview of crude oil forecasts

Institute	Project annual growth	Projection period
World Bank	2.9%	2017-2030
EIU	3.3%	2017-2021
IMF	0%	2017-2022

Based on these forecasts, COP annual growth rate of IMF was considered too optimistic, therefore, it has not been applied to the calculation. The Consultant hence conservatively applies the average COP annual growth rate of World Bank and EIU for the financial calculation, with an annual diesel price escalation of 3.1%.

6.2.5 Discount Rate

The discount factor was assumed to be 6.0%.

6.2.6 Project Financing

The Consultant received the information from GIZ that the project shall be 100% equity.

6.2.7 Degradation Rates

The annual degradation rate for PV was assumed 1.8% for year 1 and 0.5% per year afterwards, which presents common values warranted degradation rates for polycrystalline-based PV modules.

6.3 Capital and Operating Expenditure

6.3.1 Capital Expenditure

The investment costs also known as Capital Expenditure (CAPEX) were estimated on a feasibility level. The prices are based on a combination of the Consultant's experience from previous projects and budgetary offers from several product manufacturers.

Table 25 summarizes the estimated CAPEX costs for the 2 scenarios. The detailed estimated costs for each system component could be found in the following sections.

Table 25: Summary of total initial CAPEX for different scenarios

Scenario	Parameter	Value
100% diesel	Initial CAPEX Diesel	11,250 USD
	Initial CAPEX Other	29,750 USD
	Total CAPEX	**41,000 USD**
Diesel/PV/Battery hybrid system	Initial CAPEX Diesel	11,250 USD
	Initial CAPEX PV	67,782 USD
	Initial CAPEX Battery	72,000 USD
	Initial CAPEX Other	30,950 USD
	Total CAPEX hybrid	**181,982 USD**

6.3.1.1 CAPEX Diesel Generator

The estimated investment costs of 250 USD/kW for the new diesel generators include all required mechanical and control equipment, as well as installation costs. The transportation costs are also included. Additionally, the estimated CAPEX is based on the adaptation of the existing house. Thus, no additional civil costs were assumed.

Table 26: CAPEX diesel generators

Component	Parameter	Value
Diesel generator	Installed Capacity	45 kW (3x15kW)
	Initial CAPEX per unit	250 USD/kW
	Initial CAPEX	11,250 USD

6.3.1.2 CAPEX PV System

The calculated initial investment costs for PV are approximately 1,300 USD/kW and include main components such as PV modules, string inverters, combiner boxes, DC and AC cabling, transformer station and mounting structure. In addition, installation and delivery costs are included.

Table 27: CAPEX PV system

Component	Parameter	Value
PV system	Installed Capacity	52.14 kW
	Initial CAPEX per unit	1,300 USD/kW
	Initial CAPEX	67,782 USD

6.3.1.3 CAPEX Battery Storage System

The estimated CAPEX for the battery storage system costs are approximately 720 USD/kWh. Li-ion technology is selected. The CAPEX comprises mainly of battery racks, battery converter, control system, and distribution board. The battery storage prices vary between 400-950 USD/kWh which are based on budgetary offers from several manufacturers. The Consultant selected the budgetary offer of a European manufacturer, which has strong cooperation with the global leading manufacturing of solar inverters.

Table 28: CAPEX battery storage system

Component	Parameter	Value
Battery storage system	Installed Capacity	100 kWh
	Initial CAPEX per unit	720 USD/kWh
	Initial CAPEX	72,000 USD

6.3.1.4 Other CAPEX (Transmission line, prepayment energy meter, powerhouse, land cost)

The grid transmission line shall be extended for 150 m as mentioned in Chapter 3.2. During this, also all of the existing poles shall be replaced. In case of alternative location of power station building shown in Appendix 8, there might be an additional cost of grid transmission line of approx. 3,000 USD. Furthermore, the Consultant added the prepayment energy meter into the price-estimation.

For optimal lifetime of batteries and operation of battery inverter/chargers an air-conditioning system must be installed in the battery storage room located in powerhouse. The room shall be well insulated, to avoid the heat and the battery lifetime could be prolonged. The foundation shall be designed for battery weight, additional reinforcement could be expected. For the diesel's powerhouse, an air conditioner system is not required, and additional reinforcement may not be required.

The land for PV and powerhouse shall be provided by SAO, consequently, there is no land cost considered for the project.

Table 29: CAPEX (transmission line, prepayment energy meter, powerhouse)

Scenario	Component	Value
100% Diesel	Extended transmission line including the replacement of the poles	8,800 USD
	Prepayment energy meter	12,150 USD
	Powerhouse building for diesel generator	8,800 USD
	Total other CAPEX	**29,750 USD**
Diesel/PV/Battery hybrid system	Extended transmission line including the replacement of the poles	8,800 USD
	Prepayment energy meter	12,150 USD
	Powerhouse building for hybrid system	10,000 USD
	Total other CAPEX	**30,950 USD**

6.3.2 Operation Expenditures

The costs for operation, maintenance and replacement (Operation Expenditures, "OPEX") were estimated on a feasibility level. Same as for the CAPEX prices, OPEX are based on a combination of the Consultant's experience from previous projects and budgetary offers from several product manufacturers.

6.3.2.1 OPEX Diesel Generator

Table 30 summarizes the estimated OPEX costs for the diesel generators regarding the reference scenario with 100% diesel. In comparison to the hybrid system scenario, the diesel generators operate continuously over the entire year which leads to a higher maintenance effort and significantly increase of necessary replacement intervals.

Table 30: OPEX diesel generators (Reference scenario: 100% Diesel)

Component	Parameter	Value
Diesel	Replacement costs (30% of initial CAPEX)	75 USD/kW

generator	Number of diesel generator replacement over project lifetime	15
	Replacement year (according to HOMER simulation results)	3, 5, 7, 10, 12, 14, 16(2 replacements), 19, 21, 23, 26(2 replacements), 28 and 30
	O&M costs (labour, maintenance, etc.)	0.11 USD/kWh
	Fuel cost	Refer to section 6.2.4

Table 31 summarizes the estimated OPEX costs for the diesel generators of diesel/PV/hybrid system. Based on the manufacturer's information, an operational lifetime of 20,000 hours has been assumed. After reaching this value, a general revision or replacement needs to be done.

Table 31: OPEX diesel generators (Diesel/PV/battery hybrid system)

Component	Parameter	Value
Diesel generator	Replacement costs (30% of initial CAPEX)	75 USD/kW
	Number of diesel generator replacement over project lifetime	5
	Replacement year (according to HOMER simulation results)	9, 16, 21, 23 and 29
	O&M costs (labor, maintenance, etc.)	0.11 USD/kWh
	Fuel cost	Refer to section 6.2.4

6.3.2.2 OPEX PV System

Table 32 summarizes the estimated OPEX costs for the PV system. The DC/AC ratio is approximately 1.13. The PV installed capacity is 52.14 kW_p, thus string inverter capacity is 46 kW.

Table 32: OPEX PV system

Component	Parameter	Value
PV System	Replacement costs string inverters	120 USD/kW
	Number of inverter replacements over project lifetime	1
	Resulting inverter replacement costs linear over project lifetime	230 USD/a
	General O&M costs	20 $USD/kW_p/a$
	Resulting general O&M costs linear over project lifetime	1,042.8 USD/a

6.3.2.3 OPEX Battery Storage System

Reaching the battery's end of lifetime (State of Health below 80%), the battery cells (battery racks) must be replaced. Within the financial calculation, the Consultant considers a re-investment of approximately 25,000 USD/kWh after the 15th operation year (2033). The price for the reinvestment is based on the future price forecast for Li-on cells estimated in a study by Institute Bloomberg New Energy Finance. In general, Li-on batteries are almost maintenance free. Nevertheless an annual general inspection of the battery storage system by certified staff is highly recommended.

Table 33: OPEX battery storage system

Component	Parameter	Value
Diesel generator	Replacement costs battery cells and battery inverter(s) in year 2033 (based on future estimated Li-ion cell price in year 2030 according Bloomberg New Energy Finance: ~250 $US/kWh)	25,000 USD
	General O&M costs (annual inspections)	1,224 USD/a

6.3.2.4 Other OPEX (Transmission line, prepayment energy meter, powerhouse)

The OPEX of the transmission line, prepayment energy meter and powerhouse is assumed to approx. 100 USD/a.

6.4 Financial Calculation Results

6.4.1 LCOE Calculation

LCOE defines the total costs to build and operate the system over its total lifetime (as per calculation in Chapter 6.1). It includes generation costs and all additional costs such as:

- CAPEX
- OPEX
- Financing costs
- Replacement costs
- Fuel costs

Based on the energetic simulation results, the financial assumptions and estimated CAPEX as well as OPEX costs, the calculated LCOE for each scenario are summarized in Table 34. Detail of the calculation is shown in appendix 3.

To compare with the current electricity price, the current electricity price per kWh was estimated. The electricity price for the grid, operated by Khun Jaesen, was approximated from the consumption and sale price of electricity for the measured period between 18:00-23:00. According to the GIZ survey all nine (9) households pay a total of 176.26 USD/month (6,000 THB/month) or 19.58 USD/month (667 THB/month) per household on average. According to Table 7, the average daily energy demand is approx. 3.14 kWh/d. Consequently, the electricity price per kWh is around 1.87 USD/kWh (63.69 THB/kWh).

Furthermore, while the community diesel generator was operated, each household paid for the electricity supply during 18:00-23:00 around 8.81 USD/month (300 THB/month[1]). According to Table 10, the total average daily energy demand for 81 households is approx. 32.01 kWh/d. Consequently, the electricity price per kWh is around 0.74 USD/kWh (25.30 THB/kWh).

The LCOE is a function of the project timeline. In the short term, project lifetime = 10 years, the LCOE is only reduced by 1.83% compared to the reference scenario of 100% diesel. This is due to the diesel price over this period being lower and high CAPEX of the hybrid system, equating to a similar cost of electricity as PV-Battery. As we move further away, project lifetime = 20 years, the system configuration becomes increasingly optimal, due to an increased available generating capacity from solar (i.e. the solar is not curtailed as much during the day) and low OPEX, coupled with increasing fuel prices, the LCOE reduces from the reference scenario by 20.2%. At the longest project lifetime, lifetime = 30 years, the hybrid system is able to use the majority of daytime solar

[1] This electricity price was informed by the island representative during the kick-off meeting.

generation and starts to become also subject to increasing fuel prices, which increase the LCOE slightly from the 20 year scenario, where the LCOE is 27.04% less than the reference scenario As previously stated, a periodic design review allows for optimisation of the hybrid system.

Table 34: Estimated LCOE for 10-, 20- and 30-year project lifetime

Parameter	Diesel/PV/ Battery hybrid	100% Diesel scenario	Reduction (reference scenario: 100% diesel)
LCOE (10-year project lifetime)	0.535 USD/kWh (18.21 THB/kWh)	0.545 USD/kWh (18.55 THB/kWh)	1.83%
LCOE (20-year project lifetime)	0.474 USD/kWh (16.13 THB/kWh)	0.594 USD/kWh (20.22 THB/kWh)	20.20%
LCOE (30-year project lifetime)	0.483 USD/kWh (16.44 THB/kWh)	0.662 USD/kWh (22.53 THB/kWh)	27.04%

As already mentioned, the LCOE presents the costs for the whole system over the whole project lifetime. Besides the pure generation costs, LCOE includes all additional costs such as CAPEX for equipment, OPEX, replacement costs and financing costs. The LCOE is typically defined as one single number, representing all costs for the system over the total project lifetime. The way to calculate the considered input parameters of the calculated pure annual generation costs are different. As a result, actual pure generation costs of a specific year cannot be compared to the LCOE. The LCOE is used to compare various generation types over the total lifetime.

6.4.2 Real Generation Costs Calculation

However, the Consultant calculated in parallel to the LCOE the future real annual generation costs on the basis of first approximation, applying linear depreciation of the initial CAPEX for the system-specific components over the project lifetime. The calculation of the real generation costs considers therefore:

- Linear depreciation of initial CAPEX:
  - 30 years (for 30-year scenario) depreciation for the PV and the battery storage system (incl. BMS, battery inverter, etc.)
  - Years to replacement of battery
    (Computational calculation based on cycling of the batteries and end of life capacity at 80%)
  - 20,000 operating hours for the diesel generators
- OPEX
- Financing costs
- Replacement costs
- Fuel costs

The real generation costs per kWh for the Diesel/PV/Battery hybrid system also calculated for 3 project lifetime scenarios of 10, 20 and 30 years in 2018, 2022 and 2027 as shown in Figure 36. It can be seen that the real generation costs of lower project lifetime will be higher due to higher depreciation. Compared to the 100% diesel reference scenario, the costs are already lower in the first year of operation (2018).

Moreover, due to the increasing fuel price and low costs for the renewable energy sources (PV and battery), the deviation significantly increases over the whole project lifetime. The real generation costs for the whole project lifetime in each scenario are presented in Appendix 4.

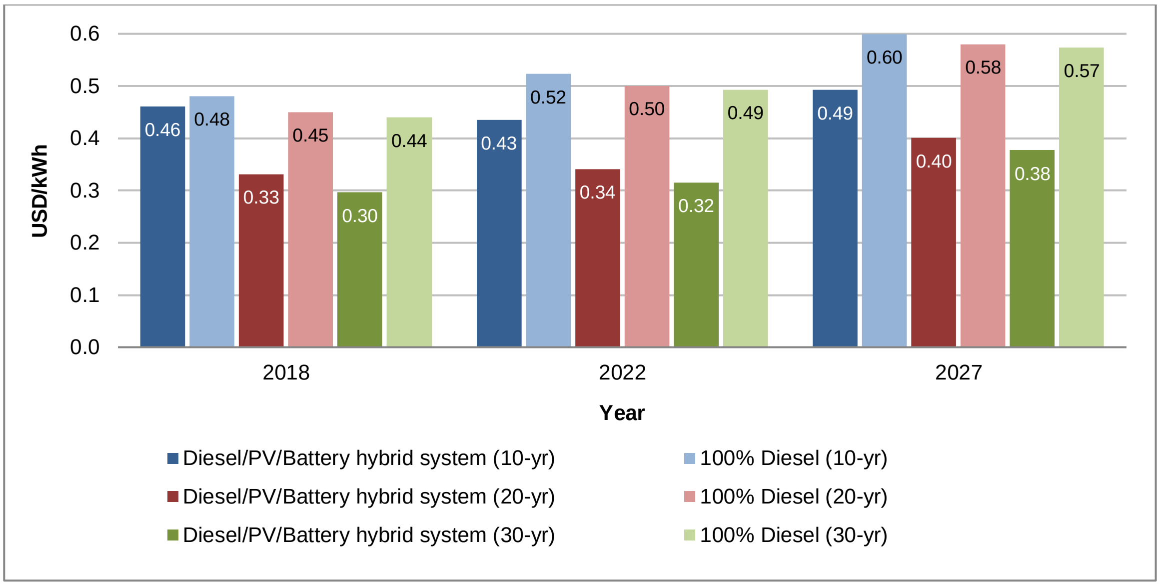


Figure 36: Estimated annual real generation costs in 2018, 2022 and 2027

In summary, the calculation results show that the hybrid system presents an attractive solution for the future electricity generation system of Bulon Don Island.

According to the estimated 24-hour residential load profile, including additional appliances in Chapter 4.4.1, the average energy demand per month of each residential household type including additional appliances in 2018 are presented in Table 35.

Table 35: Average energy demand per month of each residential households in 2018

	Average energy demand (kWh/month)
Residential type I (light, fan, mobile charger)	31.21
Residential type II (light, fan, mobile charger and TV)	59.47
Rice cooker	22.33
Fridge	16.06
Washing machine	5.63
Computer	8.55

In this example, we select a 20-year lifetime to show the costs or generation for different residential households and appliances in the year 2018, where the generation cost is 0.33 USD/kWh (11.23 THB/kWh), presented in Table 36. It can be seen that if the residential type II want to buy a rice cooker, fridge, washing machine and computer, the electricity generation cost will be 36.97 USD/month (1,258.57 THB/month). It has to be noted that this costs do not included any profit. The real generation costs for each project lifetime scenario are shown in Appendix 5.

Table 36: Electricity generation costs, willingness to pay and current electricity expenses

	Residential type I	Residential type II
Willingness to pay	14.69 – 29.38 USD/month (500 - 1,000 THB/month)	8.81 – 44.07 USD/month (300 – 1,500 THB/month)
Current electricity expenses	12.78 – 42.30 USD/month (435 – 1,440 THB/month)	12.78 – 63.45 USD/month (435 – 2,160 THB/month)
Generation costs according to 1st year of operation (2018) for 20-year lifetime scenario		
▪ Basic appliances (light, fan, mobile phone charger, TV)	10.30 USD/month (350.59 THB/month)	19.63 USD/month (668.04 THB/month)
▪ Rice cooker	7.37 USD/month (250.84 THB/month)	
▪ Fridge	5.30 USD/month (180.41 THB/month)	
▪ Washing machine	1.86 USD/month (63.24 THB/month)	
▪ Computer	2.82 USD/month (96.04 THB/month)	

6.4.3 Sensitivity Analysis

Sensitivity analysis demonstrates how uncertainty in the output of the system or model be apportioned to different levels of uncertainty in its inputs to increase a higher understanding of the relationship between input and output variables in a system or model. In general, a variable is considered sensitive, if a change of 1% implies a variation of higher or lower than 1% of the assessed value.

According to meeting between GIZ and the Consultant on 20th July 2017, GIZ and the Consultant agreed to carry out sensitivity analysis of the following parameters:

- CAPEX (±30%)
- Energy (±20%), and
- Fuel Price (±10%).

The result is demonstrated in proportion of $LCOE/LCOE_{estimated}$. The $LCOE_{estimated}$ values are referred to LCOE values of each period presented in Table 34.

It notes that the sensitivity analysis is also carried out in various project lifetime: 10 years, 20 years and 30 years.

10-years project lifetime period scenario

Figure 33 presents the results of the sensitivity analysis on LCOE/LCOE$_{estimated}$ for the variation of parameters.

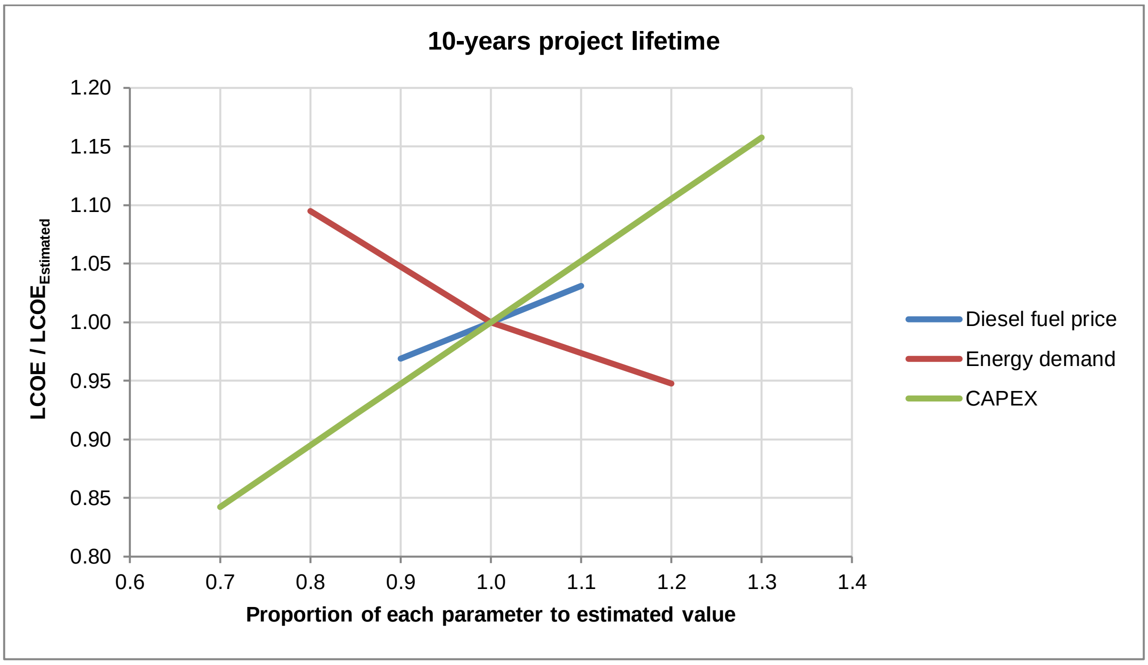


Figure 37: Sensitivity analysis results of 10-years project lifetime period scenario

Analysis of the results from the sensitivity analysis demonstrates the variation of the different variables impacting the results of the LCOE/LCOE$_{estimated}$ (ranked from the most to the least impact):

- ± 30% variation in CAPEX leads to a ± 15.76% variation in LCOE
- + 20% variation in energy demand leads to a – 5.22% variation in LCOE. – 20% variation in energy demand leads to a + 9.49% variation in LCOE.
- ± 10% variation in fuel price leads to a ± 3.10% variation in LCOE

20-years project lifetime period scenario

Figure 38 presents the results of the sensitivity analysis on $LCOE/LCOE_{estimated}$ for the variation of parameters.

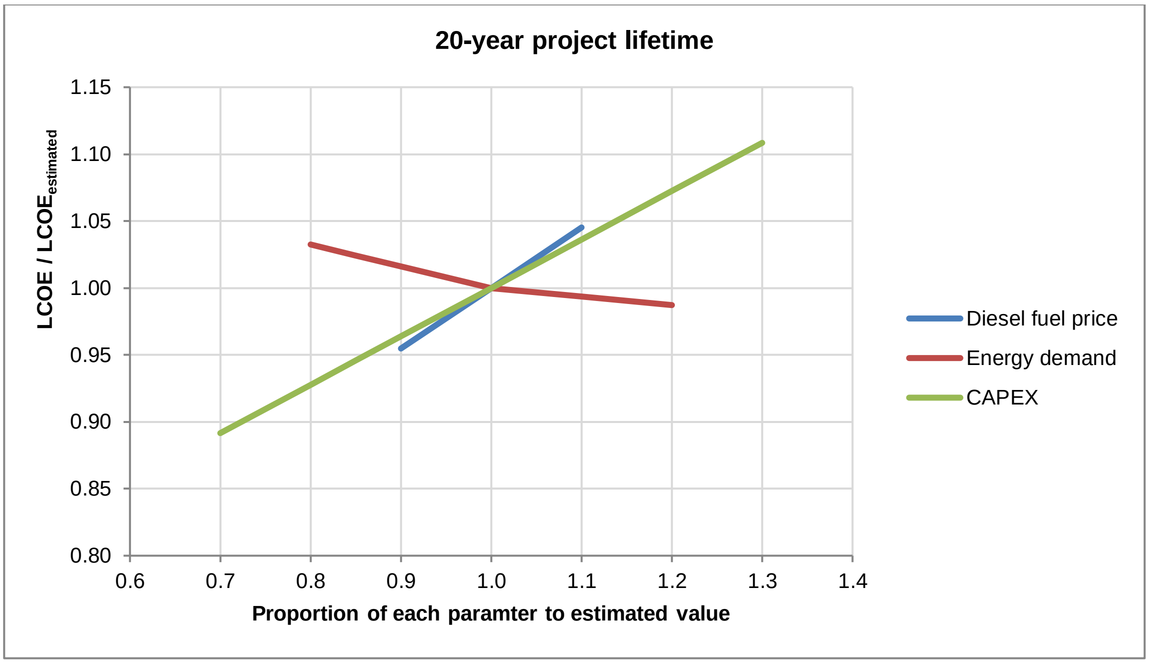


Figure 38: Sensitivity analysis results of 20-years project lifetime period scenario

Analysis of the results from the sensitivity analysis presents the variation of the different variables impacting the results of the $LCOE/LCOE_{estimated}$ (ranked from the most to the least impact):

- ± 30% variation in CAPEX leads to a ± 10.84% variation in LCOE
- + 20% variation in energy demand leads to a – 1.28% variation in LCOE. – 20% variation in energy demand leads to a + 3.25% variation in LCOE.
- ± 10% variation in fuel price leads to a ± 4.52% variation in LCOE

30-years project lifetime period scenario

Figure 39 presents the results of the sensitivity analysis on LCOE/LCOE$_{estimated}$ for the variation of parameters.

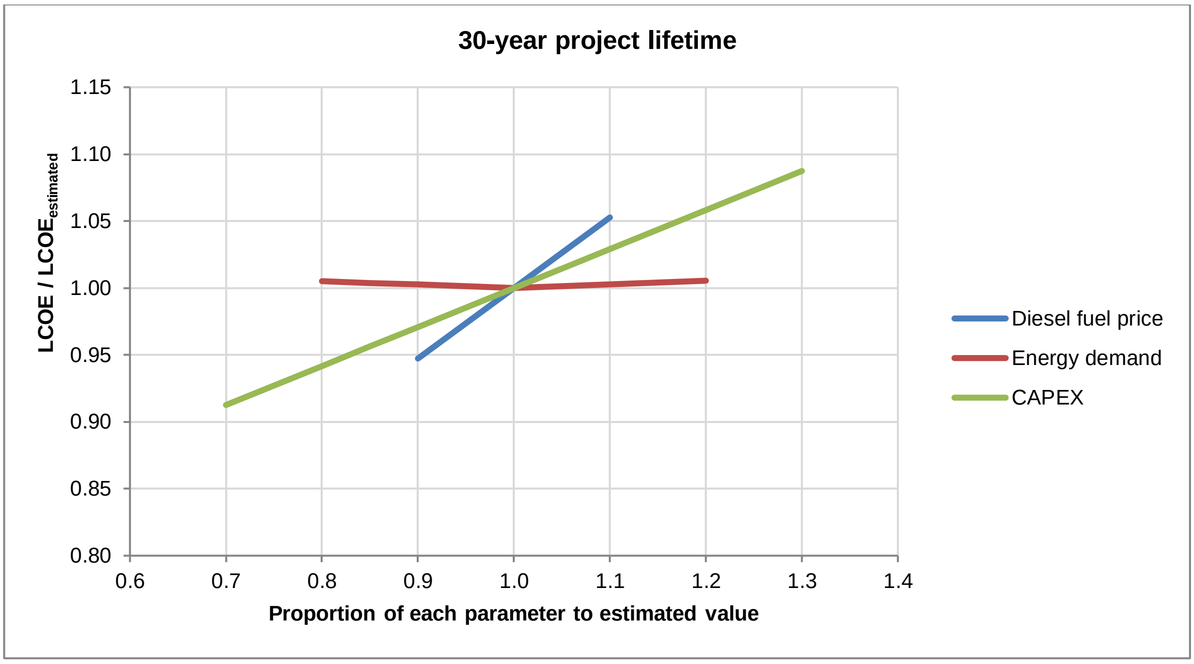


Figure 39: Sensitivity analysis results of 30-years project lifetime period scenario

Analysis of the results from the sensitivity analysis presents the variation of the different variables impacting the results of the LCOE/LCOE $_{estimated}$ (ranked from the most to the least impact):

- ± 30% variation in CAPEX leads to a ± 8.74% variation in LCOE
- + 20% variation in energy demand leads to a – 0.54% variation in LCOE. – 20% variation in energy demand leads to a + 0.51% variation in LCOE.
- ± 10% variation in fuel price leads to a ± 5.27% variation in LCOE

Overall, it is shown that the hybrid system is most sensitive to CAPEX in the short term, with demand and fuel consumption following. As the project lifetime is increased, the sensitivity to CAPEX decreases and sensitivity to energy demand almost diminishes to zero. The systems sensitivity increases in the long term, as the system uses increasing amounts of fuel from year to year.

7 APPENDICES

Appendix 1: Appliance usage assumptions of each cluster

Residential type I and type II in March

Appliance	Behaviour (as % of total appliances are running at the same time)	
Residential type I		
Light bulb	00:00-04:00 : 0% 04:00-06:00 : 50% 06:00-18:00 : 0%	18:00-23:00 : 50% 23:00-00:00 : 0%
Fan	00:00-04:00 : 50% 04:00-12:00 : 30% 12:00-15:00 : 50% 15:00-17:00 : 30%	17:00-18:30 : 50% 18:30-23:00 : 80% 23:00-00:00 : 50%
Mobile charger	80% all day	
Residential type II		
Light bulb	00:00-04:00 : 0% 04:00-06:00 : 50% 06:00-18:00 : 0%	18:00-23:00 : 50% 23:00-00:00 : 0%
Fan	00:00-04:00 : 50% 04:00-12:00 : 30% 12:00-15:00 : 50% 15:00-17:00 : 30%	17:00-18:30 : 50% 18:30-23:00 : 80% 23:00-00:00 : 50%
Mobile charger	80% all day	
TV	00:00-00:30 : 10% 00:30-04:00 : 0% 04:00-05:00 : 30% 05:00-09:00 : 50% 09:00-11:00 : 30%	11:00-12:00 : 50% 12:00-18:30 : 60%-80% 18:30-23:00 : 75% 23:00-00:00 : 10%
Other specific appliances		
Washing machine	00:00-09:00 : 0% 09:00-10:30 : 50% 10:30-19:00 : 0%	19:00-20:30 : 50% 20:30-00:00 : 0%
Boar repair	00:00-09:00 : 0% 09:00-11:00 : 50%-60% 11:00-14:30 : 0%	14:30-16:30 : 50%-60% 16:30-00:00 : 0%
Rice cooker	00:00-05:00 : 0% 05:00-07:00 : 25% 07:00-16:00 : 0% 16:00-17:00 : 10%	17:00-19:00 : 15% 19:00-20:00 : 5% 20:00-00:00 : 0%
Fridge	100 % all day	
Computer	00:00-08:00 : 0% 08:00-20:00 : 40%-65% 20:00-21:00 : 70%	21:00-22:00 : 65% 22:00-23:00 : 10% 23:00-00:00 : 0%

School during the summer season

Appliance	Behaviour (as % of total appliances are running at the same time)	
Mar, Apr (Summer season, end of semester)		
Light bulb	00:00-07:00 : 10% 07:00-08:00 : 5% 08:00-17:00 : 20%	17:00-18:00 : 5% 18:00-23:00 : 75% 23:00-00:00 : 10%
Fan	00:00-08:00 : 30% 08:00-17:30 : 40%	17:30-00:00 : 30%
TV	0% all day	
Computer	00:00-08:00 : 0% 08:00-12:00 : 50% 12:00-13:00 : 0%	13:00-17:00 : 50% 17:00-00:00 : 0%
Fridge	100% all day	
Water pump	00:00-09:00 : 0% 09:00-12:30 : 100% 12:30-14:00 : 0%	14:00-17:00 : 100% 17:00-00:00 : 0%
Network	00:00-08:00 : 0% 08:00-17:00 : 100%	17:00-00:00 : 0%
Jan, Feb, Nov, Dec (Summer season, school start)		
Light bulb	00:00-07:00 : 10% 07:00-08:00 : 5% 08:00-17:00 : 20%	17:00-18:00 : 5% 18:00-23:00 : 75% 23:00-00:00 : 10%
Fan	00:00-08:00 : 30% 08:00-17:30 : 60%	17:30-00:00 : 30%
TV	00:00-08:00 : 0% 08:00-11:30 : 100% 11:30-13:30 : 0%	13:30-17:00 : 100% 17:00-00:00 : 0%
Computer	00:00-08:00 : 0% 08:00-11:30 : 100% 11:30-13:30 : 0%	13:30-17:00 : 100% 17:00-00:00 : 0%
Fridge	100% all day	
Water pump	00:00-09:00 : 0% 09:00-12:30 : 100% 12:30-14:00 : 0%	14:00-17:00 : 100% 17:00-00:00 : 0%
Network	00:00-08:00 : 0% 08:00-17:00 : 100%	17:00-00:00 : 0%

Mosque in March

Appliance	Behaviour (as % of total appliances are running at the same time)	
Light bulb	00:00-05:00 : 0% 05:00-06:00 : 50% 06:00-18:00 : 0%	18:00-20:00 : 50% 20:00-00:00 : 0%
Fan	00:00-05:00 : 0% 05:00-06:00 : 50% 06:00-12:00 : 0% 12:00-13:00 : 50% 13:00-15:00 : 0%	15:00-16:00 : 50% 16:00-18:00 : 0% 18:00-20:00 : 50% 20:00-00:00 : 0%
Speaker[1]	00:00-05:00 : 00% 05:00-05:30 : 20% 05:30-12:00 : 0% 12:00-12:30 : 20% 12:30-15:00 : 0% 15:00-15:30 : 20%	15:30-18:00 : 0% 18:00-18:30 : 20% 18:30-19:00 : 0% 19:00-19:30 : 20% 19:30-00:00 : 0%

Health centre in March

Appliance	Behavior (as % of total appliances are running at the same time)	
Light bulb	00:00-18:00 : 20% 18:00-20:30 : 60% 20:30-21:30 : 40%	21:30-00:00 : 20%
Fan	00:00-08:00 : 50% 08:00-17:00 : 90%	17:00-00:00 : 50%
Oxygen concentrator	00:00-20:00 : 0% 20:00-20:30 : 100%	20:30-00:00 : 0%
Communication system[2]	10 % all day	

[1] In case of the speaker, the percentage is as % of total power consumption of the appliance.

[2] In case of the communication system, the percentage is as % of power consumption of the appliance.

Appendix 2: Summary of the inputs for HOMER simulation

Parameters	Values	Parameters	Values
Diesel generator		**Battery & inverter**	
Brand/model	Generac Protector	Battery Technology	Li-ion
Rated power	15 kW x 3 (Total 45 kW)	Battery capacity	100 kWh
Minimum load	30%	Battery Lifetime curve	1/N = A*(DOD)^Beta A = 0.000216 Beta = 1.7945
Lifetime	20,000 hours	Battery Initial SOC	100%
Fuel curve	Intercept: 0.635 l/hr Slope: 0.327 l/hr/kW	Battery Minimum SOC	20%
Total Capital	11,250 USD	Inverter capacity	27.3 kW
Replacement / generator	1,125 USD	Inverter Lifetime	15 years
O&M	0.105 USD/hour	Efficiency	95.8%
Diesel fuel price (2018)	0.75 USD/litre	Total O&M	1,224 USD/kWh/year
Solar PV		**Dispatch strategy**	
Total capacity	52.14 kWp	Strategy	Cycle charging (CC)
Derating factor	80%	Set point SOC	30%
Lifetime	30 years		
Capital	1,300 USD/kWp		
Replacement	0 USD/kWp		
O&M (PV & Inverter)	20 USD/kWp/year		
PV inverter			
Total capacity	46 kW		
Efficiency	98%		
Lifetime	15 years		
Capital	included in PV costs		
Replacement	120 USD/kW		

Appendix 3: Definition of inputs for LCOE calculation

$$LCOE = \frac{\sum_{n=1}^{N} \frac{I_n + F_n + O\&M_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$

- I_n Investment or Capital Expenditure in year n
- F_n Financing costs in year n
- $O\&M_n$ Operating & Maintenance costs or Operating Expenditure in year n
- Q_n Net electricity production in year n
- d Discount rate of 6 %
- N Analysis period of 30 years has been taken into consideration

PV/Diesel/Battery hybrid system

Investment or Capital Expenditure: I_n

$$I_n = CAPEX_{year0} + \text{Replacement costs}$$

$$\text{CAPEX}_{\text{year0}} = \text{CAPEX}_{\text{PV}} + \text{CAPEX}_{\text{battery}} + \text{CAPEX}_{\text{generator}} + \text{CAPEX}_{\text{other}}$$

- CAPEX_{PV} = \$67,782 ; Section 6.3
- $\text{CAPEX}_{\text{battery}}$ = \$72,000 ; Section 6.3
- $\text{CAPEX}_{\text{generator}}$ = \$11,250 ; Section 6.3
- $\text{CAPEX}_{\text{other}}$ = \$30,950 ; Section 6.3

$$\text{Replacement costs} = \text{Replacement}_{\text{PV}} + \text{Replacement}_{\text{Battery}} + \text{Replacement}_{\text{generator}}$$

$$\text{Replacement}_{\text{PV}} = \sum_{n=1}^{N} (\text{Replacement}_{\text{PV}} \times \text{kWp}) \times (1+k)^n + \sum_{n=6}^{N} (\text{Replacement}_{\text{inverter}} \times \text{kW}) \times (1+k)^n$$

- k Inflation rate of 2%
- There is no replacement for PV, therefore, $\text{replacement}_{\text{PV}} = 0$
- $\text{Replacement}_{\text{inverter}}$ = \$120/kW/year (Section 6.3.2.2 inverter replacement after year 6)

$\text{Replacement}_{\text{Battery}} = \$25{,}000$; Section 6.3.2.3 battery replacement at year 26 as per simulation

$$\text{Replacement}_{\text{generator}} = \sum_{n=1}^{N} (\text{Replacement}_{\text{generator}} \times \text{kW}) \times (1+k)^n$$

- $\text{Replacement}_{\text{generator}}$ = \$75/kW
  (Section 6.3.2.1 generator replacement occurs in year 9, 16, 21, 23 and 29 as per simulation)

Financing costs: F_n

There is no any financing costs for the project due to 100% Equity project.

Operating & Maintenance costs: $O\&M_n$

$$O\&M_n = O\&M_{Total.PV} + O\&M_{Total.battery} + O\&M_{Total.generator} + O\&M_{other}$$

$$O\&M_{Total.PV} = \sum_{n=1}^{N} (O\&M_{PV}) \times (1+k)^n$$

- $O\&M_{PV}$ = \$1,040 per year ; Section 6.3.2.2

$$O\&M_{Total.battery} = \sum_{n=1}^{N} (O\&M_{battery}) \times (1+k)^n$$

- $O\&M_{battery}$ = \$1,300 per year ; Section 6.3.2.3

$$O\&M_{Total.generator} = O\&M_{generator} + O\&M_{fuel}$$

- $$O\&M_{generator} = \sum_{n=1}^{N} (O\&M_{generator,cost} \times \text{Production}_{\text{n}}) \times (1+k)^n$$
- $O\&M_{generator,cost}$ = \$0.11 kWh/year ; Section 6.3.2.1
- $$O\&M_{fuel} = \sum_{n=1}^{N} (\text{Fuel}_{\text{consumption,n}} \times \text{Fuel}_{\text{Price,n}}) \times (1+k)^n$$
- $$\text{Fuel}_{\text{Price,n}} = \text{Fuel}_{\text{Raw}} \times (1 + k + \text{fuel escalation})^n + \text{Fuel}_{\text{other}} \times (1+k)^n$$
- Fuel_{Raw} = \$0.42 per litre
- Fuel escalation = 3.1% ; Section 6.2.3 and 6.2.4
- $\text{Fuel}_{\text{other}}$ = \$0.3059 per litre

$$O\&M_{other} = \sum_{n=1}^{N} (O\&M_{transmission line}) \times (1+k)^n$$

- $O\&M_{\text{transmission line}}$ = \$100 per year ; Section 6.3.2.4

Net electricity production: Q_n

Based on energy demand as described in chapter 4

100% Diesel scenario

Investment or Capital Expenditure: I_n

$$I_n = CAPEX_{year0} + \text{Replacement costs}$$

$$\text{CAPEX}_{\text{year0}} = \text{CAPEX}_{\text{generator}} + \text{CAPEX}_{\text{other}}$$

- $\text{CAPEX}_{\text{generator}}$ = $11,250 ; Section 6.3
- $\text{CAPEX}_{\text{other}}$ = $29,750 ; Section 6.3

$$\text{Replacement costs} = \text{Replacement}_{\text{generator}}$$

$$\text{Replacement}_{\text{generator}} = \sum_{n=1}^{N} (\text{Replacement}_{\text{generator}} \times \text{kW}) \times (1+k)^n$$

- $\text{Replacement}_{\text{generator}}$ = $75/kW/year
  (Section 6.3.2.1 generator replacement occurs in year 3, 5, 7, 10, 12, 14, 16(2), 19, 21, 23, 26(2), 28 and 30 as per simulation)
- k Inflation rate of 2%

Financing costs: F_n

There is no any financing costs for the project due to 100% Equity project.

Operating & Maintenance costs: $O\&M_n$

$$O\&M_n = O\&M_{Total.generator} + O\&M_{other}$$

$$O\&M_{Total.generator} = O\&M_{generator} + O\&M_{fuel}$$

- $$O\&M_{generator} = \sum_{n=1}^{N} (O\&M_{generator,\text{cost}} \times \text{Production}_{\text{n}}) \times (1+k)^n$$
- $O\&M_{\text{generator,cost}}$ = $0.11 kWh/year ; Section 6.3.2.1
- $$O\&M_{fuel} = \sum_{n=1}^{N} (\text{Fuel}_{\text{consumption,n}} \times \text{Fuel}_{\text{Price,n}}) \times (1+k)^n$$
- $$\text{Fuel}_{\text{Price,n}} = \text{Fuel}_{\text{Raw}} \times (1 + k + \text{fuel escalation})^n + \text{Fuel}_{\text{other}} \times (1+k)^n$$
- Fuel_{Raw} = $0.42 per litre
- Fuel escalation = 3.1% ; Section 6.2.3 and 6.2.4
- $\text{Fuel}_{\text{other}}$ = $0.3059 per litre

$$O\&M_{other} = \sum_{n=1}^{N} (O\&M_{transmission\,line}) \times (1+k)^n$$

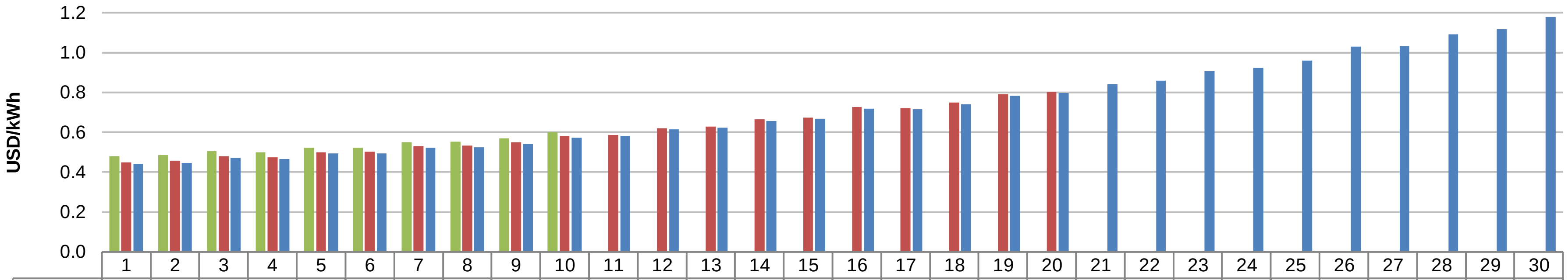
- $O\&M_{transmission\ line}$ = \$100 per year ; Section 6.3.2.4

Net electricity production: Q_n

Based on energy demand as described in chapter 4

Appendix 4: Real generation costs

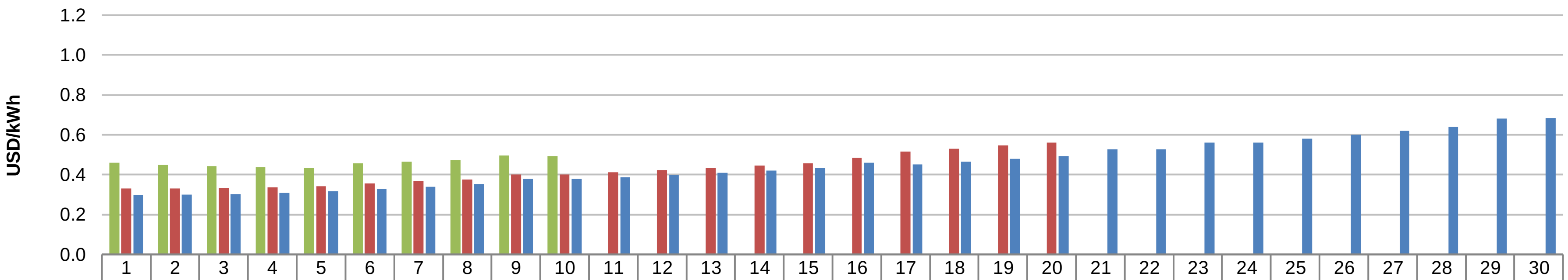
100% Diesel scenario



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
10-year	0.48	0.48	0.51	0.5	0.52	0.52	0.55	0.55	0.57	0.6																				
20-year	0.45	0.46	0.48	0.48	0.5	0.5	0.53	0.53	0.55	0.58	0.59	0.62	0.63	0.66	0.67	0.73	0.72	0.75	0.79	0.8										
30-year	0.44	0.45	0.47	0.47	0.49	0.49	0.52	0.53	0.54	0.57	0.58	0.61	0.62	0.66	0.67	0.72	0.72	0.74	0.78	0.8	0.84	0.86	0.91	0.92	0.96	1.03	1.03	1.09	1.12	1.18

Year

PV/Diesel/Battery hybrid system



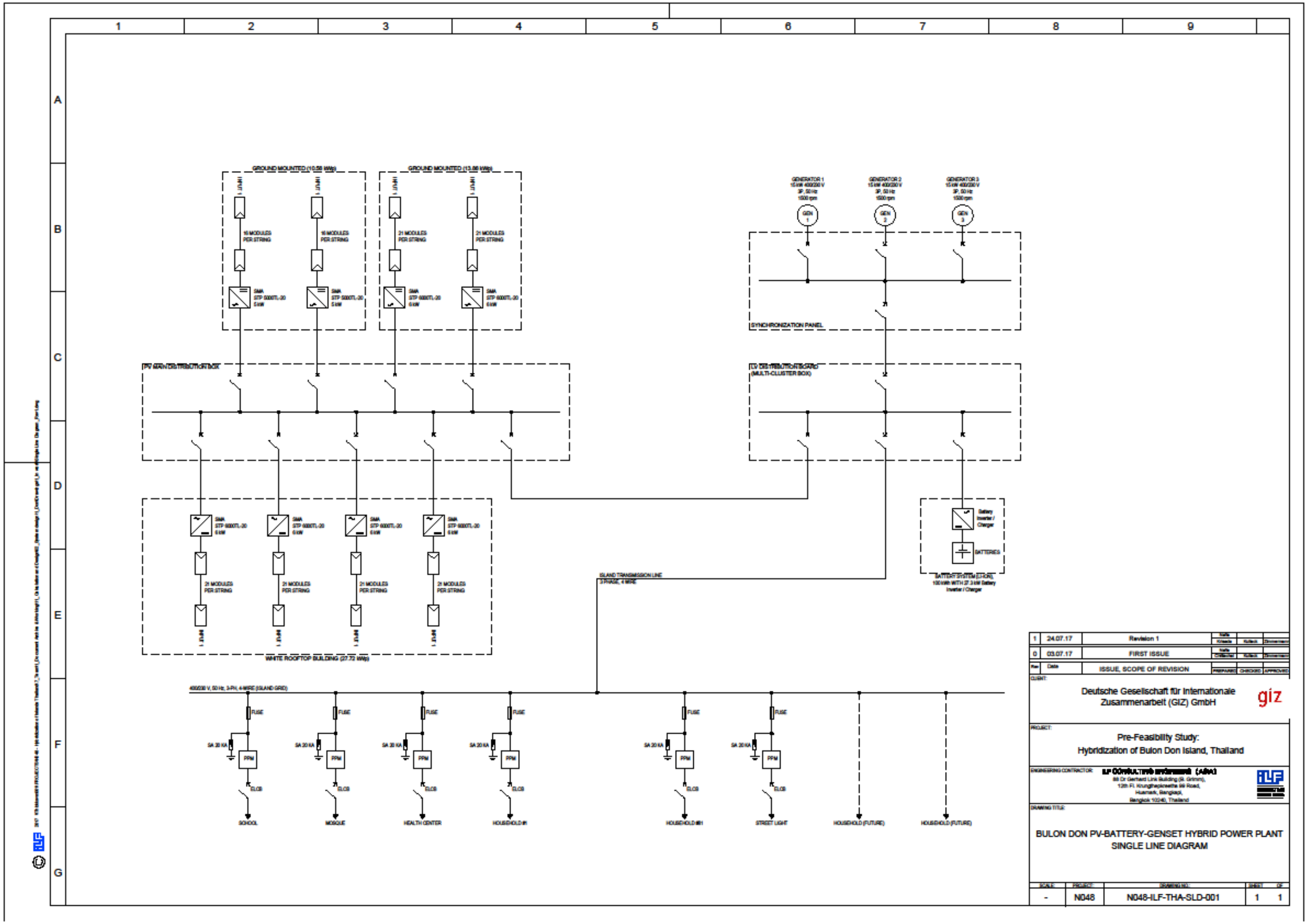
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
10-year	0.46	0.45	0.44	0.44	0.43	0.46	0.47	0.47	0.5	0.49																				
20-year	0.33	0.33	0.33	0.34	0.34	0.36	0.37	0.38	0.4	0.4	0.41	0.42	0.43	0.45	0.46	0.48	0.52	0.53	0.55	0.56										
30-year	0.3	0.3	0.3	0.31	0.32	0.33	0.34	0.35	0.38	0.38	0.39	0.4	0.41	0.42	0.43	0.46	0.45	0.46	0.48	0.49	0.53	0.53	0.56	0.56	0.58	0.6	0.62	0.64	0.68	0.69

Year

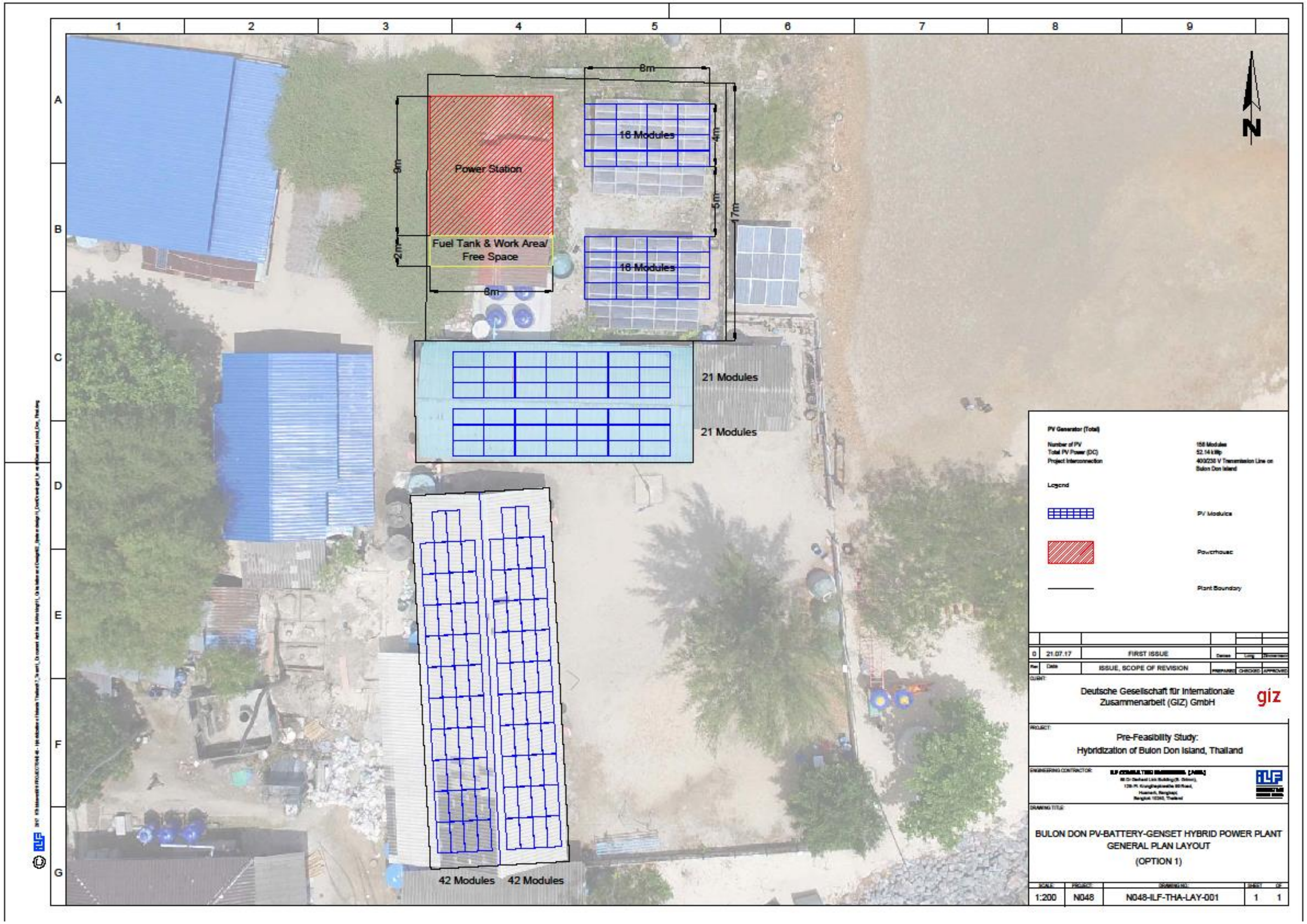
Appendix 5: Electricity real generation costs of PV/Diesel/Battery hybrid system for each cluster

	Residential type I	Residential type II
Willingness to pay	14.69 – 29.38 USD/month (500 - 1,000 THB/month)	8.81 – 44.07 USD/month (300 – 1,500 THB/month)
Current electricity expenses	12.78 – 42.30 USD/month (435 – 1,440 THB/month)	12.78 – 63.45 USD/month (435 – 2,160 THB/month)
Generation costs according to 1st year of operation (2018)		
10-year project lifetime scenario		
▪ Basic appliances (light, fan, mobile phone charger, TV)	14.36 USD/month (488.70 THB/month)	27.36 USD/month (931.21 THB/month)
▪ Rice cooker	10.27 USD/month (349.65 THB/month)	
▪ Fridge	7.39 USD/month (251.47 THB/month)	
▪ Washing machine	2.59 USD/month (88.16 THB/month)	
▪ Computer	3.93 USD/month (133.88 THB/month)	
20-year project lifetime scenario		
Basic appliances (light, fan, mobile phone charger, TV)	10.30 USD/month (350.59 THB/month)	19.63 USD/month (668.04 THB/month)
Rice cooker	7.37 USD/month (250.84 THB/month)	
Fridge	5.30 USD/month (180.41 THB/month)	
Washing machine	1.86 USD/month (63.24 THB/month)	
Computer	2.82 USD/month (96.04 THB/month)	
30-year project lifetime scenario		
Basic appliances (light, fan, mobile phone charger, TV)	9.36 USD/month (318.72 THB/month)	17.84 USD/month (607.31 THB/month)
Rice cooker	6.70 USD/month (228.03 THB/month)	
Fridge	4.82 USD/month (164.00 THB/month)	
Washing machine	1.69 USD/month (57.49 THB/month)	
Computer	2.57 USD/month (87.31 THB/month)	

Appendix 6: Single Line Diagram (SLD) of the hybrid system



Appendix 7: PV power plant layout



Appendix 8: Alternative location of power station building