CHAPTER 5 Power System Plan and Power System Analysis

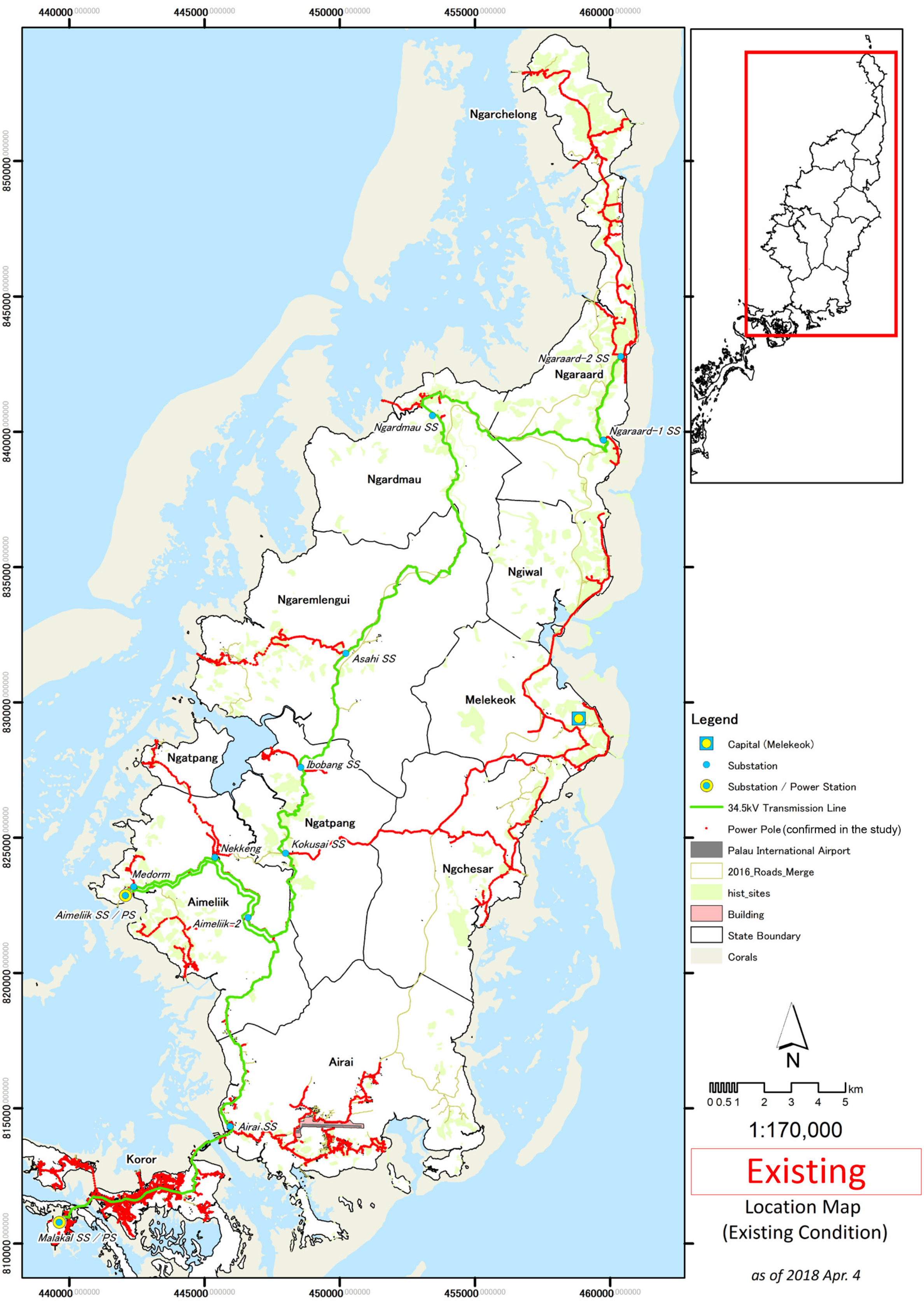
Chapter 5 Power System Plan and Power System Analysis

5-1 Present Condition of the Power System in Palau

5-1-1 Present Condition of Facilities

(1) Power system

Figure 5-1-1.1 shows the power system of Koror island and Babeldaob island, the main power system in Palau. Power demand in 2017 was approximately 12.4 MW. The power is supplied from diesel power stations located in Malakal and Aimeliik. At present, only one 34.5 kV transmission line circuit interconnects these two power stations. If any faults occur in this line, the power system is totally separated into two systems. The power demand is centered on Koror island and the southern part of Babeldaob island. The power demand from these areas reaches 10.6 MW, or 85% of the total demand of the country. There is also small-scale power demand in the central and northern parts of Babeldaob island. The 34.5 kV transmission line running from the south to north of Babeldaob island supplies power to these areas. Although the Parliament House was transferred to Melekeok State in the central-eastern area of Babeldaob island, this is only major building in this area. No other remarkable development has yet been conducted until now. One circuit of a 13.8 kV feeder supplies power to this area.



Source: Prepared by the JICA Project Team based on data provided by PPUC

Figure 5-1-1.1 Power system of Palau (Koror island and Babeldaob island)

(2) Power generation facilities

There are two power sources in the Koror-Babeldaob power system: Malakal Power Station located on Koror island and Aimeliik Power Station on Babeldaob island. These stations generate diesel power and accordingly run on diesel oil fuel. Table 5-1-1.1 summarizes the power generation facilities.

Table 5-1-1.1 Summary of power generation facilities (Koror-Babeldaob power system)

Power Station	Generator	Output Rating (kW)	Output Voltage (kV)	Rotating speed (rpm)	Year Commissioned
Malakal	Mitsubishi 12	3,400	13.8	720	1997
	Mitsubishi 13	3,400	13.8	720	1997
	Wartsila 1	2,000	13.8	1200	1996
	Caterpillar 1	1,825	0.48	1800	2006
	Caterpillar 2	1,825	0.48	1800	2006
	Niigata 14	5,000	6.6	720	2005
	Niigata 15	5,000	6.6	720	2005
	Mitsubishi 1	500	0.48	1800	2012
	Mitsubishi 2	500	0.48	1800	2012
	Mitsubishi 3	500	0.48	1800	2012
	Mitsubishi 4	500	0.48	1800	2012
Aimeliik	Mitsubishi 6	5,000	13.8	720	2013
	Mitsubishi 7	5,000	13.8	720	2013
	CAT 3516	2,000	0.48	1800	2012
Total		36,450			

Source: PPUC

(3) Transmission facilities

The present transmission facilities are shown in Table 5-1-1.2. All of the transmission facilities in Palau consist of one 34.5 kV circuit. Most of the supporting structures are concrete poles, and panther masts are partly used. The transmission line was constructed on Koror island and Babeldaob island from the south to the north and runs a total distance of approximately 80 km.

Table 5-1-1.2 Present condition of transmission facilities (Koror-Babeldaob power system)

Line	Voltage (kV)	Number of circuits	Length (km)	Conductor	Capacity (A) [(MW) : Power factor 0.9 assumed]
Malakal--Airai	34.5	1	9.184	AAC150mm^2	1200 A [21.5 MW]
Aimeliik--Airai	34.5	1	18.553	AAC150mm^2	1200 A [21.5 MW]
Aimeliik--Nekken	34.5	1	4.287	AAC150mm^2	1200 A [21.5 MW]
Nekken--Kokusai	34.5	1	8.849	AAC150mm^2	1200 A [21.5 MW]
Kokusai--Ngaraard	34.5	1	38.778	AAC150mm^2	1200 A [21.5 MW]
Total			79.651		

Source: PPUC

(4) Substation facilities

The present situation of the substation facilities is shown in Table 5-1-1.3. There are 12 substations in total in the Koror-Babeldaob power system, including the substation facilities installed in power stations for local supply. Only three of the substations, however, are equipped with line circuit breakers: Aimeliik Substation, Airai Substation and Malakal Substation. If any fault occurs on a transmission line, power outages will therefore result in all of the sections throughout the faulted line.

Table 5-1-1.3 Present condition of substation facilities (Koror-Babeldaob power system)

Name	Voltage (kV)	Capacity (MVA)	Year Commissioned
Aimeliik	34.5/13.8	10	1986
	34.5/13.8	10	1986
Airai	34.5/13.8	10	1986
Malakal	34.5/13.8	10	1994
	34.5/13.8	13	2010
Kokusai	34.5/13.8	5	1986
Aimeliik 1	34.5/13.8	0.3	1986
Nekken	34.5/13.8	0.225	1986
Aimeliik 2	34.5/13.8	0.225	1986
Ibobang	34.5/13.8	0.075	1986
Asahi	34.5/13.8	0.3	1986
Ngaradmau	34.5/13.8	0.225	1986
Ngaraard 1	34.5/13.8	0.075	1986
Ngaraard 2	34.5/13.8	0.75	1986

Source: PPUC

5-2 Current status of renewable energy and formulation of an introduction roadmap

Under Palau's Nationally Determined Contribution (NDC), which puts the nation on a trajectory to generating 45% of its energy from renewable sources by 2025, PPUC plans to formulate a master plan for achieving a 45% renewable energy (RE) scenario.

The JICA Study team has explained various expected challenges to achieving a 45% RE scenario, such as high capital and O&M costs, land issues, and technical issues such as RE output forecasting, control, and battery management. In order to compare several scenarios from financial and technical viewpoints, the JICA side proposed the preparation of an alternative scenario with a lower RE generation rate through analyses of the levelized cost of electricity (LCOE). In response, PPUC explained that the 45% RE scenario was the national target and requested the JICA side to perform detailed analyses of the phasing and sequence of the RE road map by 2025, instead of preparing an alternative plan. The JICA side agreed to do the analyses, though continued to show concern over the realization of the 45% RE scenario up to 2025.

5-2-1 Current status of renewable energy

5-2-1-1 Current status of solar power generation

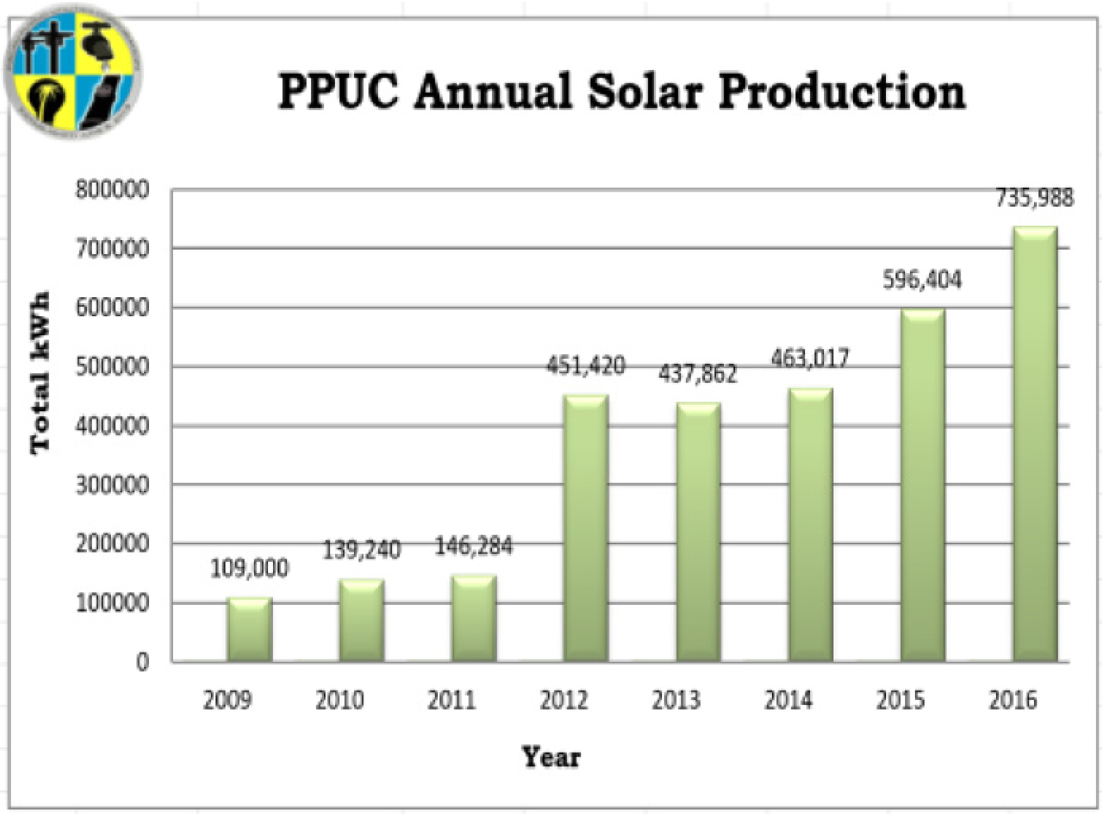
Palau receives abundant solar radiation throughout the year, and the rooftop photovoltaic power generation facilities (hereinafter, referred to as "rooftop PV") shown in Table 5-2-1-1.1 have already been installed. The rooftop facilities are connected to power systems by low-voltage interconnection, and almost all of the generated power is self-consumed. As shown in Figure 5-2-1-1, rooftop PV generated 735,988 kWh in FY2016. As the Palau government recommends rooftop PV installation proactively, the installation capacity may increase continuously in the future. On the other hand, no so-called mega solar PV power generation facilities (hereinafter, referred to as "PV power stations") have been installed. Although many countries and donors have proposed projects for PV power stations to the Palau government, no information on the proposals have been disclosed.

Table 5-2-1-1 Existing PV power generation facilities (as of July 2017)

Name	Name of Project /Funded by	Capcity (kWh)	Date Commisioned	Address	Remarks
Capitol Building	EU	100	2008	Melkeok State	Operational
Palau International Airport	JICA	225	2011	Airai State	Operational
Seebee		32		Airai State	Disconnected
NDBP Main Building	NDBP Project Loan	6.8		Airai State	Operational
NDBP/SBDC etc.	NDBP Project Loan	3.4x15			Operational
Kaleb Jr.	NDBP Project Loan	3.4		Koror State	Operational
Lorrain Tellei	NDBP Project Loan	3.4		Melkeok State	Operational
Oldias Ngiraikelau	NDBP Project Loan	3.4		Airai State	Operational
Clint Mersai	NDBP Project Loan	3.4		Koror State	Operational
Alfonsa Blesoch	NDBP Project Loan	3.4		Koror State	Operational
Marino Rechesengel	NDBP Project Loan	3.4		Airai State	Operational
Apolonia Ngirchechol	NDBP Project Loan	3.4		Koror State	Operational
Ann Kitalong	NDBP Project Loan	3.4		Airai State	Operational
Florencio Gibbons	NDBP Project Loan	3.4		Airai State	Operational
Besure Kanai	NDBP Project Loan	3.4		Airai State	Operational
Kintaro Hidencio	NDBP Project Loan	3.4		Koror State	Operational
Abby Rdialul	NDBP Project Loan	3.4		Koror State	Operational
Emmaus High School	JCM	25	2016	Koror State	Operational
Ronald Ray Carlyle	NDBP Project Loan	3.4		Airai State	Operational
Lydia Ngirmeriil	NDBP Project Loan	3.4		Koror State	Operational
Archives				Airai State	Disconnected
Koror Elementary School	Taiwan	46		Koror State	Operational
WCTC (ACE Hardware)	JCM	220		Koror State	Operational
Track & Field	EU	150		Koror State	Not working
Surangel SuperCenter	JCM	150		Koror State	Operational
Carol Ngiraidis etc.	NDBP Project Loan	3.5x37			Operational
Jovan Isaac	NDBP Project Loan	3.5	2016		Operational
Allison Sengebau/ Fred	NDBP Project Loan	3.5	2016	Airai State	Operational
Serenia Mamis	NDBP Project Loan	3.5	2016		Operational
Vernice Rechebei/Dilbuch	NDBP Project Loan	3.5	2016	Koror State	Operational
Polly Madraisau	NDBP Project Loan	3.5	2016	Aimeliik State	Operational
Sherilynn Madraisau/ Mindy	NDBP Project Loan	7	2016	Aimeliik State	Operational
Shannin Basilio	NDBP Project Loan	3.5	2016	Airai State	Operational
Kalista Ngirkelau	NDBP Project Loan	3.5	Sep-16	Airai State	Operational
Kathy West	NDBP Project Loan	3.5	Jul-16	Koror State	Operational
Wong Paulus	NDBP Project Loan	3.5	Jul-16	Koror State	Operational
Millan Issac	NDBP Project Loan	3.5	2016	Airai State	Operational
Benarry Gibbons	NDBP Project Loan	3.5	Sep-16	Airai State	Operational
Vicent Ito	NDBP Project Loan	3.5	Aug-16	Airai State	Operational
Lloyd Ueda/ Basilia Ringang	NDBP Project Loan	3.5	Aug-16	Koror State	Operational
Yutaka Gibbons Jr.	Galaxy	4	Sep-16	Airai State	Operational
Abby Rdialul/ Rachel Rdialul	NDBP Project Loan	3.5	Sep-16	Koror State	Operational
Palau High School				Koror State	prepaid meter/Not connected to grid
Ministry of Education	Taiwan	51	2010	Koror State	Operational
Ministry of Health	Taiwan	150	2008	Koror State	Operational
PIDC/Rechucher-Basement Eusevio	JCM	101.4	2016	Koror State	Operational
Marine Resources				Koror State	don't know which for solar
Koror Solid Waste				Koror State	
Comfort Hotel & Apartments	Own Fund	85	2016	Koror State	Operational
Meyuns swimming Pool	Taiwan	25	2015	Koror State	Operational
PMA	JCM	103.3	2016	Airai State	Operational
School Gymnasium Palau SDA	JCM	51.6	2016	Koror State	Operational
WCTC-Central Warehouse Malakal	JCM	220	2014	Koror State	Operational
WCTC Desekel Mall	JCM	80	2016	Koror State	Operational
Public Works				Koror State	don't know which for solar
Jeralda Koshiba	NDBP Project Loan	3.5	Oct-16	Aimeliik State	Operational
Joseph Aitaro	NDBP Project Loan	3.5	Oct-16	Airai State	Operational
Lorenzo Pedro	NDBP Project Loan	3.5	Dec-16	Koror State	Operational
Christiana Ngiramos	NDBP Project Loan	3.5	Dec-16	Koror State	Operational
Pualanie Ngiraswei/Ashley Omelau	NDBP Project Loan	3.5	Dec-16	Koror State	Operational
Kyonori Tellames	NDBP Project Loan	3.5	Dec-16	Koror State	Operational
Scott Yano	NDBP Project Loan	3.5	Dec-16	Airai State	Operational
Tony Adelbai	NDBP Project Loan	3.5	Jan-17	Koror State	Operational
Joyleen Temengil	NDBP Project Loan	3.5	Jan-17	Ngatpang State	Operational
Davis Tamtreng	NDBP Project Loan	3.5	Jan-17	Ngeremlengui State	Operational
Lester Rekemesik	NDBP Project Loan	3.5	Jan-17	Airai State	Operational
Greg Decherong	NDBP Project Loan	3.5	Jan-17	Koror State	Operational
Maura Gordon#1	NDBP Project Loan	3.5	Jan-17	Koror State	Operational
Maura Gordon #2	NDBP Project Loan	3.5	Jan-17	Koror State	Operational
Orange Beach Co	NDBP Project Loan	7	Jan-17	Koror State	Operational
Maria Basilius	Galaxy	4	Jan-17	Ngchesar State	Operational
Odelaffi Sato/Julius Mayers	NDBP Project Loan	3.5	Jan-17	Koror State	Operational
Merlyn Basilius	Galaxy	4	Jan-17	Koror State	Operational
Mars Ngirmeriil	NDBP Project Loan	3.5	Feb-17	Koror State	Operational
Minoru Ueki	NDBP Project Loan	3.5	Feb-17	Koror State	Operational
Hogan Skebong	NDBP Project Loan	3.5	Mar-17	Airai State	Operational
Vincent Ito(Utenkongel Laundromat)	NDBP Project Loan	7	Mar-17	Airai State	Operational
Justino Mechaet	NDBP Project Loan	3.5	Apr-17	Ngarard State	Operational
Peliliu Power Plant	UAE/Japan	164	May-16	Peliliu State	Not yet working
Angaur Power Plant	UAE	100	May-16	Angaur State	Not yet working
Kayangel Water Treament Plant	UAE	2.5	Apr-17	Kayangel State	Operational
Echang Basketball Court	Taiwan	20	Jan/Feb 2017	Koror State	Operational
Jerome Senior	NDBP Project Loan	3.5		Koror State	Not yet connected to grid
Charles Obechang	NDBP Project Loan	3.5	17-Jul	Airai State	Operational
Wridon Ngiralmau	NDBP Project Loan	3.5		Koror State	Not yet connected to grid
Harley Edeluchel	Galaxy	4	May-17	Airai State	Operational
Palau Rainbow Travel Service	Galaxy	4	May-17	Koror State	Operational
Palau Pacific Resort	Own Fund	26	2011	Koror State	Operational
TOTAL CAPACITY		2356.1			

Out of the Koror - Babeldaob System

Source: PPUC



Source: PPUC

Figure 5-2-1-1 Trends of rooftop PV annual power generation

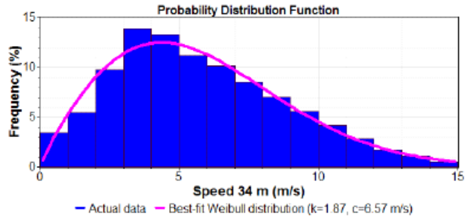
5-2-1-2 Current status of wind power generation

At present, there is no wind power generation facility (hereinafter, referred to as "WT") in Palau. For about 2 years from 2013, NREL measured wind conditions at 3 sites on Babeldaob Island. As shown in Figure 5-2-1-2.1, even in observations at a point of 82 m above sea level (height of observation tower: 32 m), the wind speed reaches 6 m/s with a frequency of about 57%. While the wind speed does fall below the average of 6 m/s or more, the level considered appropriate for wind power generation, IRENA has determined that a certain effect can be expected from introduction. Meanwhile, NREL also determined that the State of Ngaraad in the eastern part of the Babeldaob Island would be suitable for wind power generation. The site, however, was far from the Compact Road. For construction, the site is rife with challenging conditions related to land, the development of infrastructures to carry construction equipment in and out, measures to address environmental issues, etc., as in the case of PV. Additionally, according to the actual results of WT introduction in the surrounding islands, the actual operating ratio is estimated to be approximately 60%, given the frequent occurrence of unexpected faults and the poor supply of spare parts from the manufacturer. While PV is basically maintenance-free, WT has many moving parts that require periodical maintenance. For this reason, it would be difficult to maintain and operate WT appropriately with PPUC's manpower. In view of the above, the introduction of WT to Palau should be examined cautiously.

Ngaarard – Wind Speed Distribution

WIND

Ngaraard	
Variable	**Value**
Latitude	N 7.654617
Longitude	E 134.641300
Elevation	50 m
Duration	20 months
Wind power density at 50m	293 W/m²



Ngaarard				
Bin	Bin Endpoints (m/s)		Occurrences	Frequency
(#)	Lower	Upper	(#)	(%)
1	0	1	3,125	3.441
2	1	2	4,958	5.460
3	2	3	8,940	9.845
4	3	4	12,663	13.945
5	4	5	12,116	13.342
6	5	6	10,170	11.199
7	6	7	9,235	10.170
8	7	8	7,753	8.538
9	8	9	6,430	7.081
10	9	10	5,139	5.659
11	10	11	3,819	4.206
12	11	12	2,633	2.899
13	12	13	1,588	1.749
14	13	14	1,064	1.172
15	14	15	522	0.575
16	15	16	314	0.346
17	16	17	166	0.183
18	17	18	81	0.089
19	18	19	36	0.040
20	19	20	15	0.017
21	20	21	7	0.008
22	21	22	8	0.009
23	22	23	3	0.003
24	23	24	4	0.004
25	24	25	2	0.002
26	25	26	3	0.003
27	26	27	3	0.003
28	27	28	0	0.000
29	28	29	1	0.001
30	29	30	1	0.001
31	30	31	1	0.001
32	31	32	1	0.001
33	32	33	0	0.000
34	33	34	2	0.002
35	34	35	0	0.000
36	35	36	1	0.001
37	36	37	1	0.001
38	37	38	3	0.003
39	38	39	1	0.001
40	39	40	0	0.000
	All bins		90,809	100

Source: NREL Palau Wind Resource Summary – Weibull Distributions (October 2016)

Figure 5-2-1-2.1 Wind conditions in Palau
(May 2013 to April 2025, 10-minute interval measurement data)

5-2-1-3 Other renewable energies

Though there is little prospect of being able to utilize, and little significance in utilizing, the following RE sources at this point, the recommended approach is to carefully watch for future changes in factors such as the technological development and to consider utilization as necessary.

(1) Hydropower generation

In spite of the fact that annual rainfall in Palau is approximately 3,800 mm, about 2.4 times that of Tokyo, the rainfall difference between rainy season and dry season is extreme. It would be difficult to obtain an effective head for hydropower generation, in light of the geography and the invariably small size of Palau's rivers. A plan was formulated for a small-scale hydropower generation plant with approx. 200 kW output using overflow from the Ngerimel dam for drinking water, but the low elevation difference (under 15 m) limits the potential for hydropower generation. Operating a hydropower generation facility requires know-how, and at this point, the need for proactive introduction is considered low, given the potential of the alternatives, solar and wind power generation.

(2) Ocean thermal energy conversion

Saga University conducted a verification test under a cooperation agreement with MRD (then) in 2001, but no results of any practical value were produced. Though ocean thermal energy conversion technology has advanced since the days the test was conducted, it has not reached commercial viability in any parts of the world. In Palau, ocean thermal energy conversion is not regarded as a renewable energy source that can be used in the very-near future.

(3) Geothermal, biomass, etc.

No thermal source usable for geothermal power generation has been found in Palau so far. The country's population is just around 20,000, and the types waste that can be used as fuel for power generation are too scarce to be stably supplied as a renewable energy source.

5-2-1-4 Treatment policy of RE sources in formulating the RE roadmap

Considering for the environment in Palau, the RE roadmap examined in this study considers PV to be the only RE source that makes it possible to achieve an RE ratio of 45% in 2030.

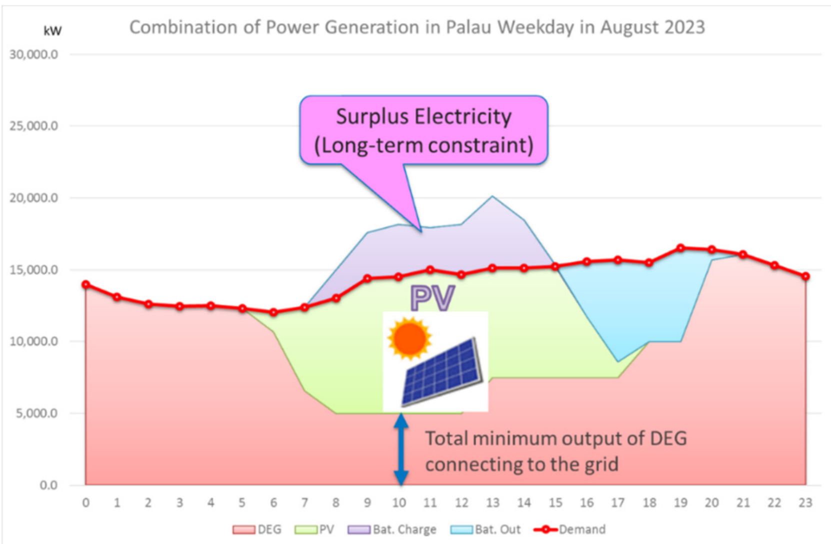
5-2-2 Examination of the RE Roadmap

A large fluctuation caused by RE output makes it difficult to keep the balance between supply and demand. A poor supply-balance stability could be a significant issue for a small-scale power system like that in Palau.

The major issues caused by a fluctuation of PV output are explained below.[1]

(1) Surplus energy (long-term fluctuations)

The electric power company operates power supply by controlling the output of each power plant according to the ever-changing power demand so that the demand and supply are equal at all times. If, however, the amount of renewable energy power (a type of power whose output is difficult to control) increases, a gap between the supply and demand may occur during periods of low load due to conflict between the RE power output and the output lower limit of the existing firm generation. This issue is studied in section 5-2-2-1.



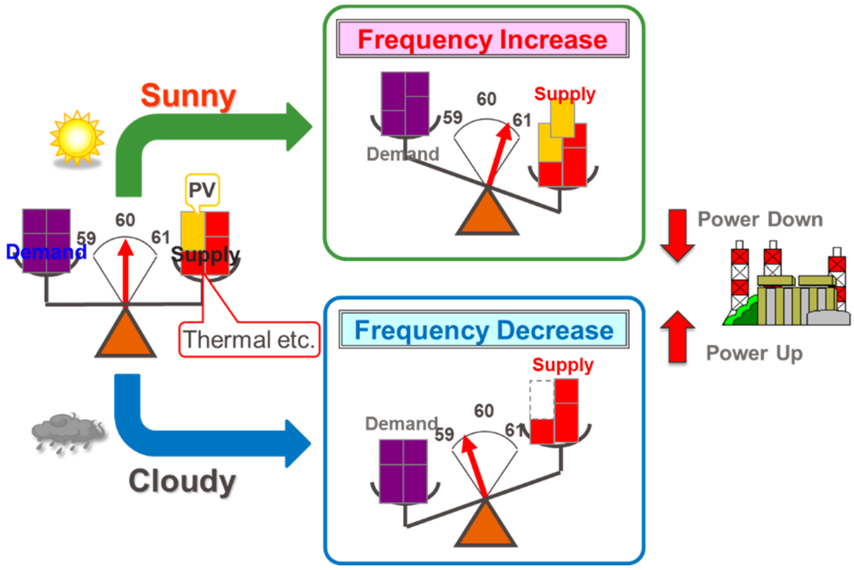
Source: JICA team

Figure 5-2-2.1 Excess electricity

[1] NEDO Renewable Energy Technology White Paper

(2) Frequency fluctuation (short-term fluctuations)

The "quality of electricity" describes the degree to which the frequency and voltage stably are stably maintained. To keep the frequency at a constant value, an electric power company controls the output of each power plant according to a constantly fluctuating demand. A large deployment of an RE power source such as PV and WT may affect the "quality of electricity." If frequency fluctuates over a certain value, mechanisms to protect the generators are triggered, which trips the circuits (disconnect from the power grid) one after another and can potentially cause a blackout. This issue is studied in section 5-2-2-2.



Source: JICA team

Figure 5-2-2.2 Frequency fluctuation by weather

(3) Rise in distribution system voltage

If a large number of RE power sources are interconnected to the distribution system (distribution lines), such as PV systems installed in homes (solar home system), and voltage at the interconnection point may violate the proper value (in Japan 101 ± 6 V) due to reverse power flow in the distribution system. Maintaining voltage at the proper value is necessary from the perspective of impact on the lifetime and normal use of electrical equipment on the customer side, as well as protection of equipment on the grid side. Measures such as curtailing output and stopping PV generation, such that the voltage does not exceed proper values, are therefore needed. This issue is studied in section 5-4.

(4) RE Islanding and unnecessary disconnection

The three problems described in (1)-(3) are related to normal operating conditions, but if a fault occurs on a grid, a RE Islanding and unnecessary disconnection should be the issues of concern.

1) Islanding

Islanding refers to a condition where distributed energy sources, including RE, continue to operate while connected to grids where power supply should normally be stopped and where no voltage should be present due to system faults caused by lightning, etc. or for construction. Given the risks that people or workers may be shocked, equipment may be damaged, or fire-fighting activities may be impaired, etc., these power sources must be disconnected from the grid.

2) Unnecessary disconnection

Unnecessary disconnection refers to a condition where RE sources disconnect unnecessarily when grid frequency and voltage fluctuations occur when normally they should not disconnect, for either of the following reasons: 1. an anti-islanding device is unnecessarily triggered; 2. impact of transient under-voltage or other disturbances. If many RE power sources over a wide area disconnect at once, the resulting drop in supply causes an imbalance in supply and demand and may disrupt the supply of power. As for this issue, PPUC has no grid code for capacities of more than 100 kW RE power source interconnection or high-voltage RE power source interconnection. The establishment of these grid codes is recommended in section 5-2-4.

5-2-2-1 Examination of PV and battery capacity from the viewpoint of long-term fluctuation

This section explains a basic method to estimate the amount of PV facilities necessary for achieving an RE ratio of 45% by 2025 and the amount of battery necessary for absorbing surplus PV output energy.

Because it is an essential responsibility for a grid operation to keep the balance between demand and supply, a balance simulation is conducted in this study with basic assumptions made concerning the demand curve, PV output curve, and conditions for diesel energy generator (DEG) operation.

(1) Examination of the demand curve

PPUC has data on net supply power recorded for 8,760 hours from January 1 to December 31, 2016. The demand curves in the future are formed using the recorded data in 2016 and the forecasted demand shown in Table 5-2-2-1.1.

Because the PPUC staff recorded the values of the output power shown on monitors by hand, there were blanks, omissions, and errors in the record. Though they were complemented and corrected adequately for use in the demand-supply simulation, the accuracy of the curve is not sufficient. Through the technology transfer, the JICA Study Team recommended that PPUC innovate the automating data acquisition system in order to save labor and keep accuracy.

Table 5-2-2-1.1 Demand forecast

	2017	2018	2019	2020	2021	2022	2023	2024	2025
Demand (MWh)	84,870	88,020	91,290	96,880	100,210	102,920	106,920	110,040	115,110

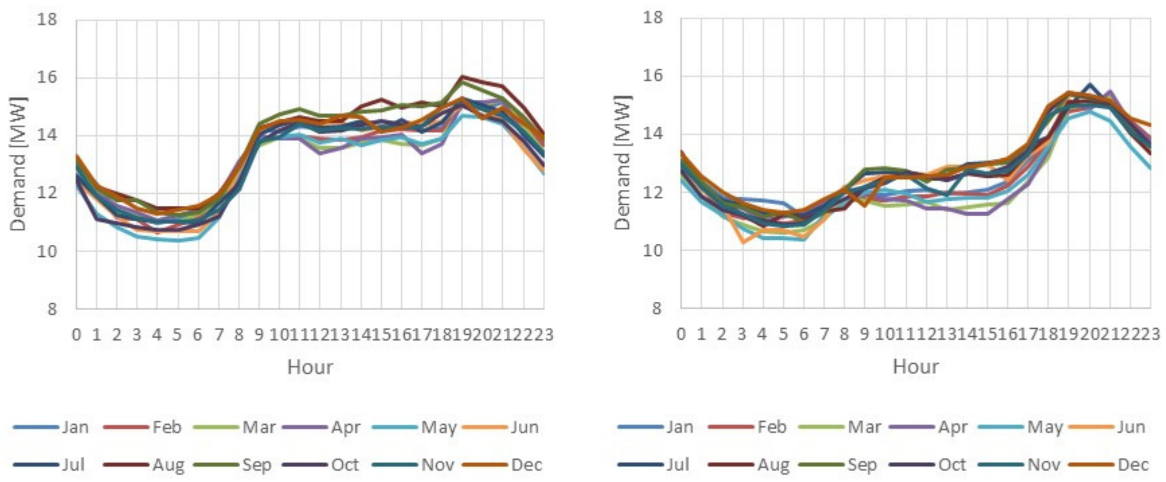


Figure 5-2-2-1.1 Monthly demand curves in 2025 (left, weekday; right, weekend)

(2) Examination of the PV output curve

The supply-demand balance simulation requires not only the demand curve but also the PV output curve. The PV output curves in this study are estimated using the PVWatts Calculator (http://pvwatts.nrel.gov/index.php) under the conditions shown in Table 5-2-2-1.2.

The rated capacity of a PV panel is generally defined as the output at solar radiation of 1,000 W/m^2. Figure 5-2-2-1.2 shows the histograms for the output of a PV system consisting of 2 MW of PV panel. The panel output ranges up to about 1.5 MW, somewhat below rated power, because of DC system loss and so on. It would therefore be wasteful to install a power conditioning system (PCS) with the same rated power same as the PV panel. In this case, the generated electric power may be maximized by fitting 1.5 MW of PCS to 2.0 MW of panel. In order to suppress the initial cost, 1.0 MW of PCS is applied in this study. Even in this case, the annual electric energy only decreases by about 3%.

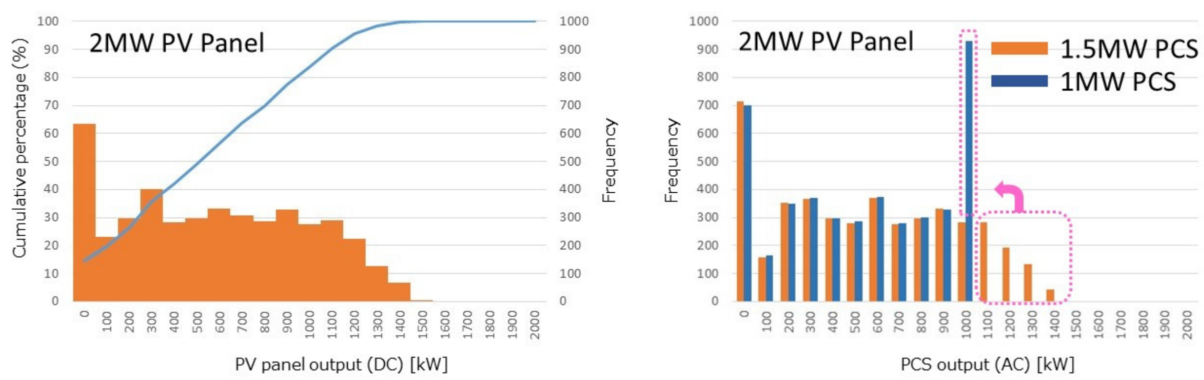


Figure 5-2-2-1.2 Histogram for PV system output (left, PV panel output; right, PCS output)

Table 5-2-2-1.2 Setting on the PVWatts Calculator
(left, typical PV power station; right, typical rooftop PV)

Left (typical PV power station)

RESULTS **2,529,057** kWh/Year*

System output may range from 2,367,956 to 2,594,053 kWh per year near this location.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	4.73	211,118	696,691
February	5.06	200,409	661,351
March	5.29	232,445	767,068
April	5.07	218,793	722,017
May	4.57	211,511	697,987
June	4.00	184,556	609,034
July	4.22	199,016	656,754
August	4.61	209,899	692,666
September	4.72	208,568	688,274
October	5.23	227,576	751,000
November	5.21	214,057	706,388
December	4.84	211,108	696,658
Annual	4.80	2,529,056	$ 8,345,888

Location and Station Identification		
Requested Location	palau	
Weather Data Source	(INTL) KOROR ISLAND, PALAU	14 mi
Latitude	7.33° N	
Longitude	134.48° E	

PV System Specifications *(Residential)*	
DC System Size	2000 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	20°
Array Azimuth	180°
System Losses	14.08%
Inverter Efficiency	98%
DC to AC Size Ratio	2

Right (typical rooftop PV)

RESULTS **161,348** kWh/Year*

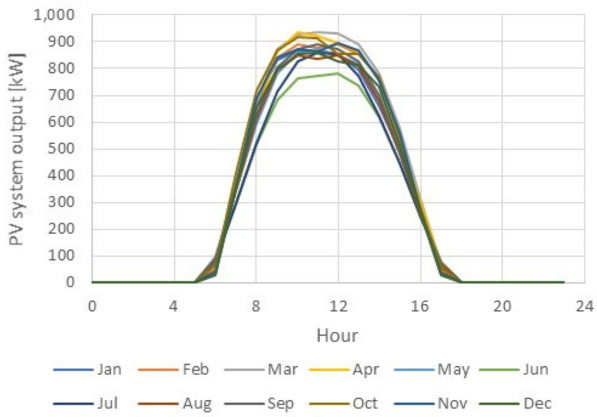
System output may range from 151,070 to 165,495 kWh per year near this location.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	4.73	13,661	45,082
February	5.06	13,210	43,594
March	5.29	15,228	50,253
April	5.07	13,933	45,979
May	4.57	13,040	43,032
June	4.00	11,140	36,762
July	4.22	12,088	39,891
August	4.61	13,107	43,253
September	4.72	13,104	43,243
October	5.23	14,833	48,949
November	5.21	14,147	46,685
December	4.84	13,856	45,725
Annual	4.80	161,347	$ 532,448

Location and Station Identification		
Requested Location	palau	
Weather Data Source	(INTL) KOROR ISLAND, PALAU	14 mi
Latitude	7.33° N	
Longitude	134.48° E	

PV System Specifications *(Residential)*	
DC System Size	120 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	20°
Array Azimuth	180°
System Losses	14.08%
Inverter Efficiency	98%
DC to AC Size Ratio	1.2

The PV output curve used for the demand-supply balance simulation is obtained by averaging the output values of the same month and the same time based on the PCS output of 8,760 hours obtained from the PVWatts Calculator (Refer to Figure 5-2-2-1.3). According to the PVWatts Calculator, the annual electric energy produced by the PV power station and rooftop PV are 2,530 MWh and 160 MWh, respectively.



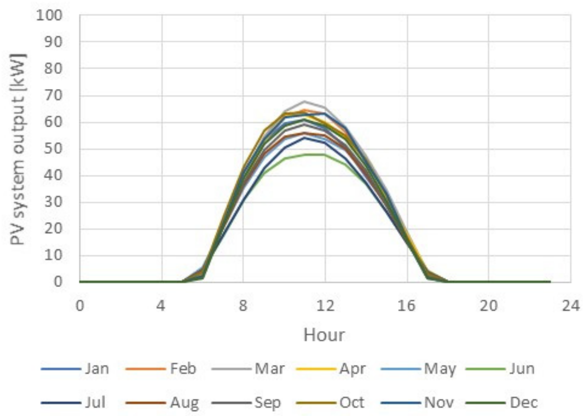


Figure 5-2-2-1.3 Curves for average PV output obtained by the PVWatts Calculator (left, PV power station; right, rooftop PV)

On the other hand, the rooftop PV varies in size from several kW installed in homes to relatively large -capacity systems installed in hotels, public facilities, and so on. The panel capacity here is set to 120 kW as a representative case. If the panel capacity is 3 kW, the annual electric energy generated by the system is 4 MWh, a level that corresponds to 1/40th of the energy generated by the system composed of 120 kW of panels.

According to Figure 5-2-1-1.1, the electric energy generated by rooftop PV has been increasing year by year, with the annual rates of increase recently reaching about 20%. Assuming that the power generation will be increasing at the same rate, the electric energy generated by rooftop PV and the capacity of rooftop PV are forecasted to stand at the levels shown in Table 5-2-2-1.3.

Table 5-2-2-1.3 Forecast for Rooftop PV

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Electric energy (MWh)	596	736	883	1,060	1,272	1,526	1,831	2,198	2,637	3,164	3,798
Panel capacity (kW)	450	560	670	810	970	1,200	1,400	1,700	2,000	2,400	3,000
PCS capacity (kW)	380	470	560	680	810	1,000	1,170	1,420	1,670	2,000	2,500

(3) Operating conditions for DEG

The 14 diesel engine generator units shown in Figure 5-2-2-1.4 have been installed in the Koror-Babeldaob system, the key system in Palau, and provide a total power generation capacity of 34.8 MW. In actual operation, electric power is supplied with 4 units of 5 MW rated power generation capacity as the main generators, with adjustments made in the number of units according to the power demand. Other units are used during emergencies and during maintenance work on the main generators.

In examining RE system interconnection, the use of Mitsubishi 16-19 high-speed diesel engine generators installed in Malakal Power Station may improve the frequency characteristics of the system and reduce expenses associated with the introduction of batteries as a countermeasure against short-term fluctuation, etc. Nevertheless, PPUC is reluctant to rely on the constant use of high-speed diesel engine generators, mainly because of the associated fuel cost increases and complications with generator operation. Consequently, the RE roadmap was examined based on 4 units of 5 MW main generators.

MALAKAL POWER STATION

11 units installed with corresponding present capacity:

Units	Installed Capacity	Present Capacity
Nigata 14	5.0 MW	5.0 MW
Nigata 15	5.0 MW	5.0 MW
Mitsubishi 12	3.4 MW	2.5 MW
Mitsubishi 13	3.4 MW	2.8 MW
Wartsila	2.0 MW	1.5 MW
CAT 1	2.0 MW	1.5 MW
CAT 2	2.0 MW	1.5 MW
Mitsubishi 16	0.5 MW	0.45 MW
Mitsubishi 17	0.5 MW	0.45 MW
Mitsubishi 18	0.5 MW	0.45 MW
Mitsubishi 19	0.5 MW	0.45 MW
TOTAL	24.8 MW	20.6 MW

AIMELIIK POWER STATION

2 units installed with corresponding present capacity:

Units	Installed Capacity	Present Capacity
MITSUBISHI # 6	5.0 MW	5.0 MW
MITSUBISHI # 7	5.0 MW	5.0 MW
TOTAL	10.0 MW	10.0 MW

Source: PPUC

Figure 5-2-2-1.4 All DEG installed in the Koror-Babeldaob system

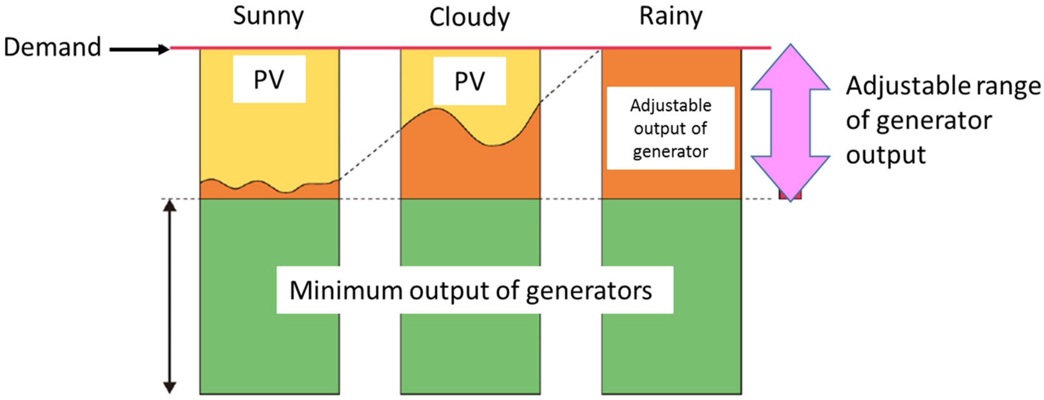
According to a generator manufacturer, the rated minimum output (for a short period of time only) of the 4 main generators is 30%. The generators are operated with the target output set at 50% or more for continuous operation, and a load fluctuation of 25% (1.25 MW) can be followed within one minute's time. The key elements are summarized in Table 5-2-2-1.4.

Table 5-2-2-1.4 Principal specification of % MW DEG

Power Station	Malakal		Aimeliik	
Unit	Nigata14	Nigata15	MITSUBISHI#6	MITSUBISHI#7
Governor Control	Droop	Droop	Droop	Droop
Speed Control Ratio (%)	3.1	3.1	3.92	4.05
Load-following Capacity	25 % / min.	25 % / min.	25 % / min.	25 % / min.
Rated Minimum Output (%)	30	30	30	30

Source: JICA Team

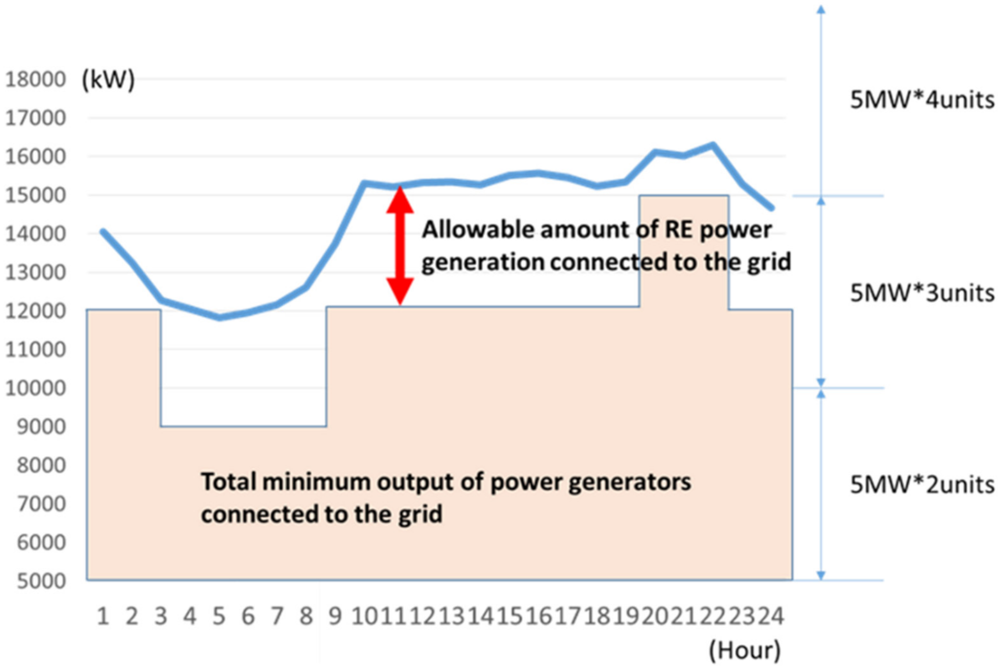
The allowable amount of RE for long-term fluctuation depends on the variance between the adjustable range of generators (lower limit of generator output) and total demand (see Figure 5-2-2-1.5). As mentioned previously, the rated minimum output of all main generators in Palau is 30%. As a result of discussions with PPUC in consideration of operational achievements so far, the fuel efficiency, the impact on DEG, and other factors, the minimum output rate of DEG was set at 50% in the calculation to determine the allowable amount of RE for long-term fluctuation in this project.



Source: NEDO

Figure 5-2-2-1.5 Adjustable range of generators

The amounts of PV and WT generation depend on the weather and are accordingly at risk of sudden drops to zero. In view of this, sufficient generators should be connected to the power grid in order to provide constant protection against blackouts and thereby secure a so-called spinning reserve. At least two units must be connected to the system for this operation: two 5 MW DEGs for >10 MW demand, three 5MW DEGs for >10 MW and <15 MW demand, and four 5MW DEGs for >15 MW and <20 MW demand (see Figure 5-2-2-1.6).



Source: Created by the Survey Team

Figure 5-2-2-1.6 Relation between generator operation and long-term allowable amount of RE (image)

According to the demand-supply balance simulation described later, when DEGs are operated under the above conditions, the annual energy generated by DEGs in 2025 is estimated to be 67,859 MWh. On the other hand, the demand in 2025 is estimated to be 115, 110 MWh. Therefore, even if 47,251

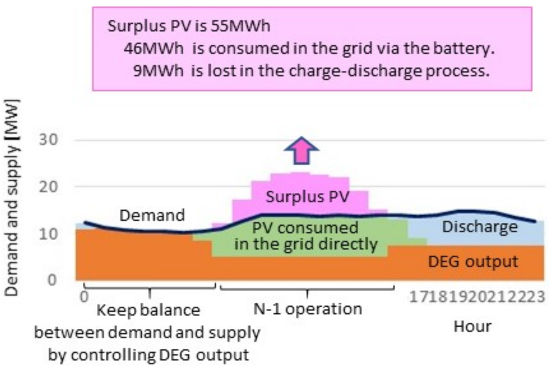
MWh corresponding to the supply shortage is supplied by PV, the RE ratio is 41%, which falls below the 45% target. Therefore, in order to improve the ratio, the number of DEGs to be operated will inevitably have to be reduced. If you reduce the number of DEGs at night, the amount of insufficient power should be compensated by discharge from the battery. In this case, the necessary battery capacity increases. If, on the other hand, the number of DEGs operated is decreased in daytime, it becomes possible to utilize rather than suppress the surplus power generated by PV. Note that the inertial force brought by a rotating machine such as a diesel generator or a turbine generator contributes to keep a system stability. Therefore, the supply-demand balance simulation is conducted under conditions where up to one DEG can be allowably reduced and where at least two DEGs are connected to the grid.

(4) Supply-Demand balance simulation

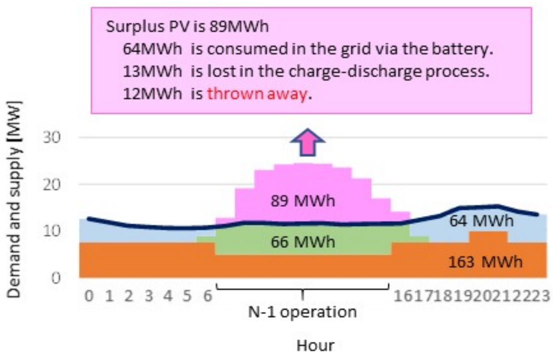
Before conducting the supply-demand balance simulation, the capacity of PV necessary for achieving the 45% RE ratio in 2025 may be estimated roughly as follows. The results show that 38 MW of PV panel will be required in 2025.

- The demand in 2025 is forecasted to be 115, 110 MWh. In order to achieve the 45% RE ratio, 51,800 MWh should be supplied by PV.
- A single rooftop PV unit supplies 158 MW annually. When 3 MW rooftop PV is installed in 2025, the PV can supply 3,950 MWh annually. Therefore, the remaining 47,850 MWh must be supplied by the PV power stations.
- Since a single PV power station may supply 2,496 MWh annually, a total of 38 MW of PV power stations should be developed by 2025.

Next, the demand-supply balance calculated using Excel is explained. According to the roughly estimated result, 38 MW of panel will be required for achieving the 45% RE ratio. However, there are situations in which the surplus energy generated by PV cannot be completely consumed at nighttime (see Figure 5-2-2-1.7). For example, all of the surplus energy is consumed on weekday nights in May 2025. On the other hand, the surplus energy cannot be consumed, and part of it is discarded, on a weekend in March 2025, which decreases the RE ratio. Therefore. the 45% RE ratio cannot be achieved with the panel capacity of 38 MW.



PV panel 38MW, Weekday on May 2025



PV panel 38MW, Weekend on March 2025

Figure 5-2-2-1.7 Case study for treatment of surplus PV energy

In order to improve the value of RE ratio, it is necessary to increase the amount of surplus electricity during the day by installing more PV and utilizing it at night (see Fig. 5-2-2-1.8). For example, when 38 MW of PV panel is installed, the surplus energy is 55 MWh, of which 46 MWh, the remainder after deducting charge/discharge loss, can be utilized at nighttime. As a result, the RE ratio on this day is 42.4%. On the other hand, when 44 MW of PV panel is installed, 62 MWh can be utilized at nighttime and the RE ratio increases from 42.4% to 47.9%. Note that in order to use more surplus energy at nighttime, it becomes necessary to install a larger capacity battery.

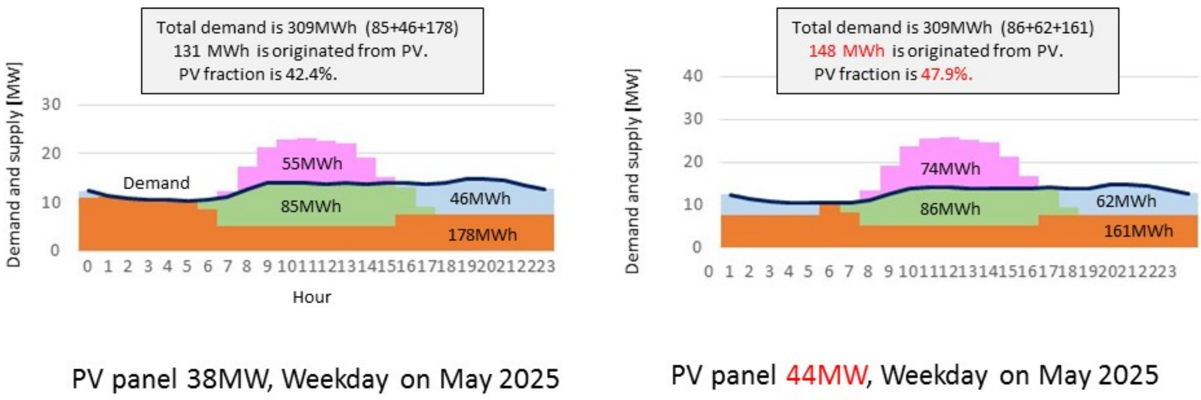


Figure 5-2-2-1.8 Improvement of RE ratio by additional installation of PV

The demand-supply balance simulation indicates that 42 MW of panel capacity is required to achieve the RE ratio of 45% (see Figure 5-2-2-1.9). Considering possible delays in land acquisition and reduced utilization rates due to maintenance or troubles, 2 MW, corresponding to one PV power station, will be added as a margin.

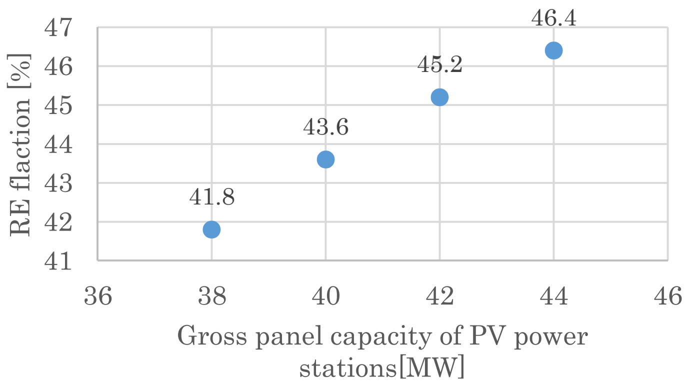


Figure 5-2-2-1.9 Relationship between the panel capacity and RE ratio of PV power station

Following is a description of the method for estimating the necessary capacities of battery and PCS combined with batteries, based on the supply-demand balances on weekdays in January 2025, as another example (see Figure 5-2-2-1.10). Because the maximum surplus power is 12 MW, the capacities required for battery and the PCS for the battery will each be 12 MW.

On the other hand, the surplus energy generated in daytime is 73 MWh. When the energy is supplied via the battery at nighttime, 61 MWh (the level remaining after the charge-discharge loss is deducted), can be consumed at nighttime. The efficiencies of the battery and PCS applied for the simulation are set at 85% and 98%, respectively. Since, supply shortage at nighttime is 74 MWh, the supply-demand balance can be maintained if the remaining 13 MWh is supplied by increasing the output of the DEGs.

As a result, the necessary battery capacity and its PCS would be 12 MW-73 MWh and 12 MW, respectively.

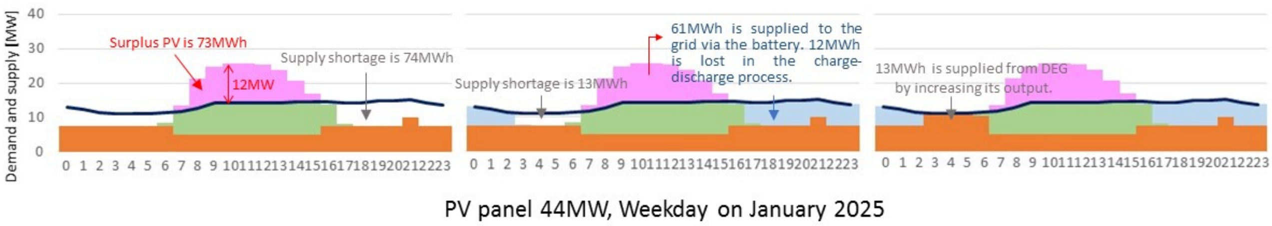


Figure 5-2-2-1.10 Necessary capacities of a battery and a PCS combined with a battery (Part 1)

The simulation process based on the supply-demand balances on a weekend in May 2025 is described as an example (see Figure 5-2-2-1.11). Because the maximum surplus power is 14 MW, the capacity required for the battery and PCS would be 14 MW, respectively.

On the other hand, the surplus energy generated in daytime is 91 MWh. When the energy is supplied via the battery at nighttime, 76 MWh (the level remaining after the charge-discharge loss is deducted) can be consumed at nighttime.

However, the available energy of 76 MWh overcompensates for the supply shortage of 65 MWh at nighttime. Therefore, the necessary battery capacity would be 65 MWh (including the charge-discharge loss).

As a result, the necessary capacities of the battery and PCS would be 14 MW-65 MWh and 14 MW, respectively.

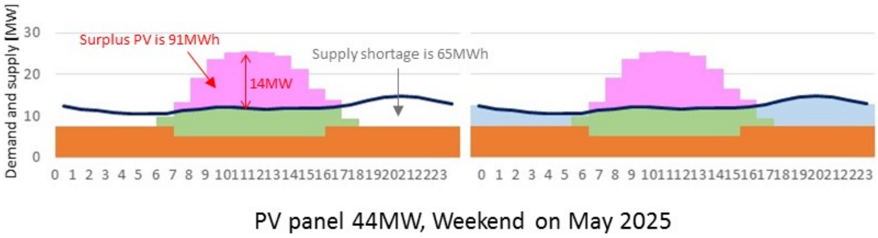


Figure 5-2-2-1.11 Necessary capacities of a battery and a PCS combined with a battery (Part 2)

According to the supply-demand balance simulation carried out for the weekdays and weekends of each month, the required battery capacity and PSC would be 16 MW-92 MWh and 16 MW, respectively, in 2025 (see Table 5-2-2-1.5).

Table 5-2-2-1.5 Results of the supply-demand simulation in 2025

Input													
Rooftop pannel	3,000	kW											
PV Station pannel	44,000	kW											
Target of PV Fraction	45	%											
Output (WeekDay)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Power Supply		Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough
Monthly PV Fraction (%)		46	49	48	48	48	43	44	44	46	49	48	46
Battery (MW)	14 MW	12	12	14	13	12	9	11	11	11	13	12	11
Battery (MWh)	83 MWh	73	83	79	78	74	55	62	72	72	81	82	72
Days		22	20	23	20	23	22	21	23	21	22	22	21
Demand (MWh/Year)	83,296	7,082	6,362	7,279	6,344	7,098	6,982	6,714	7,661	6,954	6,942	7,025	6,853
DEG (MWh/year)	44,559	3,817	3,259	3,795	3,300	3,696	4,008	3,766	4,274	3,772	3,520	3,621	3,731
PV (MWh/Year)	38,737	3,265	3,103	3,484	3,044	3,402	2,974	2,948	3,388	3,182	3,422	3,404	3,122
Output (WeekEnd)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Power Supply		Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough	Supply Ehough
Monthly PV Fraction (%)		47	47	45	46	46	44	45	47	47	46	47	47
Battery (MW)	16 MW	14	14	16	15	14	11	13	13	13	15	14	13
Battery (MWh)	87 MWh	87	85	76	81	78	68	74	81	81	80	86	87
Days		9	8	8	10	8	8	10	8	9	9	8	10
Demand (MWh/Year)	31,814	2,735	2,395	2,339	2,973	2,334	2,429	3,093	2,433	2,785	2,751	2,432	3,118
DEG (MWh/year)	17,164	1,463	1,280	1,280	1,600	1,260	1,365	1,709	1,300	1,485	1,485	1,280	1,658
PV (MWh/Year)	14,650	1,272	1,115	1,059	1,373	1,074	1,064	1,383	1,133	1,300	1,266	1,152	1,461
Total													
Demand	115,110	MWh/year											
DEG	61,723	MWh/year											
PV	53,387	MWh/year											
DG+PV	115,110	MWh/year											
DEG fraction	53.6	%											
PV fraction	46.4	%											
Battery	16	MW											
Margin for Battery	5.0	%											
Battery	92	MWh											

On the other hand, the RE ratio obtained by HomerPro is 36.9%. Considering the result from HomerPro, two DEGs are running at rated power at nighttime even though there is a margin in the SOC of the battery (see Figure 5-2-2-1-12). Though the reason for this is difficult to explain without the knowledge for the algorithm in HomerPro, this situation might be one of the reasons to set the RE ratio lower than the value obtained by the Excel simulation used for the previous considerations.

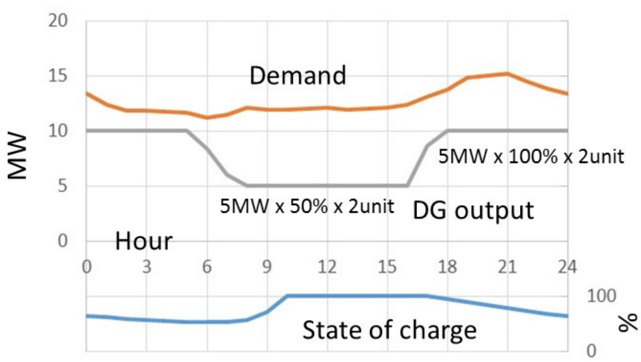


Figure 5-2-2-1.12 Curves of demand, DEG output, and state of charge on the same day obtained by HomerPro

HomerPro has great advantages. In addition to evaluating the supply-demand balance, it can also make cost evaluations to determine optimum combinations of equipment. On the other hand, as in this example, differences in the operating conditions of DEGs greatly affect the output. Therefore, it is recommended to examine the results by multiple methods (multiple viewpoints) and analyze why differences occur.

(5) Conclusion

Because it is difficult to control the output of an RE source arbitrarily, the supply-demand balance can be maintained by coordinating with DEG and/or battery.

This section considers the demand-supply balance from the viewpoint of long-term fluctuation using a supply-demand balance simulation.

The results indicate that in order to achieve an RE ratio of 45% in 2025, the required capacity of the battery and PSC would be 16 MW-92 MWh and 16 MW, respectively.

5-2-2-2 Examination of battery capacity from the viewpoint of long-term fluctuation

When a large amount of RE source is penetrated, fluctuation of the RE output could potentially make the system frequency unstable. The system frequency can be kept within an appropriate range by satisfying the following relationship: fluctuation capacity (kW) $\leqq$ absorbable capacity (kW).

(1) Outline of the algebraic method

Special simulation tools such as the Y Method of the Central Research Institute of Electric Power Industry (CRIEPI) and MATLAB/Simulink of MathWorks can quantitatively calculate the frequency fluctuation caused by the output fluctuation of an RE power source. However, the high skilled technique should be required to utilize such simulation tool(s).

Considerations on the short-term fluctuation in this project are conducted using the algebraic method. The Power System Working Group of the Ministry Economic, Trade and Industry of Japan (METI), the Tohoku Electric Power Company, and others have reported that the results acquired by the algebraic method are nearly equal to those acquired using special simulation tools.

According to the algebraic method, if elements such as the fluctuation sources and absorption sources in this study are independent of each other, the relationship between them is as shown in Fig. 5-2-2-2.1.

As mentioned above, 47 MW of PV panel (3 MW of rooftop PV + 44 MW of PV power station) will be penetrated to the grid in 2025. This section aims to estimate the battery capacity required to absorb the fluctuation caused by the PV output. The method proceeds in the following steps.

1. Evaluation of the demand fluctuation (fluctuation source)
2. Evaluation of the LFC adjustability (absorption source)
3. Evaluation of the adjustable margin (absorption source)
4. Evaluation of the allowable PV output fluctuation rate
5. Evaluation of the fluctuation caused by PV output
6. Evaluation of the battery capacity necessary to absorb fluctuation

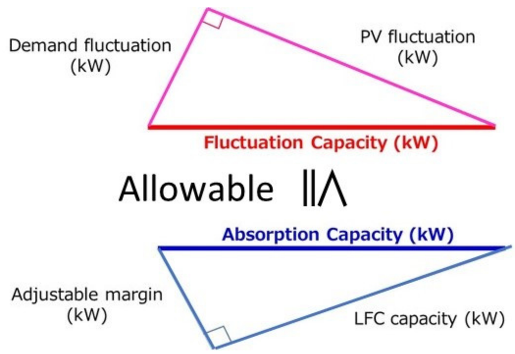


Figure 5-2-2-2.1 Relationship between fluctuation and absorption sources in the algebraic method

(2) Demand fluctuation

Because the short-term fluctuation treats the fluctuation in a short time range of several minutes or less, a time resolution on the order of the hourly demand data used in 5-2-2-1 is too rough to evaluate in short-term fluctuation. The demand fluctuation has therefore been evaluated based on the data measured at 5-second intervals at the Malakal substation for 48 hours.

The procedure and results of the demand fluctuation calculation are described below.

The demand fluctuation rate is defined as $|D(T) - D_{ave}(T)| \div D_{ave}(T) \times 100$ (%), where D(t) is the demand at t, and Dave (T) is the average demand from t = T-5 minutes to t = T+5 minutes. The histogram below shows the results after calculating the demand fluctuation rate (see Figure 5-2-2-2.2).

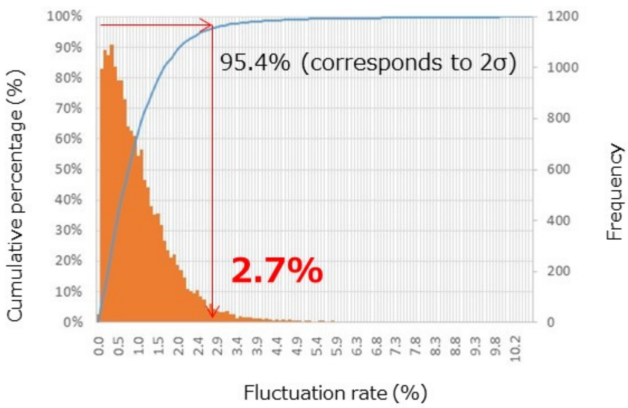


Figure 5-2-2-2.2 Histogram of the demand fluctuation rate

Given that a large fluctuation rate only occurs about several times a year, the increase in the battery capacity necessary to absorb the fluctuation in the system design might be uneconomical. Therefore, 3σ values (considering up to 99.7% of all events) or 2σ values (considering 95.4% of all events) are generally adopted.

As a result of the confirmation with PPUC on how the risks will be handled, PPUC has decided to apply the 2σ value.

From Figure 5-2-2-2.2, the demand fluctuation rate is required to be 2.7%. The amount of demand fluctuation is defined as demand (kW) × demand fluctuation rate ÷ 100.

In this study, the demand tends to be lowest at around 15 o'clock in the weekend of April. Adopting a small demand value will estimate a small amount of fluctuation. At the same time, however, the adjustable margin that acts as an absorption source also becomes small and has a larger influence on the balance between the amount of fluctuation and absorption sources, considering the conditions in this study. To stay on the safe side, therefore, the demand at 15 o'clock is adopted for the evaluation of the amount of demand fluctuation.

Before penetrating a large amount of PV sources, it is recommended to collect more demand data and evaluate the load fluctuation rate again.

(3) LFC adjustability

The LFC (Load Frequency Control) controls the generator output automatically by determining the amount of generator adjustment required for the power area with respect to the frequency fluctuation due to demand fluctuations in a period of roughly 10 minutes or less. Since PPUC does not use the LFC function, LFC adjustability is defined as zero.

(4) Adjustable margin

The adjustment remaining (kW) is defined as demand (kW) × system constant (% kW / Hz) × Allowable frequency fluctuation range (Hz) ÷ 100. Demand is as the same as shown in 5-2-2-2 (2).

1) System constant

Since the system frequency and power flow change according to the demand fluctuation, generators should be controlled so as to keep the system frequency at a stable level. PV and WT are unstable power sources, which makes it difficult to control the generator output in accordance with the demand load. The existing generators (thermal power generation, diesel generator, etc.) are essential as control devices to match the demand load. A power system has a characteristic due to affection from loads and generators (including governor function) connected to the system, as shown below. Here, K is defined as the system constant. The algebraic method calculates the value for the maximum allowable power fluctuation using the system constant estimated during a generator rejection test performed to calculate the allowable adjustable margin.

$\Delta P / \Delta F = K$ (constant value: %kW/Hz)

(ΔP (%kW) = ΔP (kW) / total rated output of parallel input generators)

The system constant is generally calculated based on the results of the generator rejection tests, starting from a state of interconnection to a power system. In this regard, the unfavorable effect of a generator rejection test on the power system and generator becomes a concern. After discussions with PPUC on whether or not the generator rejection test should be done, PPUC decided not to conduct the generator rejection test. The risk of outage resulting from the test, together with the great burden on the generator, PPUC determined, could cause a breakdown. Instead, 10% of the standard system constant for remote islands that are supplied with DEG electricity is adopted. Conducting a generator rejection test or detailed simulation to estimate the system constant is required ahead of the RE system introduction.

2) Allowable frequency fluctuation range

According to the guideline for renewable energy system interconnection created under the PPUC "Guidelines, Standards and Regulations for Renewable Energy Generation Systems Connecting to the Palau Central Grid," the allowable frequency fluctuation range is ±2 Hz/0.16s.

(5) Allowable PV output fluctuation rate

According the calculation of allowable PV output fluctuation based on the data obtained in 5-2-2-2 (2) - (3), the allowable PV output fluctuation in 2025 is 2,233 kW (See Table 5-2-2-2.1).

Table 5-2-2-2.1 Allowable PV output fluctuation rate

	2019	2020	2021	2022	2023	2024	2025
(a) Demand (kW)	8,938	9,485	9,811	10,076	10,468	10,774	11,270
(b) Demand fluctuation (kW)	241	256	265	272	283	291	304
(c) Adjustale Margin (kW)	(a)×System constant 10%/kW/Hz ×Permissive freq. deviation 2Hz÷100						
	1,788	1,897	1,962	2,015	2,094	2,155	2,254
(d) Allowable fluctuation of PV (kW)	$\sqrt{\{(c)^2-(b)^2\}}$						
	1,771	1,880	1,944	1,997	2,074	2,135	2,233

(6) Fluctuation caused by PV output

The rated capacity of the PV panel is defined as the output at a solar radiation intensity of 1,000 W/m^2. Assuming that the PV panel output is proportional to the solar radiation intensity, data on the solar radiation intensity is required for the estimation of the PV output.

PPUC has 10-minute cycle measurement data collected by NRELover the 2-year period from 2013 to 2015. Cycle measurement data with a cycle time of a few seconds are required to check the short-term fluctuation rate of the solar radiation intensity. This time, therefore, 10-second cycle measurement data measured by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in Aimeliik in 2007 (see the upper side of the table) are used to analyze the PV generation data over a 365-day period from 6:00 to 18:00.

When a PV power station consists of 2 MW of panel and 1 MW of PCS as described in 5-2-2-1 (2), the station's output is 1 MW (the output is 1 MW, not 1.2 MW, for example, under a solar radiation condition of 600 W/m^2). Similarly, the output of rooftop PV is limited to 100 kW.

The PV output fluctuation is defined as follows;

The PV output fluctuation is defined as [Pmax (T) - Pmin (T)] ÷ PCS rated capacity × 100, where P_{max} (T) and P_{min} (T) are the maximum and minimum output within 5 minutes before and after T, respectively.

As a result, the fluctuation rates of PV plants and rooftop PVs are 65% and 72%, respectively (see Figure 5-2-2-2.3). The difference between the two fluctuation rates stems from the difference in capacity ratios between PV panel and PCS.

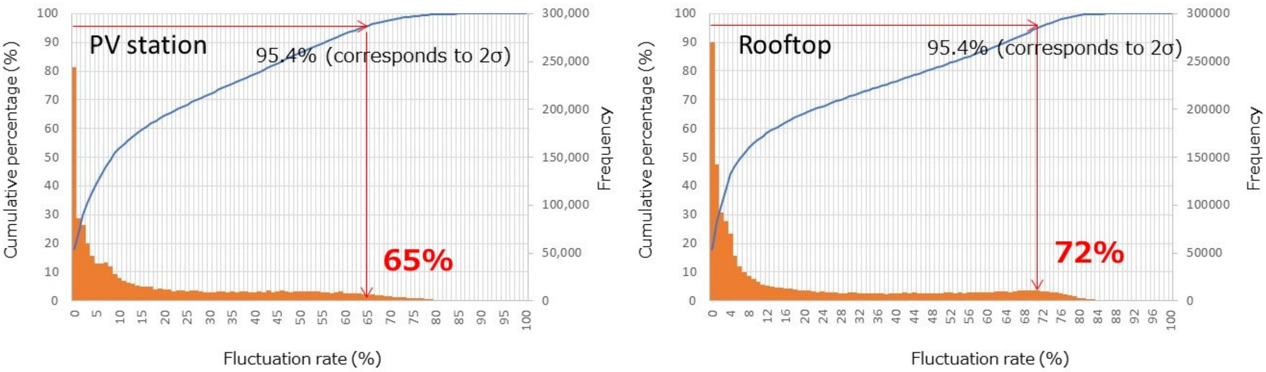


Figure 5-2-2-2.3 Histogram of the output fluctuation ratio for PV systems

The amount of PV output fluctuation is defined as: PCS rated capacity (kW) × PV output fluctuation rate (%) ÷ 100.

In this case, 22,000 kW of PCS (corresponds to 44,000 kW of panel capacity) for PV power station and 2,500 kW of PCS (corresponds to 3,000 kW of panel capacity) for rooftop PV will be installed by 2025.

Therefore, the total output fluctuation will be 16,100 kW (14,300 kW and 1,800 kW originating from PV power station and rooftop PV, respectively), an amount far exceeding allowable fluctuation of 2,233 kW estimated in 5-2-2-2 (5).

A countermeasure for suppressing the fluctuation is to disperse the PV power stations. This can be expected to have a smoothing effect. When the PV power plants are dispersed at distances from each other, the possibility that all outputs will fluctuate at the same time becomes low. Assuming that the outputs of the PV power stations are independent from each other, their output fluctuations can be represented by vector sums rather than simple additions.

The total amount of fluctuation can be expressed as $\sqrt{\sum_{i=1}^{N}(Pi \times \alpha i)^2}$, where Pi is the rated power of PCS, αi is the fluctuation rate, and N is the number of PV power stations.

We also need to obtain the output fluctuation in consideration of the smoothing effect. Based on the site locations of the PV power stations proposed by PPUC, the synthesized output fluctuation amount of PV was calculated again (see Table 5-2-2-2.2). In addition, because most of the rooftop PVs would be installed in Malakal, they would be treated as one PV power station, in this study.

As a result, the composite amount of the fluctuation decreases from 16,100 kW to 5,187 kW, but it still remains above the allowable value. In order to keep the amount of fluctuation within the acceptable limit of 2,233 KW, it becomes necessary to set the output fluctuation rate of the PV power plant to 17% or less.

The recommended method to analyze the fluctuation while accurately considering the smoothing effect is to measure the solar radiation at each candidate site or presume the radiations based on past weather data.

Table 5-2-2-2.2 Output fluctuation when the smoothing effect is expected

Values in table crrespond to PCS capacity (kW)

PV Installation Plan	2019	2020	2021	2022	2023	2024	2025
Rooftop	810	1,000	1,170	1,420	1,670	2,000	2,500
Aimeliik	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Ngaramiengui		3,000	3,000	3,000	3,000	3,000	3,000
Ngargmau*						2,000	2,000
Ngargmau**						3,000	3,000
Ngiwal							2,000
Meiekeok					2,000	2,000	2,000
Ngchesar					2,000	2,000	2,000
Ngatpang	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Airport				3,000	3,000	3,000	3,000

PV fluctuation	2019	2020	2021	2022	2023	2024	2025
Rooftop	583	720	842	1,022	1,202	1,440	1,800
Aimeliik	1,950	1,950	1,950	1,950	1,950	1,950	1,950
Ngaramiengui		1,950	1,950	1,950	1,950	1,950	1,950
Ngargmau*						1,300	1,300
Ngargmau**						1,950	1,950
Ngiwal							1,300
Meiekeok					1,300	1,300	1,300
Ngchesar					1,300	1,300	1,300
Ngatpang	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Airport				1,950	1,950	1,950	1,950
Total Fluctutation by Algebric Mthod	2,415	3,133	3,163	3,761	4,234	4,903	5,187

(7) Battery capacity necessary for absorbing fluctuation

Another countermeasure to alleviate PV output fluctuation is to absorb the fluctuation using a battery system (see Figure 5-2-2-2.4). The black dashed line, red line, and blue line in the figure below indicate the PV system output, charge-discharge, and output of a PV power station, respectively. The goal is to suppress the output fluctuation rate of the PV power station (the blue line) to 17% or less.

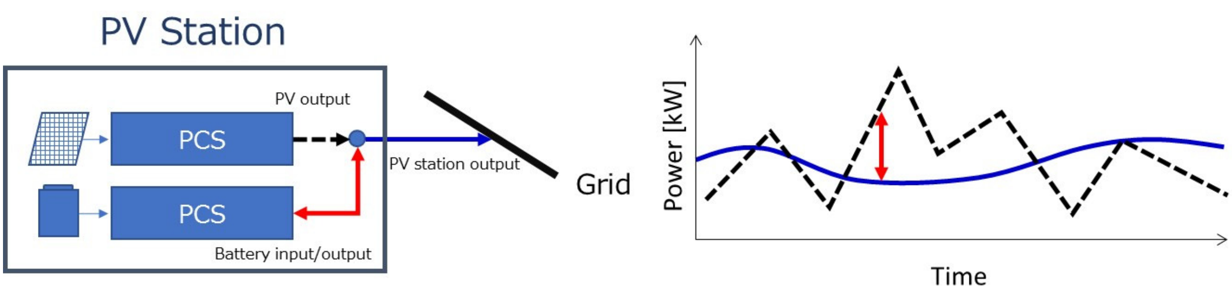


Figure 5-2-2-2.4 Battery system model for suppressing the fluctuation of the PV power station output

Consider controlling the output of the PV power station to a value (moving average value) obtained by averaging the PV station output in the last T minutes. T = 0 minutes means the PV power station without the battery system, that is, the output of the PV power station itself. The PV output data are the same as those used in 5-2-2-2 (6).

The output of the PV power plant can be smoothed by increasing T (see Figure 5-2-2-2.5). If T is set to 25 minutes or more, the fluctuation rate of the PV power station output will be 17% or less (Figure 5-2-2-2.5).

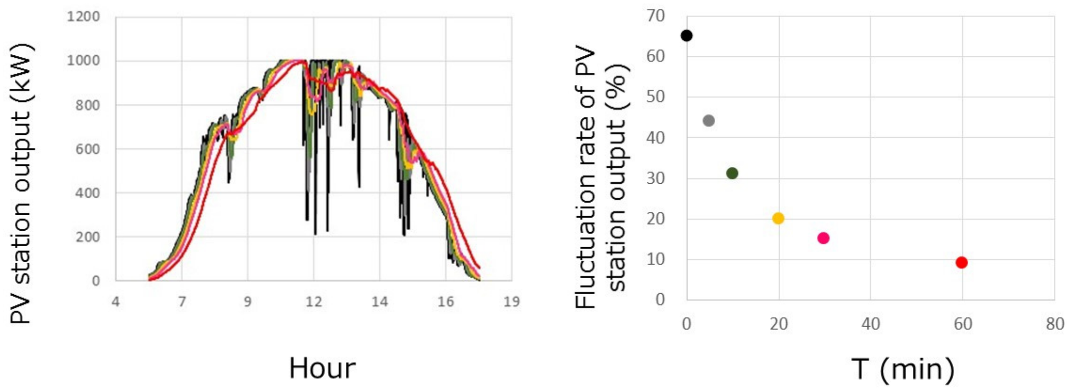


Figure 5-2-2-2.5 Relationship between the moving average time (T), PV power station output, and the output fluctuation rate (left, PV power station output; right, fluctuation rate)

Figure 5-2-2-2.6 shows histograms of the fluctuation rate of the PV power station output for each T.

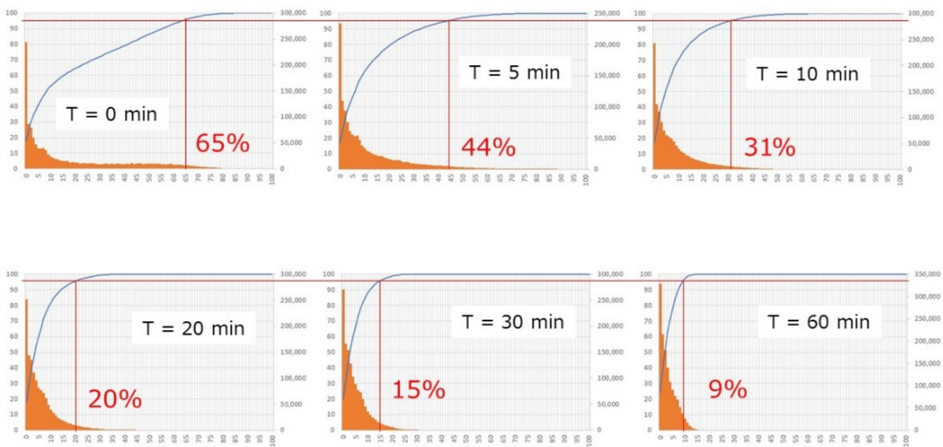


Figure 5-2-2-2.6 Histograms of the fluctuation rate of the PV power station output for each moving average time (T)

The output difference between the PV system and PV power station corresponds to the charge and discharge (see Figure 5-2-2-2.7). If the output of the PV system is larger than that of the PV power station, the difference is charged to the battery. In the opposite case, the balance is compensated by the discharge from the battery.

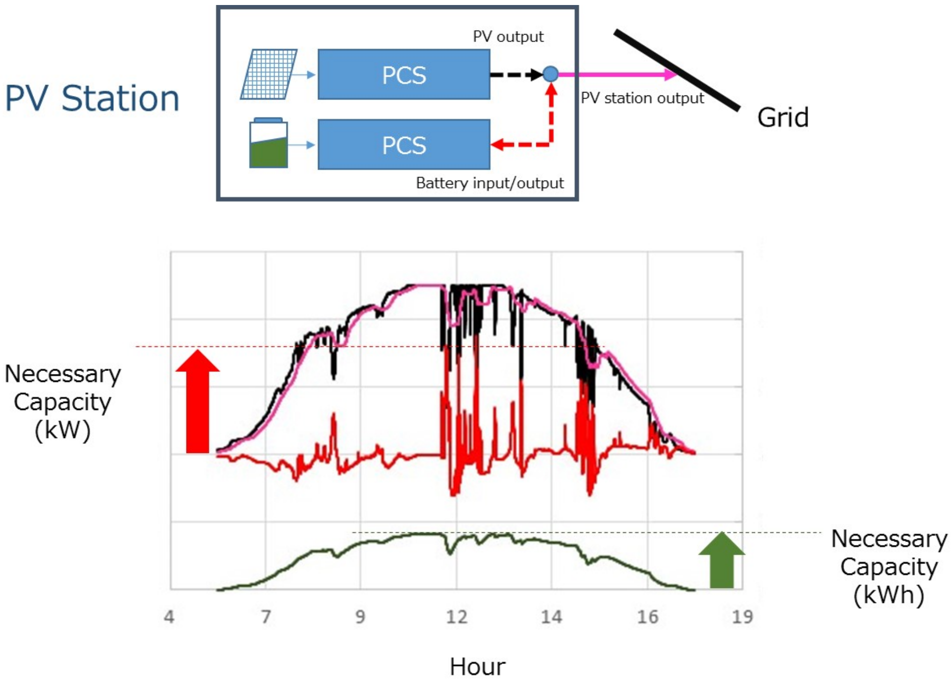


Figure 5-2-2-2.7 Charge and discharge

The battery capacity necessary for absorbing the fluctuation is estimated by the model mentioned above, where the capacity (kW) of the battery is the maximum input/output power (kW) on that day and the capacity (kWh) of the battery is the maximum amount (kWh) of the charged energy to the battery on that day. This calculation is conducted for all days except days with missing data.

Figure 5-2-2-2.8 and 5-2-2-2.9 show histograms of the battery capacity for each T. T = 0 corresponds to the condition without battery use, so no histogram for T=0 is provided

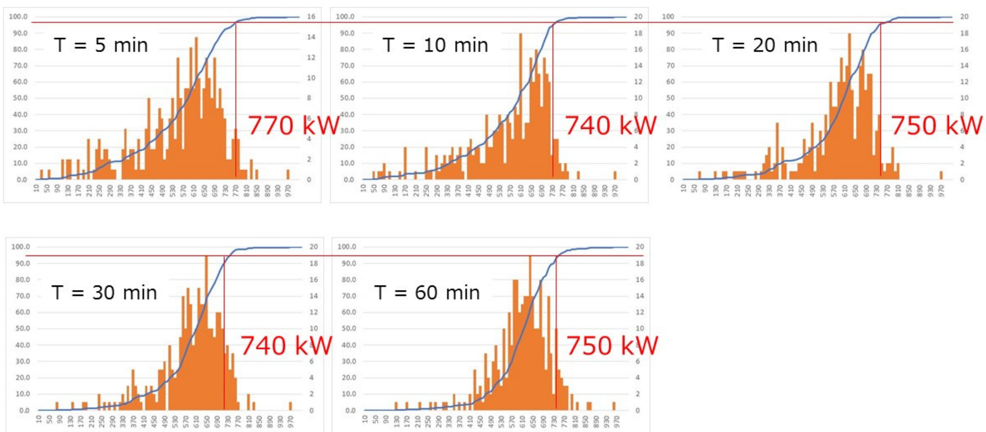


Figure 5-2-2-2.8 Histograms of the battery capacity (kW) for each moving average time (T)

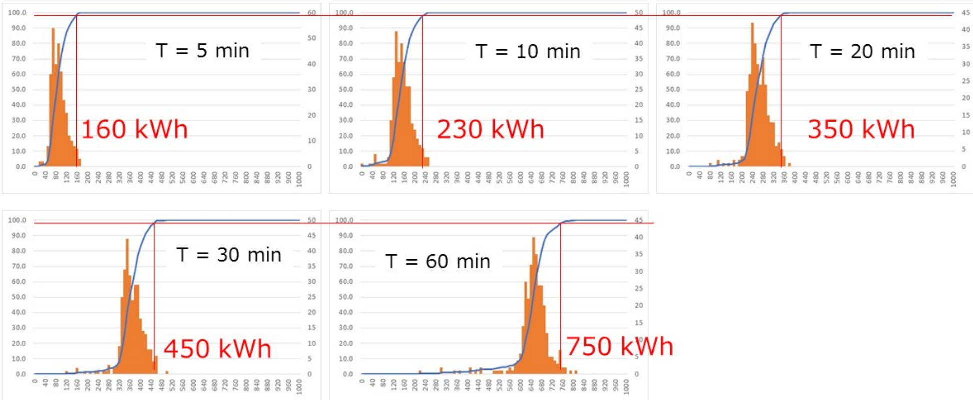


Figure 5-2-2-2.9 Histograms of the battery capacity (kWh) for each moving average time (T)

The capacity (kW) of the storage battery is almost constant irrespective of the fluctuation rate. On the other hand, the battery capacity (kWh) increases as the fluctuation rate decreases (see Figure 5-2-2-2.10). According to Fig. 5-2-2-2.10, the battery capacity required to suppress the fluctuation to 17% or less would be 800 kW and 425 kWh, including a tolerance of about 5%, for the PV power station consisting of 2 MW of panel and 1 MW of PCS.

Therefore, the battery capacity necessary to suppress the fluctuation rate to within an allowable level of PV power stations totaling 44 MW of panel and 22 MW of PCS is estimated to be 17,600 kW and 9,400 kWh, in total, by 2025.

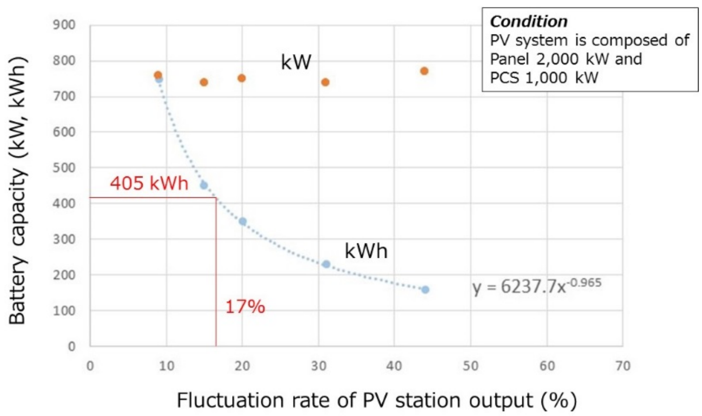


Figure 5-2-2-2.10 Relationship between the fluctuation rate and battery capacity

(8) Conclusion

The output of an RE source changes rapidly depending on the weather. A short-term fluctuation of output influences the frequency. In order to keep the frequency within an appropriate range, it is therefore necessary to absorb the fluctuation using, for example, a battery.

According to the result in 5-2-2-1, the amount of PV power station installed by 2025 is estimated to be 44 MW and 22 MW for panel and PCS capacity, respectively.

In this section, the fluctuation caused by PV output is evaluated quantitatively by the algebraic method.

Two countermeasures are proposed for suppressing the fluctuation to the lowest possible level. One is to disperse the PV power stations in anticipation of the smoothing effect. This effect, however, has not been verified in Palau. The recommended approach is therefore to verify the effect before installing a large amount of PV. With the smoothing effect considered, an economic system design may be possible.

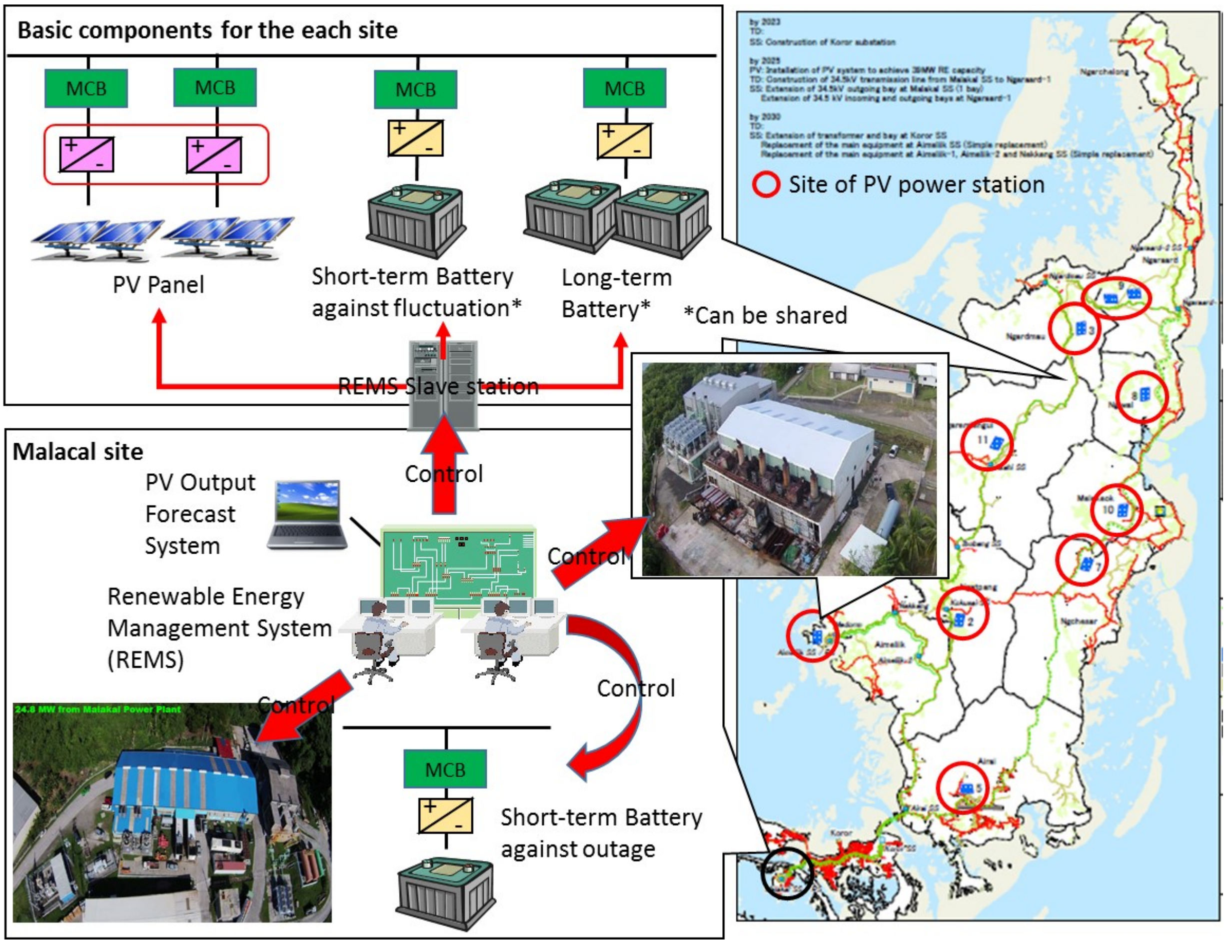
As a result, a battery capacity of 17,600 kW-9,400 kWh in 2025 would be required keep the fluctuation within the allowable level.

5-2-3 Results of the renewable energy roadmap formulation

The RE roadmap is formulated to achieve a 45% RE ratio in 2025 by reflecting confirmed and analyzed values and various conditions. The following matters were considered in formulating the RE roadmap.

- ✓ Stabilized power supply
- ✓ PPUC's O&M capacity and manpower

The whole image of the RE system introduction assumed in the roadmap is shown in Figure 5-2-3.1. Each site is interconnected with substations or a transmission line in its neighborhood, and short-term and long-term RE output fluctuations are controlled by inverters with 50% of the PV panel rated capacity. Two output restriction methods are generally used in practice: [1] Output control using inverters with 50% of the PV panel rated capacity and [2] Output control using the inverter's MPPT control function. This roadmap assumes the adoption of [1] and the installation of lithium ion (Li-ion) batteries for short-term (frequency fluctuation) and long-term output fluctuation. Short-term and long-term Li-ion batteries can be used concurrently. As stated previously, 1 DEG unit stopping operation is considered, in principle, during the daytime (7:00–18:00), or a peak of PV power generation. In the case of an RE power drop, the load will be provided by battery for only a short period (max. of about 30 minutes), and the DEG output is increased or additional generators are started to supply load in the meantime. Li-ion batteries for this purpose (to cope with power outage) have been installed in PPUC's power stations (installation in Malakal Power Station is recommended). Additionally, a monitoring control system (REMS: Renewable Energy Management System) has been introduced to the newly established Palau Load Dispatching Center. A concurrently introduced PV Power Generation Forecast System is used to adjust supply and demand, along with an REMS for monitoring and control of the existing DEG and RE power sources.



Source: Created by the Survey Team

Figure 5-2-3.1 Image of the entire RE system in Palau

The red circles in Figure 5-2-3.1 indicate candidate PV sites presented by PPUC (see Table 5-2-3.1). To achieve a 45% RE ratio in 2025 (as described in red in Table 5-2-3.1), a further capacity increment of the PV facility from the plan is required. In view of the time required for land acquisition and the lead time to 2025, prompt land acquisition is needed.

Table 5-2-3.1 Candidate PV sites presented by the Palau government and amounts that need to be added

No.	Location	Capacity	Owner	Distance	Area (Acre)
1	Aimeliik (Next to power plant) This is already planned with PPUC.	5 MWp +1MWp	PPUC	0.2 km from the nearest transmission line	15 acres +α
2	Ngatpang (Kokusai)	2-3 MWp +1MWp	PPUC	0.1 km from Kokusai SS	8 acres +α
3	Ngardmau (Terraces of Hill)	2-3 MWp +1MWp	PPUC	0.28 km from the nearest transmission line	7 acres +α
4	Airai Airport side by road	3 MWp +3MWp	PPUC	0.8 km from Airport	8 acres +α
5	Ngchesar	3 MWp +1MWp	PPUC	2.2 km	8 acres +α
6	Ngiwal	3 MWp +1MWp	PPUC	7.7 km	9 acres +α
7	Ngardmau	5 MWp +1MWp	PPUC	.08 km	15 acres +α
8	Melekeok	3 MWp +1MWp	PPUC	.76 km	9 acres +α
9	Ngaremlengui	5 MWp +1MWp	PPUC	.55 km	18 acres +α
Total		33MWp +11MWp			

Source: Created by Energy Admin., PPUC and survey team

5-2-3-1 Li-ion batteries for short-term and long-term fluctuations

Table 5-2-3-1.1 shows the major characteristics of the various batteries used for measures to mitigate output fluctuations. Considering the required parameters for introduction to the island country of Palau in this project, Li-ion batteries, a type highly versatile and used widely around the world, will be adopted. Li-ion batteries have high outputs and long lifetimes, properties that make them suitable for countermeasures against short-term fluctuations. For both the short-term fluctuation and the long-term fluctuation, Li-ion batteries can be used concurrently, and there is a possibility of introduction capacity reduction of Li-ion batteries.

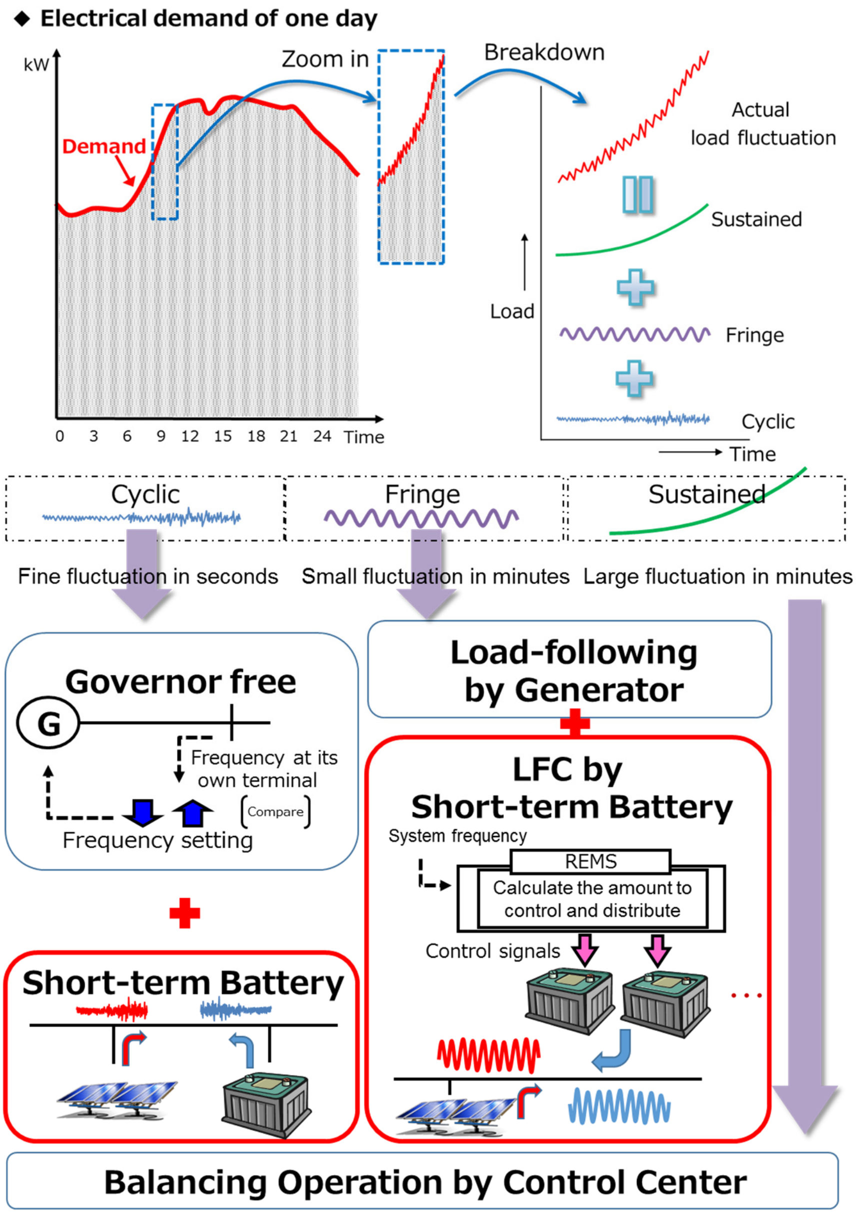
Table 5-2-3-1.1 Types and characteristics of major batteries

	Lead Battery	Sodium-Sulfer Battery	Nickel-Hydrogen Battery	Lithium-Ion Battery
Energy Density*1	25 Wh/kg (167 Wh/kg)	87 Wh/kg (786 Wh/kg)	22.5 Wh/kg (225 Wh/kg)	92 Wh/kg (585 Wh/kg)
Energy Efficiency*2	85%	90%	95%	95%
Lifetime*3	4,500	4,500	3,500	15,000

*1: Electric power charging capacity per 1kg
*2: Discharge efficiency based on full charge as 100
*3: No. of charge and discharge cycle

Source:The Institute of Electrical Engineers of Japan, Technical Report No.1403, Table 3.3

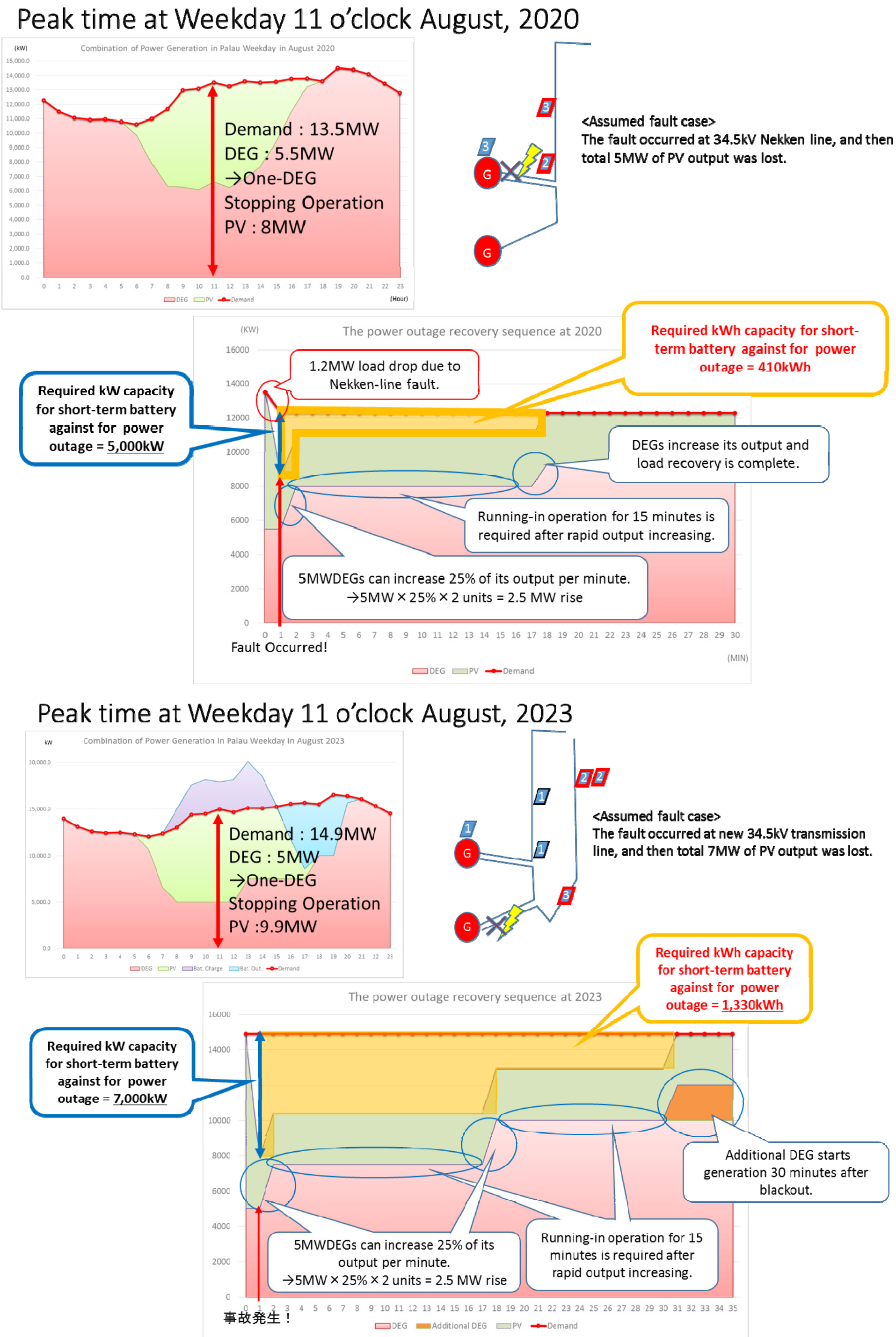
The role-sharing of DEG and batteries to deal with short-term fluctuation is summarized in Figure 5-2-3-1.1. Short-term fluctuation can be categorized into small fluctuation lasting less than minutes, medium fluctuation lasting from more than minutes to less than 10 minutes, and long fluctuation lasting more than 10 minutes. In Japan's case, each fluctuation is called "cyclic," "fringed," or "sustained." In general, short-term fluctuations are fringed and cyclic. In normal operation, these fluctuations are controlled by the functions framed in blue in Figure 5-2-3-1.1 and keep the system frequency at a standard level. In order to take care of the RE power source introduction, the countermeasure against short-term fluctuations framed in red in Figure 5-2-3-1.1 are newly required. In this system, cyclic and fringed components are controlled by DEG and batteries, so fine tuning of the battery outputs of the PV sites and DEG output will be required. Especially careful tuning is required for the fringed component, because batteries can respond more quickly to short-term fluctuations than DEG, which may diminish the battery lifetime.



Source: Created by the Survey Team

Figure 5-2-3-1.1 Role sharing of battery and DEG to deal with short-cycle fluctuation

Because, as mentioned previously, 1 DEG unit stopping in operation will be conducted in this project, Li-ion batteries will be introduced to compensate for abrupt PV power drops and prevent power outages. For details on the method to calculate the required capacity, please refer to Figure 5-2-3-1.2. The largest PV power drops occurring each year were examined, with the output increase sequence of various power sources combined. The Li-ion battery against outages can be used to mitigate frequency fluctuations after completion of the loop system in 2025.



Source: Created by the Survey Team

Figure 5-2-3-1.2 Theoretical calculation for the required capacity of the batteries against outages

5-2-3-2 RE roadmap until 2025

The transition to a three-phased equipment configuration from 2018 to 2025 is shown in Table 5-2-3-2.1.

Figure 5-2-3-2.1 to Figure 5-2-3-2.4 show the equipment installation steps at each site, by year and by phase.

Table 5-2-3-2.1 RE introduction roadmap in Palau (2018-2025)

			Phase1		Phase2			Phase3	
		Unit	2019	2020	2021	2022	2023	2024	2025
Rooftop PV	Panel	kW	970	1,200	1,400	1,700	2,000	2,400	3,000
(Rooftop)	PCS	kW	810	1,000	1,170	1,420	1,670	2,000	2,500
PV system	Panel	kW	10,000	16,000	16,000	22,000	30,000	40,000	44,000
(PV station)	PCS	kW	5,000	8,000	8,000	11,000	15,000	20,000	22,000
Battery system (Against long-term fluctuation)	Battery	kWh					34,500	57,500	92,000
		kW					6,000	10,000	16,000
	PCS	kW					6,000	10,000	16,000
Battery system (Against short-term fluctuation)	Battery	kWh	2,300	3,500	3,500	4,800	6,500	8,600	9,400
		kW	4,000	6,400	6,400	8,800	12,000	16,000	17,600
	PCS	kW	4,000	6,400	6,400	8,800	12,000	16,000	17,600
Battery system (Against power outate)	Battery	kWh		500	500	500	1,400	1,400	1,400
		kW		5,000	5,000	5,000	7,000	7,000	7,000
	PCS	kW		5,000	5,000	5,000	7,000	7,000	7,000

Source: Created by the Survey Team

Following are the assumed conditions in the roadmap, year by year.

<–2019 assumed conditions>

- Short-term batteries against frequency fluctuation are starting installation works.

<2020 assumed conditions>

- 1 DEG unit stopping operation starts. Short-term battery against outage are installed in PPUC power stations (Malakal is recommended).
- Concurrently with the start of the operation with one DEG unit stopping in operation, remote control system (SCADA) is renewed and the load dispatching center is set up to adjust the supply-demand balance by DEG and renewable energy power sources. At the same time, the PV power generation forecast system is introduced.

<2023 assumed conditions>

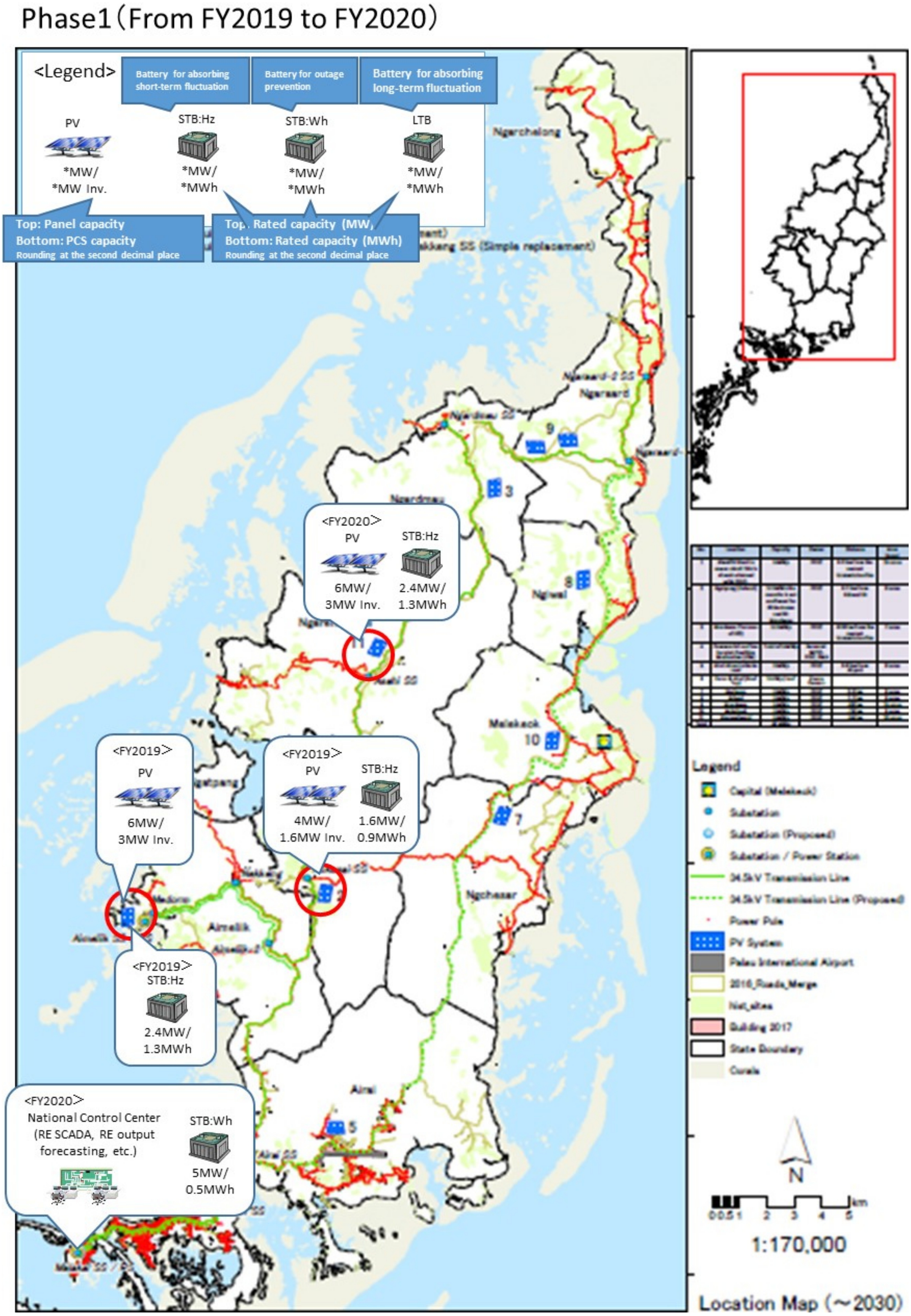
- Long-term batteries are installed at around the time of completion of the construction of the 34.5 kV power transmission line on the east side of the Babeldaob Island.

<2024 assumed conditions>

- The total rated capacity of 10 MW PV is introduced at the NGARDMAU site, but the connection of these PVs to the grid is postponed until 2025 so as to prevent big impact on the grid from faults in the Nekken-line (in this case, a max. PV output of 10 MW may be lost).

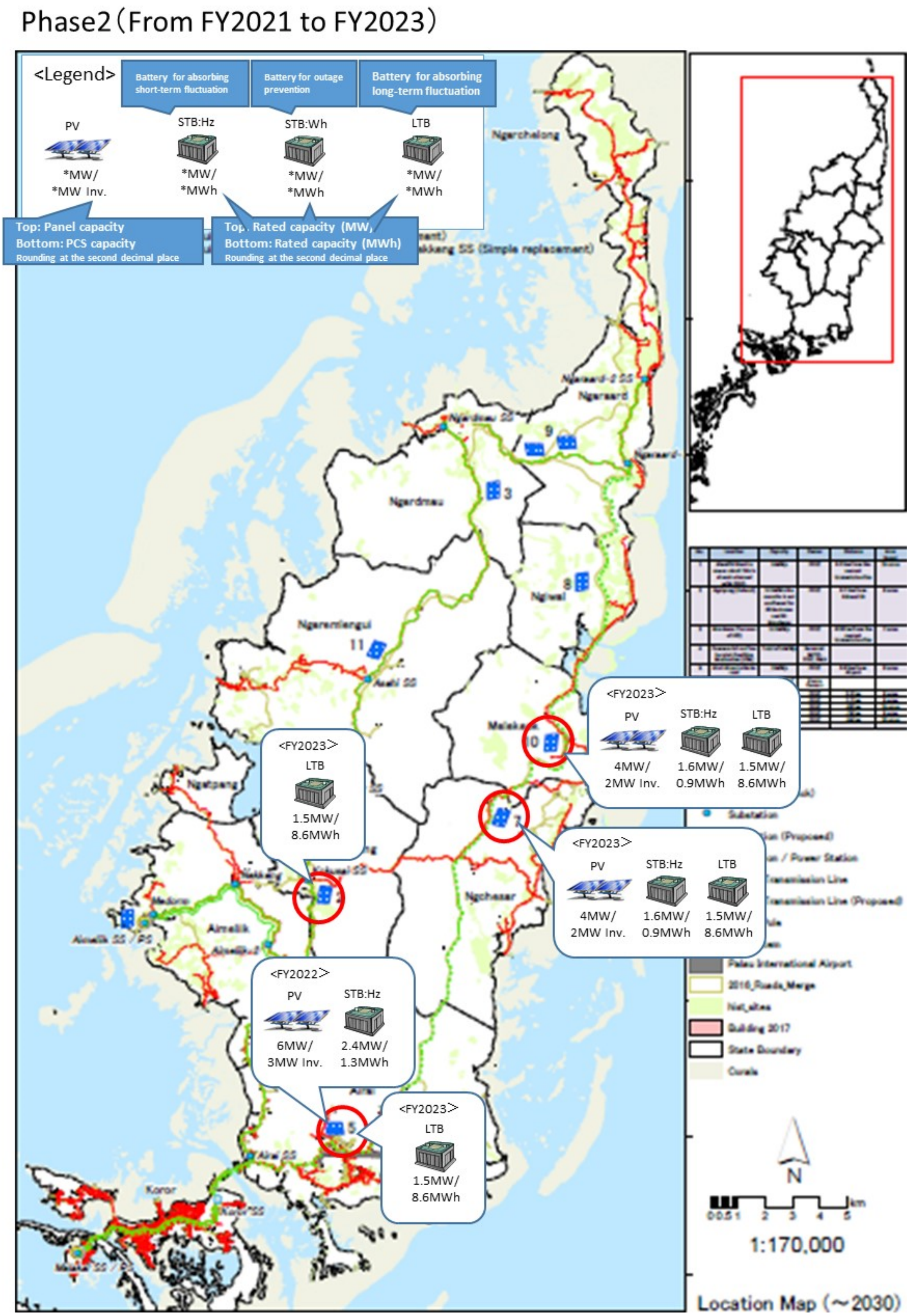
<2025 assumed conditions>

- The looped Koror-Babeldaob system is completed. All PV should be connected to the grid.



Source: Created by the Survey Team

Figure 5-2-3-2.1 RE equipment installation steps in Phase 1 (2018–2020)



Source: Created by the Survey Team

Figure 5-2-3-2.2 RE equipment installation steps in Phase 2 (2021–2023)