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RENEWABLE ENERGY ROADMAP

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ABBREVIATIONS

CO_2	carbon dioxide
EV	electric vehicle
GHG	greenhouse gas
GWh	gigawatt hour
HOMER	hybrid optimisation of multiple energy resources
ICE	internal combustion engine
IPP	independent power producer
IRENA	International Renewable Energy Agency
kg	kilogramme
Km^2	square kilometre
kW	kilowatt
kWh	kilowatt hour
LCOE	levelised cost of electricity
Li-Ion	lithium ion
MPa	megapascal
MW	megawatt
MWh	megawatt hour
NDC	Nationally determined contribution
O&M	operation and maintenance
OTEC	ocean thermal energy conversion
PEA	Palau Energy Administration
PPA	power purchase agreement
PPUC	Palau Public Utilities Corporation
PV	photovoltaic
USD	United States dollar
VRE	variable renewable energy
WACC	weighted average cost of capital

EXECUTIVE SUMMARY

On 12 November 2020, the Ministry of Public Infrastructure, Industry and Commerce of the Republic of Palau requested assistance from the International Renewable Energy Agency (IRENA) to develop a technology-specific energy roadmap.

This roadmap was to provide the government of Palau with clearly defined options for the least-cost deployment of renewables, with the goal of supporting the achievement of 100% renewable energy in the power sector by 2050, as well as decarbonising Palau's transport sector.

The resulting roadmap also built on an earlier version that IRENA had developed for the country in 2016-2017. That version had then been used to help inform the development of the country's current nationally determined contributions (NDCs) under the Paris Agreement, which include a target of 45% renewable energy[1] by 2025.

The analysis performed in this study charts the way to net zero by 2050 for Palau's power and transport sectors, looking in detail at several options for a least-cost, fully decarbonised power system.

To achieve such an ambitious target – and with Palau's current power system still dominated by fossil fuel generation – various renewable energy technologies have had to be considered and evaluated.

In terms of electricity generation, the options considered were: utilityscale solar photovoltaic (PV); utilityscale wind; and green hydrogen, complemented by battery storage. Ocean thermal energy conversion (OTEC) was not considered as an option in this analysis, due to this technology being relatively new and therefore not mature enough to be deployed. With regard to the road transport sector, the potential deployment of battery electric vehicles (EVs) was assessed. The roadmap also looked into the maritime transport sector, and specifically, hydrogen speedboats.

In the study, various models were developed and optimised using HOMER Pro software, a tool used for optimising and financially evaluating minigrid systems. Initially, a calibration model was developed for the current power system of Palau. Subsequently, several scenarios were modelled for providing the least-cost solution for a 100% renewable energy share by 2050.

The five main scenarios modelled in this roadmap were:

1. Optimal system[2]
2. 100% renewable energy, PV plus wind
3. 100% renewable energy, PV only
4. 100% renewable energy, with hydrogen
5. 100% renewable energy, with hydrogen plus EVs.

[1] *Intended for the power sector only.*

[2] *The optimal system includes the current power system together with additional renewable capacity coupled with battery storage.*

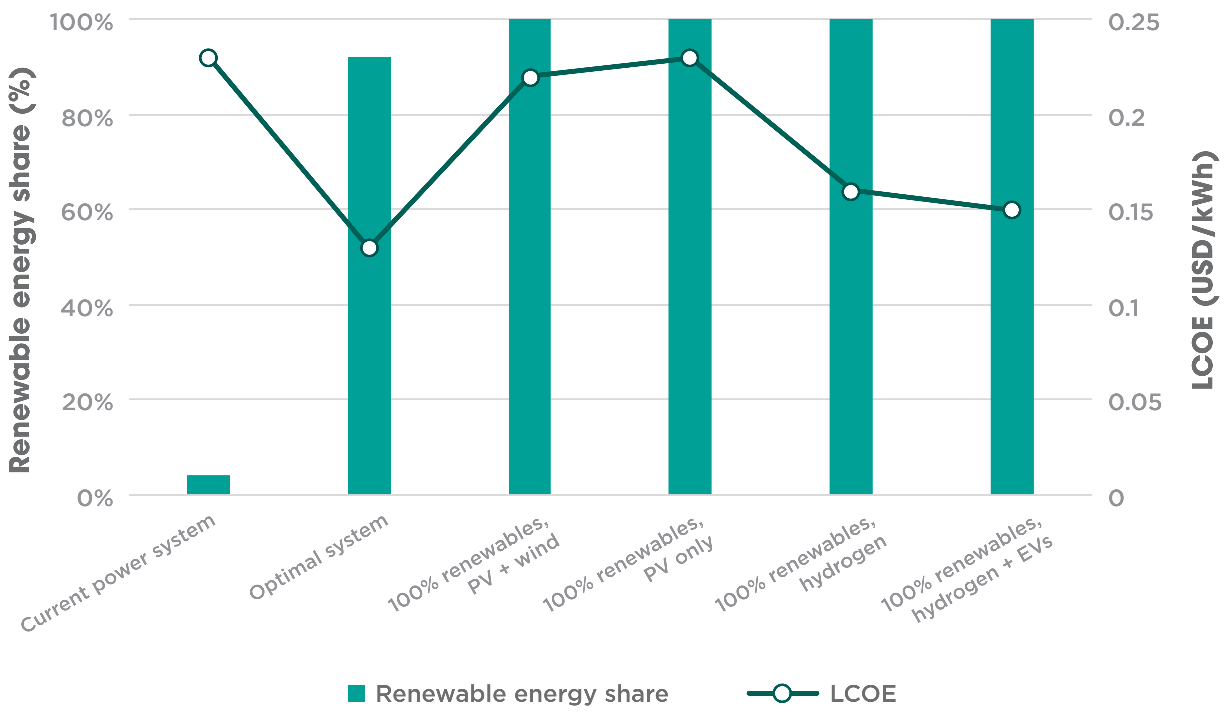
The overall results of the five scenarios in terms of the share of renewables mapped against the levelised cost of electricity (LCOE) can be seen in Figure I.

The results of the optimisation show that Palau's current power system is dominated by diesel generation, with renewable energy only taking a small share (just 4%). With more deployment, however, the share taken by renewables could potentially increase to more than 92%. This corresponds to the lowest average system LCOE. To achieve this, significant acceleration in the deployment of solar PV, wind turbines and battery storage systems is essential.

In addition, achieving 100% renewable energy in the power sector by 2050 also means covering the remaining 8%, and for this, several distinct scenarios were analysed. These were: 100% renewables, PV plus wind; 100% renewables, PV only; and 100% renewables, with green hydrogen. Of these, the green hydrogen scenario was found to be the most cost-effective.

Based on this result, an additional scenario, of 100% renewable, with green hydrogen plus EVs, was developed. This was in order to consider the impact that the full replacement of gasoline and diesel vehicles with EVs by 2050 would have. This scenario also aimed to identify the cheapest 100% renewable energy plan, while at the same time decarbonising road transport. This last scenario, inclusive of green hydrogen production and EVs, has an estimated LCOE of USD 0.15 per kilowatt hour (kWh), making it the least-cost option between the four 100% renewable energy scenarios considered in this roadmap.

Figure S1: Roadmap overview: 100% renewable energy in the power sector by 2050



The investment requirements for these four scenarios, plus the optimal system, can be seen in Table I.

Table S1: Investment requirements for each scenario

MODEL/SCENARIO	OPTIMAL SYSTEM	100% RENEWABLE ENERGY, PV+WIND	100% RENEWABLE ENERGY, PV ONLY	100% RENEWABLE ENERGY, HYDROGEN	100% RENEWABLE ENERGY, HYDROGEN+EVs
INITIAL CAPITAL COST (USD MILLIONS)	126	249	266	179	189

For the optimal system, an initial investment of approximately USD 126 million would be required. This investment would mainly be related to the additional solar PV, wind and battery capacity necessary to reach a 92% share for renewables.

Regarding the 100% renewable energy scenario with PV and wind, the initial capital cost almost doubles, to USD 249 million. This significantly increases the cost of electricity for a less than 8% increase in the share of renewables. If no wind turbine capacity is added, however, and solar PV and batteries are relied on alone, the result is the roadmap's highest initial investment, at USD 266 million. This highlights the synergies available when combining wind and PV, compared to investing in one single generation technology. Without the wind turbines, more battery storage capacity and solar PV are required to store sufficient solar electricity, especially during cloudy days, to reliably serve the load every hour of the year.

When green hydrogen production is added to the power system, however, in order to reach a 100% share for renewables, the flexibility provided by electrolysers and the large scale storage of renewable power in the form of hydrogen aids in reducing the need for battery storage to compliment the whole system. Adding this also reduces renewables curtailment, and hence the initial capital cost also decreases, to USD 179 million.[3]

Finally, with the deployment of EVs together with hydrogen, the initial investment required would be about USD 189 million, for a significantly higher load. Essentially, this would replace the need to import petroleum products to fuel cars for decades to come, for an additional upfront investment of USD 10 million. Although data on fuel imports and related costs are not available, the estimated payback period for replacing gasoline and diesel used by cars with renewable electricity used in EVs in this scenario is less than two years.[4]

This roadmap has outlined several options to fully decarbonise the island. A key thing to note, however, is that without the appropriate policies and regulations in place, the outcome of the various scenarios analysed in this study is unlikely to be achieved. A key recommendation for the government, if it is to achieve its proposed target of a 100% share for renewables by 2050, is to accelerate deployment of solar PV and battery storage systems through a combination of Palau Public Utilities Corporation (PPUC) investments and power purchase agreements (PPAs).

[3] *An alternative would be to replace the 8% share taken by diesel with biodiesel, with no upfront investment required. This was not, however, considered as one of the options for this analysis.*

[4] *It is assumed that EV is a consumer choice based on lower total cost of ownership (TCO), hence the 2 years payback only refers to the replacement of fuel imported to use in ICE cars with electricity produced locally to charge EVs.*

Furthermore, the government should ensure that any identified locations for solar PV and wind farms are aligned with grid development, for which PPUC has a key role in planning in an organic way. Another recommendation is to identify a suitable mix of financing mechanisms for deploying the technologies identified in this roadmap. A combination of grants, soft loans and de-risked investments by independent power producers (IPPs) could be considered.

Before scaling-up renewable energy deployment, the government should also ensure that PPUC is comfortable with planning, operating and maintaining the various technologies, as well as with adjusting its operations to the new mix of resources. This would include taking onboard important practices, such as: day ahead and intraday forecasting; the redesign of reserve requirements; and transition towards a system where the frequency is set by grid forming inverters, rather than synchronous generators.

Finally, in reaching a 100% renewable energy share at least cost, once local green hydrogen production can be justified by a highly decarbonised power system (such as the one in the optimal scenario), pilot projects should be established for hydrogen speedboats, hydrogen storage and for internal combustion generators able to run on 100% hydrogen fuel.

In conclusion, by following the recommendations outlined in this roadmap, the Republic of Palau will be on the road to achieving a fully decarbonised power system, based on solar and wind power for electricity and transport and supported by battery storage and green hydrogen.

1. INTRODUCTION TO THE PALAU ROADMAP

1.1. ROADMAP OBJECTIVE

Located in the North Pacific, the Republic of Palau consists of more than 300 islands and six island groups. The total area of the country is 459 km^2 and the topography varies from high mountainous land, such as on the main island of Babeldaob, to low, coral islands usually bordered by large coral reefs (CIA, 2021). According to the World Bank, in 2020, the Republic of Palau had a population of 18 092 people (World Bank, 2021).

The government of Palau has proposed a target of achieving 100% of its electricity generation from renewable energy sources by 2050. With the country's energy sector being dominated by conventional fossil fuel generation, transitioning to 100% renewable electricity would eliminate carbon dioxide (CO_2) emissions from the power sector and simultaneously create the necessary environment for decarbonised transport through the adoption of electric vehicles (EVs). These could be charged using 100% renewable power, while potentially, hydrogen motorboats powered by locally-produced green hydrogen could also be used.

In this context, the government of Palau requested the International Renewable Energy Agency (IRENA) undertake a study to outline a roadmap for transitioning to 100% renewable energy in the power sector by 2050. The resulting roadmap builds upon the draft energy roadmap that IRENA had earlier developed for the Republic of Palau, back in 2016-2017, which had the initial objective of achieving a 45% share for renewable energy by 2025. The previous roadmap is now being used as the basis for the enhancement of Palau's nationally determined contributions (NDCs) under the Paris Agreement, which further strengthen the country's energy security.

The main objective of this study is therefore to develop a technology-specific energy roadmap that can provide the government of Palau with clearly defined options for the least-cost deployment of renewable energy, supporting the achievement of 100% renewable energy in the power sector by 2050. The roadmap also explores renewable energy options for road and marine transportation.

In addition, the study supports the development of the Republic of Palau's national climate action plans. It also illustrates how further deployment of renewables can aid in lowering energy system costs, reduce dependence on imported, polluting fossil fuels and ultimately lower greenhouse gas (GHG) emissions. The roadmap will focus on the country's power and transport sectors and explore multiple renewable energy sources, along with different scenarios for achieving the target of 100% renewable energy by 2050 – a goal under consideration, as of 2021.

1.2. ROADMAP ANALYSIS OVERVIEW

This chapter describes the overall methodology for developing the roadmap and the various technology options considered for the power and transport sectors. Figure 1 is a flow chart of the methodology and models used for this study.

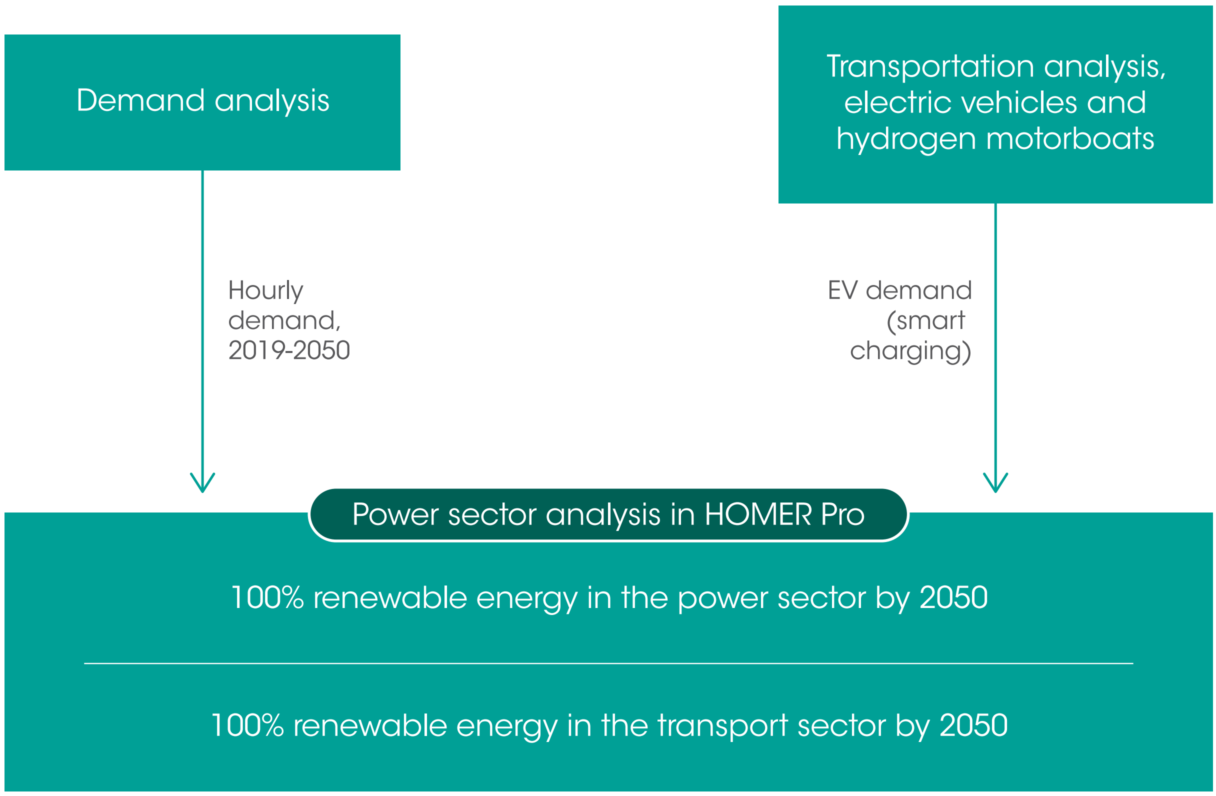
To model Palau's power and transport sectors, the Hybrid Optimisation of Multiple Energy Resources (HOMER) software was selected. HOMER is an optimisation tool used for designing both on-grid and off-grid power systems. It can be used to optimise systems for distributed generation, stand-alone and remote applications. The model allows the user to choose between a number of different energy resources and provides the user with the least-cost, viable solution based on the system inputs.

The following three sectors/applications were examined in depth to analyse the deployment of renewable energy options in the Republic of Palau:

i. Electricity generation
ii. Road transportation
iii. Maritime transportation.

The following chapters describe the details of all three applications, including the different technology options considered in order to achieve the ambitious 100% renewable energy target.

Figure 1: Roadmap methodology flow chart



Electricity generation

Analysis of the Palau power sector includes a detailed optimisation of the current power system, together with that of 2050. Indeed, in order to prepare a detailed model of the latter, with a 100% renewable energy share, the model had to first be calibrated by preparing an analysis of the current power system. For the calibration model, the initial step was to prepare a baseline demand forecast to which additional renewable energy generation was added, in order to achieve the 100% target by 2050. Chapter 2 describes more in depth the steps undertaken in preparing the baseline demand from data on diesel generation provided by the Palau Public Utilities Corporation (PPUC).

With the Republic of Palau being highly dependent for generation on fossil fuels, such as diesel, it is of the utmost importance to evaluate a variety of renewable energy technologies in order to achieve the government's proposed target.

From the various technologies available in the market the following were therefore selected for the roadmap analysis:

- **Utility scale solar photovoltaic (PV):** ground-mounted PV arrays
- **Utility scale wind:** onshore wind farms
- **Hydrogen:** production of green hydrogen from solar and wind through electrolysis of water.

If further rooftop PV is deployed in Palau, this would reduce the need for utility scale PV. This possibility is not explicitly considered in this analysis, however, as no specific target or assessment of solar PV potential in Palau is currently available. On a cost-only basis, rooftop PV is more expensive than utility scale, although it does not require the securing of land for ground installation. In order to deploy a large capacity of renewable energy generation, battery storage systems will also be crucial to balance the system, provide more flexibility and ultimately achieve the target of 100% renewable energy by 2050. Excess electricity from solar PV and wind turbines can be stored in batteries for later use (*e.g.* for night time, or to meet peak demand).

Road transportation

Similar to the power sector, Palau's road transportation sector is also highly dominated by diesel and gasoline-powered vehicles, with no electric vehicles (EVs) currently present in the country. Thus, the study looked into the gradual deployment of the following:

- **EVs powered by renewable energy:**[5] the potential deployment of battery EVs – and the increase in renewable electricity generation required to power them – were evaluated.

The transport sector analysis for Palau was also performed using the HOMER software, with the demand, or load, for EVs inputted as deferrable. According to HOMER Energy, a deferrable load can be defined as an electrical load that requires a certain amount of energy within a given time period. The transport sector analysis was performed together with the power sector analysis, by adding the EV load to the model representing Palau's power system for 2050.

[5] *The roadmap looked into full deployment of EVs for smart charging in order to decarbonise Palau's transport sector by 2050.*

Maritime transportation

Maritime transportation represents a key sector in Palau's economy, mainly due to tourism and the multiple diving boats present in the country. Most of these boats are powered by expensive and polluting high-power outboard gasoline engines, to enable them to reach the outer reef in a short time. One option would be to replace this gasoline with a synthetic variant produced from renewable hydrogen and biomass. As an alternative, in the absence of a reliable and affordable supply of synthetic gasoline, a change in technologies would be required. Therefore, the roadmap's analysis for maritime transportation included the following options to decarbonise speedboats:

- **Hydrogen speedboats.** The potential deployment of hydrogen fuel cell boats was explored, with a particular focus on high-power speedboats for diving and tourism in general. This essentially requires a change in the drivetrain, replacing a gasoline outboard motor with an electric motor, powered by a hydrogen fuel cell. The same electric motor could be powered by renewable electricity stored in a battery system. For Palau's requirements, in terms of speed and distance travelled, however, this solution might be applicable only for some boats. In particular, those would be vessels that could accept a lower cruising speed or a shorter range, due to the intrinsic limitations of today's battery technologies (i.e. those for which a large battery capacity, with consequently higher costs, is not needed).

- **Battery-powered hydrofoiling boats.** This solution requires a new boat design. While the first prototypes were becoming available in 2021, allowing for high speed and high energy efficiency running a battery-powered electric motor, this option requires fitting boats with hydrofoiling hulls. This represents a significantly larger investment than replacing only the motors. This solution would, however, require significantly less battery capacity, reducing the investment in batteries or fuel cells.

2. SCENARIOS

The roadmap includes several detailed scenarios based on the data and information provided by the Palau Energy Administration (PEA). The data were used to calibrate the model by first looking at the country's current power system, with this serving as the foundation for the other subsequent scenarios analysed in the study.

The model included large amounts of diesel generation, with a minimal share of renewable energy coming from the solar PV systems currently present in Palau. The current power system was modelled to estimate the current share of renewable energy in the country and to understand how much more renewable energy capacity needs to be deployed to reach the ambitious target of 100% by 2050. In order to model the system in HOMER, the baseline load/demand for 2019 had to be estimated. The detailed hourly demand for 2015 which was used for the previous roadmap for Palau, from 2016-2017, was scaled up by using the annual demand value for 2019 provided by the government. This is discussed in more detail in Chapter 3 (Demand analysis).

The study was focused on modelling the two main islands of Koror and Babeldaob. The model therefore considered the four main generators at the Malakal and Aimeliik power stations, which are located on the two islands and have a total capacity of 20 megawatts (MW). The calibration model also included the renewable energy capacity present in the country, at 2.5 MW of solar PV. The solar PV systems were assumed not to have any battery storage or converter. Once all the inputs were added to the model, an optimisation was then performed in HOMER.

After the model had been calibrated based on the current power system of Palau, the different scenarios considered in the roadmap were prepared. The study includes the following five scenarios:

- **i.** Optimal system
- **ii.** 100% renewables, PV + wind
- **iii.** 100% renewables, PV only
- **iv.** 100% renewables, with hydrogen
- **v.** 100% renewables, with hydrogen and EVs.

Table 1 shows the different scenarios analysed in the Roadmap, together with the type of technologies considered

Table 1: Scenarios considered

SCENARIOS	TECHNOLOGY CONSIDERED
Optimal system	PV + wind + diesel + batteries
100% renewables, PV + wind	PV + wind + batteries
100% renewables, PV only	PV + batteries
100% renewables, with hydrogen	PV + wind + hydrogen + batteries
100% renewables, hydrogen + EVs	PV + wind + hydrogen+ EVs + batteries

The optimal system was the first scenario simulated in the roadmap. This scenario represents the optimal solution that can be achieved by deploying further renewable energy capacity to the current power system of Palau. Using the HOMER optimiser, the additional capacity of solar PV and wind was estimated. The reason for selecting this scenario was to show how close the government could get to reaching the proposed 100% renewable energy share target by just increasing their current renewable energy capacity. The model was also used to optimise the ideal size of the battery storage system and the converter. Hydrogen is not considered in this scenario, as it is an additional level of complexity that should only be considered once the full potential of solar and wind plus battery storage has been reached.

The second scenario analysed in this study was the 100% renewables scenario with solar PV and wind. As the name suggests, this scenario included solely solar PV and wind turbines as renewable energy technologies in achieving the 100% target. This scenario also assumes that all the diesel generators currently present in Palau would be decommissioned. This specific scenario was selected to show how the target could be achieved without adding green hydrogen, but that in this case, the storage capacity would increase. It was also chosen to show how the levelised cost of electricity (LCOE) would differ, as opposed to the current power system and the optimal solution of the first scenario.

The 100% renewables with solar PV was the third scenario analysed in the roadmap. This scenario was selected to demonstrate how the LCOE and battery storage capacity of the system would vary, as opposed to the previous scenario with solar and wind. The third scenario gives an option to the government of Palau to achieve their proposed target of a 100% share for renewable energy by 2050 with exclusively solar PV systems. As with the previous scenarios, the HOMER optimiser was used to estimate the ideal converter and battery storage size.

The fourth scenario analysed in the roadmap was the 100% renewables scenario inclusive of green hydrogen production. This scenario looked into the possibility of achieving the proposed target with solar PV, wind turbines and green hydrogen production. It was also chosen to see how the LCOE would differ from the other scenarios in the roadmap.

In order to simulate green hydrogen in HOMER, a hydrogen tank, fuel cell and electrolyser were added in the model to optimise their ideal capacity. The battery and converter capacity were also re-optimised in HOMER to a smaller size, while renewable generation was increased to feed the hydrogen production process, which has higher losses compared to batteries.

The last scenario considered for the power system analysis was the 100% renewables scenario with hydrogen and EVs. This scenario was selected to estimate how much more renewable energy capacity would be required to cover the demand for hydrogen as well as the demand for charging the EVs.

In order to model EVs in HOMER, a deferrable load was added to represent the EV load. A hydrogen tank, fuel cell and electrolyser were also added in the model for green hydrogen production. Adding all these components and the EV load increased the total annual demand of the country significantly. The HOMER optimiser was then used to optimise the additional capacity of solar PV and wind needed to cover demand, in addition to the ideal size of the battery and converter.

Chapter 4 covers in more detail the results of the different scenarios analysed in the roadmap for both the power and transport sectors.

3. KEY ASSUMPTIONS

The following chapter describes all the key assumptions considered for the roadmap. It includes: the assumptions considered for calculating the baseline electricity demand for 2019; the power sector assumptions including those for each component added in HOMER; and the assumptions for the transport sector analysis for estimating the EV load.

3.1. DEMAND ANALYSIS

The baseline demand for 2019 was estimated using the 2015 hourly load and 2019 total electricity demand from PPUC. This chapter includes details on the data provided by PPUC and the methodology used to estimate the 2019 hourly load.

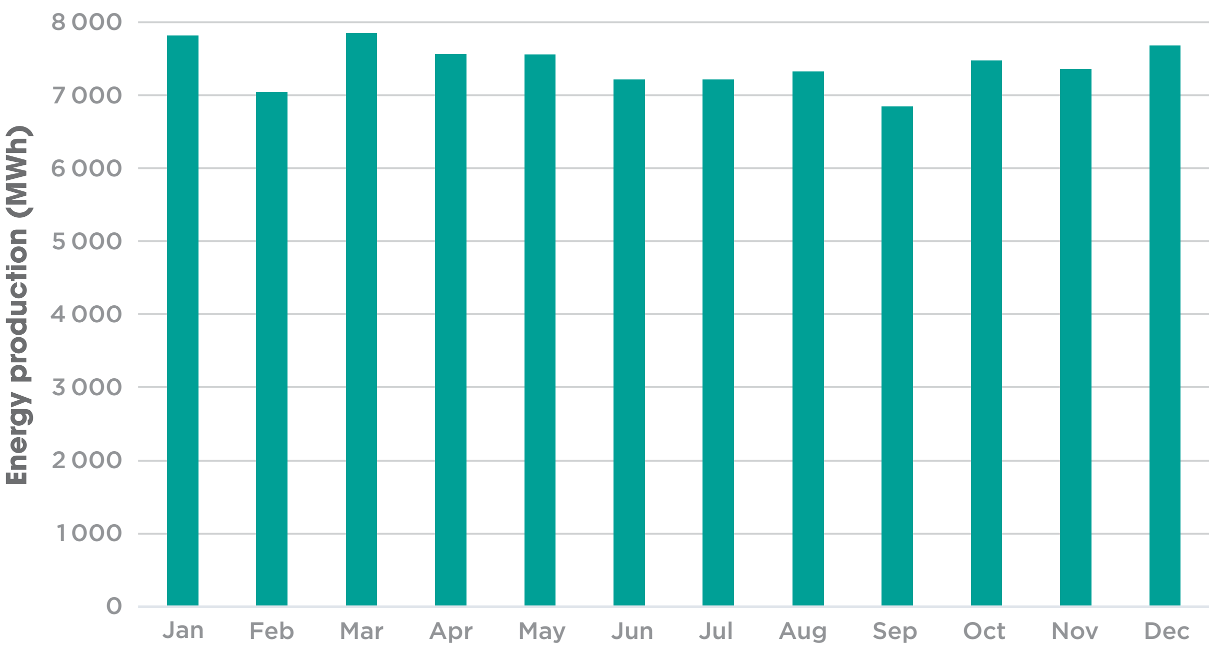
Baseline electricity demand in 2019

In order to model all the scenarios considered in this study, a baseline demand for Palau was required, to which the deployment of further generation capacity could be referred. To undertake this, data on each power plant and generator present in the country was required. All this information was provided by PPUC.

For the baseline year of 2019, the government of Palau estimated a total annual demand of 89 gigawatt hours per year (GWh/year). This demand was then used to scale-up the hourly load given in the previous roadmap, for 2015, using HOMER.

Figure 2 shows monthly electricity production and demand for the baseline year of 2019.

Figure 2: Electricity demand for 2019



Source: PPUC and PEA data (n.d.).

3.2. POWER SECTOR ASSUMPTIONS

The Republic of Palau's power sector is highly dependent on conventional fossil fuel generation, with diesel generators supplying electricity to cover most of the country's total demand. Currently, there are a total of five main power plants on different islands in Palau, supplying electricity to meet the load. The two largest power plants are the Malakal and Aimeliik power stations, which have total generation capacities of 15.5 MW and 10 MW respectively. As mentioned earlier, this study focused on the four main generators which have a total capacity of 20 MW.

The other three power stations (Angaur, Peleliu and Kayangel) have significantly smaller generators, with a combined capacity of 2.8 MW.

The roadmap analysis focuses on the two main power stations – Malakal and Aimeliik – as they are located on the two largest islands – Koror and Babeldaob. For this study, it was assumed that the total diesel generation capacity of Palau's current power system is 20 MW (the four largest generators present in Palau). Table 2 shows in more detail the generation capacity for each power plant currently present in the country.

Table 2: Power plant generation capacity

POWER PLANT	GENERATOR UNIT	FUEL	CAPACITY (MW)
Malakal power station	Niigata 14	Diesel	5
	Niigata 15	Diesel	5
	Mitsubishi 13	Diesel	2.5
	CAT # 2	Diesel	1.2
	Mitsubishi 16	Diesel	0.45
	Mitsubishi 17	Diesel	0.45
	Mitsubishi 18	Diesel	0.45
	Mitsubishi 19	Diesel	0.45
Aimeliik power station	Mitsubishi 6	Diesel	5
	Mitsubishi 7	Diesel	5
Outer islands			
Angaur power station	Cummins 4	Diesel	0.12
	Cummins 5	Diesel	0.15
	Perkins # 2	Diesel	0.12
	Hatz 1	Diesel	0.028
	Hatz 2	Diesel	0.028
	Hatz 3	Diesel	0.028
	Hatz 4	Diesel	0.028
Peleliu power station	Yanmar 1	Diesel	0.75
	Yanmar 2	Diesel	0.75
	FG Wilson	Diesel	0.275
	Hatz 1	Diesel	0.028
	Hatz 2	Diesel	0.028
	Hatz 3	Diesel	0.028
	Hatz 4	Diesel	0.028
	Hatz 5	Diesel	0.028
	Hatz 6	Diesel	0.028
Kayangel power station	Cummins 6	Diesel	0.09
	Cummins 7	Diesel	0.12
	Cummins 8	Diesel	0.1

Source: PPUC and PEA data (n.d.).

Together with a large amount of diesel generation, Palau also has some installed solar PV capacity. Indeed, the country's current renewable energy capacity includes a total of 2.5 MW of utility-scale solar PV systems (see Table 3).

A schematic diagram based on the HOMER interface, illustrating the current power system of the Republic of Palau, can be seen in Figure 3.

This diagram represents the country's current power system, which is composed of the four larger generators from the Malakal and Aimeliik power stations, the current installed solar PV capacity and the total electricity load for the baseline year 2019.

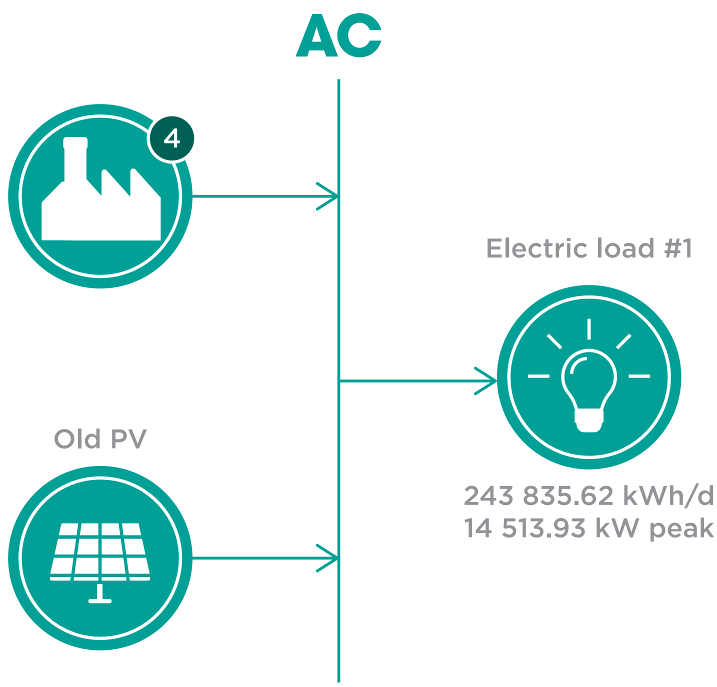
In order to perform a detailed analysis of the power sector in HOMER, several key assumptions had to be made for each scenario modelled in the study. These include the main components considered, such as the renewable energy technologies, the battery storage systems, the converter and the diesel generators. Furthermore, some general assumptions in terms of the economics of the project were also made and are discussed in detail in the following sections.

Table 3: Renewable energy capacity in Palau in 2019

RENEWABLE ENERGY TECHNOLOGY	CAPACITY (MW)
Solar PV	2.5

Source: PPUC and PEA data (n.d.).

Figure 3: Schematic diagram of the current power system



Solar PV

Some generic assumptions were made for all the solar PV panels considered in the various scenarios. These include the capital cost, the replacement cost, the operating cost and lifetime of the panels. Such assumptions were based on IRENA's 2019 costing analysis (IRENA, 2020a).

For the current installed solar PV capacity of Palau, which has already been installed, the capital cost was assumed to be zero. The replacement and operating cost were assumed to be USD 400/kW and USD 4/year/kW, respectively. For the additional solar PV generation optimised on HOMER, the capital cost was assumed to be USD 600/kW. While the replacement cost was assumed to be USD 500/kW and the operating cost USD 10/year/kW. All solar PV panels considered in the roadmap were assumed to have a derating factor of 80% and a lifetime of 25 years.

Wind turbine

For the future scenarios of Palau's power system, renewable electricity from wind turbines was also considered. It was assumed that each turbine would be a 275 kW Vergnet turbine with a hub height of 55 metres. For a single turbine, the capital and replacement costs were assumed to be USD 411 675. The operating cost, on the other hand, was assumed to be USD 4 116.75/year. The lifetime for each wind turbine was assumed to be 20 years.

Battery storage

A generic lithium-ion (Li-Ion) battery was selected in HOMER for each scenario modelled in this study. The assumptions included a capital cost of USD 250/kWh and a replacement cost of USD 150/kWh. The battery was assumed to have a degradation limit of 30%, an initial state of charge of 100% and a minimum state of charge of 20%.

Battery inverter/rectifier

The battery inverter/rectifier was assumed to have both capital and replacement costs of USD 105/kW. Other assumptions included an efficiency of 95%, a lifetime of 15 years and a relative capacity of 100%.

Diesel genset

All the current diesel generators present in Palau were assumed to have zero capital cost, as they are already installed and running. For their replacement, a cost of USD 500/kW was assumed. The operating cost for the generators was assumed to be USD 0.03/hour of operation. Based on the data provided by PPUC, the diesel fuel price was inputted as USD 0.66/litre. While the lifetime of each generator was assumed to be 15 000 hours, all gensets were assumed to have a minimum load ratio of 25%.

Electrolyser

Using the HOMER software, an electrolyser was selected for modelling green hydrogen production. Assumptions were made based on IRENA's latest report on electrolysers (IRENA, 2020b). The capital and replacement costs were assumed to be USD 450/kW and USD 250/kW respectively, for a deployment date of 2035 and beyond. The electrolyser was assumed to have an operating cost of USD 25/year/kW and a lifetime of 15 years. The efficiency and minimum load ratio were inputted as 70% and 0%.

Hydrogen tank

Another key component for modelling green hydrogen production in HOMER is the hydrogen tank. The capital cost for every kilogramme of this was assumed to be USD 500. The replacement cost for every kilogramme was assumed to be USD 350 and the operating cost to be USD 1/year. The lifetime of the hydrogen tank was inputted as 25 years.

Fuel cell

A fuel cell was also needed to model green hydrogen production in HOMER. The capital and replacement costs of the fuel cell were assumed to be USD 600 and USD 400 respectively. The operating cost was assumed to be USD 0.01/hour of operation and the lifetime was inputted as 50 000 hours.

General techno-economic assumptions

Together with the key assumptions for the main components, some general techno-economic assumptions were also needed in order to model the different scenarios in HOMER. These assumptions included a project lifetime of 25 years, an expected inflation rate of 1.9%, a nominal discount rate of 7% and an annual maximum capacity shortage of 1%. Other general assumptions included a load in current time step of 10%, solar power output of 20 % and wind power output of 30%.

After inputting all the key and general assumptions for the power sector, a HOMER optimisation was performed for each scenario. The various results, including average daily and weekly minimum and maximum variable renewable energy (VRE) dispatch graphs, can be seen in Chapter 4 (Results).

Table 4: Key assumptions

COMPONENTS	CAPITAL COST	REPLACEMENT COST	O&M COST	LIFETIME	FUEL PRICE
SOLAR PV (INCLUDING INVERTER)	600 USD/kW	500 USD/kW	10 USD/kW/year	25 years	-
WIND TURBINE (275 KW PER UNIT) FROM 2030	411 675 USD/unit	411 675 USD/unit	4 116 USD/unit/year	20 years	-
BATTERY STORAGE	250 USD/kWh	150 USD/kWh	0	-	-
BATTERY INVERTER/ CHARGER	105 USD/kW	105 USD/kW	0	15 years	-
DIESEL GENSET	0 (existing)	500 USD/kW	0.03 USD/kW/ op. hour	15 000 hours	0.50 USD/l
ELECTROLYSER (AFTER 2035)	450 USD/kW	250 USD/kW	25 USD/kW/ year	15 years	-
HYDROGEN TANK (AFTER 2035)	500 USD/kg	350 USD/kg	1 USD/kg/year	25 years	-
FUEL CELL (AFTER 2035)	600 USD/kW	400 USD/kW estimate	0.01 USD/kW/ op. hour)	50 000 hours	-

Adapted from IRENA (2021).

3.3. TRANSPORT SECTOR ASSUMPTIONS

The following chapter encompasses all the key assumptions taken into consideration for the transport sector analysis. It includes assumptions and calculations made for EVs, as well as those made for hydrogen speedboats.

EVs

In addition to the power sector, the Republic of Palau's transport sector is also strongly dominated by fossil fuels. From data provided by the Statistics Office, Division of Tax, and the Bureau of Public Safety, the total number of road transport vehicles currently present in Palau was estimated to be around 7 500. Currently, no EVs are present in Palau. Given the limited data on the number of vehicles fuelled by gasoline and those fuelled by diesel, the roadmap study assumed that all vehicles currently circulating in the country were using gasoline. Furthermore, without information on the type of vehicles, it was assumed that all vehicles were automobiles.

The roadmap looked at replacing all 7 500 gasoline vehicles with the same number of EVs by 2050. Table 5 shows the current fleet of vehicles along with the fuel type which were assumed for the transport analysis.

The Republic of Palau has a relatively small land area, at 459 km^2. EVs therefore represent an attractive way to cut fossil fuel consumption and use renewables to meet a large part of the transportation sector's energy demand. In order to support such an increase in the share of renewables, however, EVs must be charged with electricity coming from renewable sources.

To simulate EVs in HOMER, the EV load or demand first had to be inputted as a deferrable load. To do so, an electric load for the EVs first had to be estimated. This was done by making various assumptions in terms of the current total distance being travelled by vehicles in Palau, as well as the charging characteristics of the EVs. As mentioned previously, calculations were made assuming that all vehicles in Palau were automobiles and were to be replaced by the same number of EVs by 2050. Furthermore, a daily driving demand of 25 km per day was assumed for all EVs.

Table 6 shows the assumptions considered for the deployed EVs, along with the daily driving demand.

For the charging characteristics of the EVs, it was assumed that all of them had a nominal battery capacity of 42 kWh. This number was based on the characteristics of the latest EVs available in today's market. An EV efficiency of 0.14 kWh/km was also assumed, based on the currently available EVs. The EV load calculation along with the assumed EV charging characteristics can be seen in Table 7.

To estimate the deferrable load for simulating EVs in HOMER, a 0.30 contemporaneity factor was used for the calculations. In order to calculate the total storage capacity for all the vehicles, the battery nominal capacity was multiplied by the number of vehicles and the contemporaneity factor. The total estimated nominal capacity for all the EVs was then estimated to be around 94 500 kWh.

Next, the internal charger capacity was multiplied by the number of vehicles and the contemporaneity factor to give a total peak load of 8 325 kW. Finally, to estimate the deferrable load, or scaled annual average, the number of vehicles was multiplied by the daily driving demand and the EV efficiency. The deferrable load was estimated to be 26 250 kWh/day. This could be further increased if most of the generation was connected to the medium voltage transmission system and the losses between generation and distribution-connected EV charging remained high (these were estimated at 18%, currently). The three values in Table 8 were then used as inputs for modelling EVs in HOMER.

Table 5: Total road vehicles by fuel type, 2021

FUEL TYPE	VEHICLE TYPE	TOTAL VEHICLES
Gasoline	Cars	7 500

Table 6: Deployed EV assumptions

FUEL TYPE	VEHICLE TYPE	NUMBER OF EVs	KM/DAY
Electricity	Cars	7 500	25

Table 7: EV load calculation and charging characteristics

BATTERY NOMINAL CAPACITY (kWh/VEHICLE)	EV EFFICIENCY (kWh/KM)	DAILY DEMAND PER EV (kWh)	INTERNAL CHARGER CAPACITY (kW/VEHICLE)	kWh/DAY
42	0.14	3.5	3.7	26 250

Table 8: HOMER EV inputs

SCALED ANNUAL AVERAGE (kWh/DAY)	26 250
STORAGE CAPACITY (kWh)	94 500
PEAK LOAD (kW)	8 325

Hydrogen speedboats

A major part of fossil fuel consumption in the Republic of Palau comes from the maritime transportation sector. This includes speedboats for tourism, as well as boats used for diving. In total, these consume large quantities of gasoline.

A good example of this is provided by the Rock Islands. These are a group of several hundred limestone islands located within a marine lagoon between Koror and Peleliu. Now part of Koror State, the islands are surrounded by coral reefs and include a wide range of marine habitats (World Heritage Datasheet, 2012). They represent one of Palau's key tourist attractions, with numerous visitors travelling every year for diving and snorkelling. According to information provided by PEA, an average 38 foot open boat with a 250 horsepower twin engine consumes approximately 40 gallons of gasoline when travelling back and forth to the Rock Islands.

The roadmap therefore looked into the possibility of converting the current fleet of speedboats into hydrogen speedboats. With limited data available on fuel consumption and on marine transportation, however, this study has only looked at providing an estimate, based on what data there were for deploying hydrogen speedboats, rather than performing an optimisation analysis in HOMER.

The following chapter discusses in detail the various assumptions and calculations made for assessing the deployment of hydrogen speedboats in Palau's marine transportation sector.

Table 9 illustrates the total number of boats registered in Palau between 2016 and January to August 2020. It should be noted that these numbers also include registration renewals from the previous year. As the baseline year for the optimisation analysis of Palau's power sector was 2019, the marine transport analysis has also focused on data from that year.

Although a relatively new technology, various manufacturers have been exploring the development of hydrogen speedboats, with one example being the Japanese engine manufacturer Yanmar. On 24 March 2021, they conducted a field test demonstration of a speedboat powered by a hydrogen fuel cell (see Figure 4).

Table 9: Registered boats in Palau

YEAR	NUMBER OF REGISTERED BOATS
2016	232
2017	233
2018	191
2019	343
2020 (January to August)	72

Source: Ministry of Justice, Republic of Palau (n.d.).

Figure 4: Hydrogen speedboat prototype

Source: Yanmar, 2021.

The Yanmar speedboat consists of a system that includes hydrogen fuel cell modules manufactured by Toyota. Detailed specifications of the prototype boat can be seen in Table 10 below.

The importance of considering hydrogen for speedboats is that boat design can remain mostly unchanged, with the diesel engine simply replaced by an electric motor driven by a fuel cell. A compressed hydrogen tank (at 700 bar), however, is also expected to be around five times larger than a diesel one, which might make the conversion challenging for smaller boats.

Using the data provided by PEA, the total fuel consumption per year was then estimated. The study assumed that each of the 343 boats was travelling back and forth from Koror to the Rock Islands for a total of 200 working days per year. The total gasoline consumption per year was then estimated as around 10 million litres. This value was then used to estimate the total annual and daily demand for hydrogen if all 343 boats were to be replaced by hydrogen speedboats. The efficiency of a gasoline powered diving boat was assumed to be 25%, while the efficiency of the fuel cell was assumed to be 50%. The daily hydrogen demand for all the boats was then estimated as approximately 4 tonnes. Table 11 shows the estimation of the total amount of hydrogen that would be consumed when replacing the current fleet of boats with hydrogen speedboats.

The roadmap mainly looked into hydrogen boats for reducing fossil fuel consumption in Palau's marine transportation sector. Thanks to progress and cost reductions in batteries, however, another option that could become a solid alternative in the future is that of high-speed, high-efficiency battery-powered boats.

In particular, a technology that could be considered for future electric boats is hydrofoiling. The Swedish company Candela has, for example, successfully engineered a hydrofoil boat which uses a wing located below the keel to lift the hull above the water's surface. Made of carbon fibre, with a 55 kW motor and a 400 kWh Li-Ion battery, the boat has a top speed of 30 knots. At a cruising speed of 22 knots it can reach a maximum range of 50 nautical miles.

One important thing to note about such a technology, however, is that for hydrofoiling to work successfully, the boat has to be light enough to be above the surface of the water. If the boat is heavy, then the foil must be wider, but this increases its contact area, reducing the drag efficiency. The size of the battery also has to be noted, as batteries come at a significant upfront cost, even assuming battery cost declines. As a reference, EV batteries in 2021 cost USD 132/kWh (BNEF, 2021). This would translate into a USD 52 800 battery pack for the Candela hydrofoil. As battery costs are expected to continue declining, however, battery-powered electric motors might become a more viable proposition, not only on new, high-efficiency hydrofoiling boats, but also as a retrofit option for existing boats.

Table 10: Specifications of hydrogen speedboat

MODEL	EX38A (FC PROTOTYPE)
Gross tonnage	7.9 tonnes
Length/breadth	12.4 metres/3.4 metres
Propulsion output	250 kW
Fuel cell type	Polymer electrolyte fuel cell x 2 modules
Hydrogen tank	70 Megapascal (MPa) x 8 tanks
Inspection body	Japan Craft Inspection Organization
Test location	Kunisaki, Oita, Japan

Source: Yanmar, 2021.

Table 11: Hydrogen speedboat demand estimation

YEAR	TOTAL BOATS	FUEL CONSUMED PER DAY (LITRES)	FUEL CONSUMED PER YEAR (LITRES)	ANNUAL HYDROGEN DEMAND (KG)	DAILY HYDROGEN DEMAND (KG)
2019	343	51 936	10 387 200	1 480 176	4 055

Source: PEA and IRENA data (n.d.).

4. RESULTS

The following chapter covers in detail the main results of the various scenarios modelled in this roadmap. The results of the different scenarios are discussed in depth with key charts/figures showing how the government of Palau can achieve the proposed target of 100% renewable energy in the power sector by 2050.

Each of the five scenarios considered in this analysis were simulated in HOMER in order to determine how much additional renewable energy capacity would be needed for today's current power system to transition to a carbon-neutral system with a 100% renewable energy share. Table 12 illustrates the overall results obtained from the detailed modelling of the five scenarios.

Table 12: Results of the roadmap

MODEL/ SCENARIO	CURRENT POWER SYSTEM	OPTIMAL SYSTEM	100% RENEWABLES, WITH PV + WIND	100% RENEWABLES, WITH PV	100% RENEWABLES, WITH HYDROGEN	100% RENEWABLES, WITH HYDROGEN + EVs
ELECTRICITY DEMAND (GWh/ YEAR)	89	100	100	100	120	127
EXCESS ELECTRICITY (GWh/YEAR)	0	27	199	244	38	40
CURRENT PV (MW)	2.5	2.5	2.5	2.5	2.5	2.5
NEW PV (MW)	0	76	190	248	83	86
WIND (MW)	0	9	20	0	20	24
HYDROGEN TANK (TONNES)	0	0	0	0	25	25
ELECTROLYSER (MW)	0	0	0	0	25	25
FUEL CELL (MW)	0	0	0	0	50	50
DIESEL (MW)	20	18	0	0	0	0
STORAGE (MWh)	0	259	412	464	168	182
BATTERY INVERTER/ RECTIFIER (MW)	0	31	41	33	34	31
RENEWABLES SHARE (%)	4	92	100	100	100	100
CO_2 EMISSIONS (TONNES/YEAR)	54 073	5 555	0	0	0	0
LEVELISED COST OF ELECTRICITY (USD/kWh)	0.23	0.13	0.22	0.23	0.16	0.15
INITIAL CAPITAL COST (USD MILLIONS)	0	126	249	266	179	189
NET PRESENT COST (USD MILLIONS)	294	188	309	328	227	237
OPERATING COST (USD MILLION/ YEAR)	20.7	4.36	4.3	4.45	3.41	3.42

The overall results of the roadmap show that the government of Palau can accomplish the proposed target of 100% renewable energy. To do this, it will have to add additional renewable energy capacity to its power system and decrease the high current level of fossil fuel-based generation. The calibration model representing Palau's current power system also confirms this dominance of fossil fuels and the low share taken by renewable energy. The government can achieve its 100% target through the deployment of more solar PV, wind and battery storage systems, in addition to decommissioning the diesel generators currently operating in the island.

The roadmap looked into four specific scenarios and options to achieve the 100% renewable target. The first looked at solar PV and wind, while the second looked at solar PV deployment only. The results of the third 100% scenario show that hydrogen provides more flexibility in the system, which decreases the levelised cost of electricity. Finally, the fourth scenario, which includes green hydrogen production and EVs, shows that EVs provide additional flexibility in the system, further decreasing the cost.

The results of each scenario, together with dispatch graphs for the maximum and minimum VRE week, are discussed in more detail below.

An overview of the main results of the roadmap, in terms of LCOE and renewable energy share can be seen in Figure 5.

From the figure it can be noted that with Palau's current power system, the government is still far from achieving its proposed target of 100% renewable energy. When adding additional renewable energy capacity to the power system along with battery storage systems, however, the share of renewables increases to more than 92%. The figure also shows how with the optimal system, the LCOE decreases from the current USD 0.23/kWh to USD 0.13/kWh. The graph also shows the four different options considered for reaching the 100% target by 2050. The LCOE increases with both scenarios where green hydrogen has not been considered. The reason for this is that to establish a system with such a high penetration of VRE, significant battery storage capacity is needed, which increases the cost. When adding green hydrogen production, the LCOE decreases to USD 0.16/kWh, as hydrogen provides more flexibility to the power system, reducing the need for larger battery storage, hence decreasing the cost. The figure also shows how with EVs and the additional flexibility provided to the system, the cost decreases even further, to USD 0.15/kWh.

Figure 6 shows a proposed timeline for the Republic of Palau in terms of renewable energy deployment that has been developed based on the results of the roadmap.

The figure shows that as per the 2016-2017 roadmap, Palau can achieve a 45% share for renewable energy in its power sector by 2025. In 2030, based on the optimal system scenario, the government could increase solar PV capacity to 76 MW and battery storage to 259 MWh. Furthermore, EV deployment to replace internal combustion engine (ICE) vehicles could also commence gradually over the next decade, increasing the share of EVs in newly registered vehicles. By 2035, the wind capacity identified in the optimal system scenario (9 MW) could also be installed. By 2040, the government of Palau could add electrolysis and reach 100% EV stock, having reached 100% of new registrations in the early 2030s and gradually replaced old ICE vehicles with EVs. The figure below also highlights the next milestone – that by 2045 Palau should be able to reach the final 100% renewable energy scenario, inclusive of green hydrogen production and EVs. Finally, by 2050, both the power and transport sectors (including boats) of the Republic of Palau could be fully decarbonised, with gasoline motors replaced by electric motors powered by renewable electricity, either stored in hydrogen form or in batteries.

Figure 5: Roadmap overview

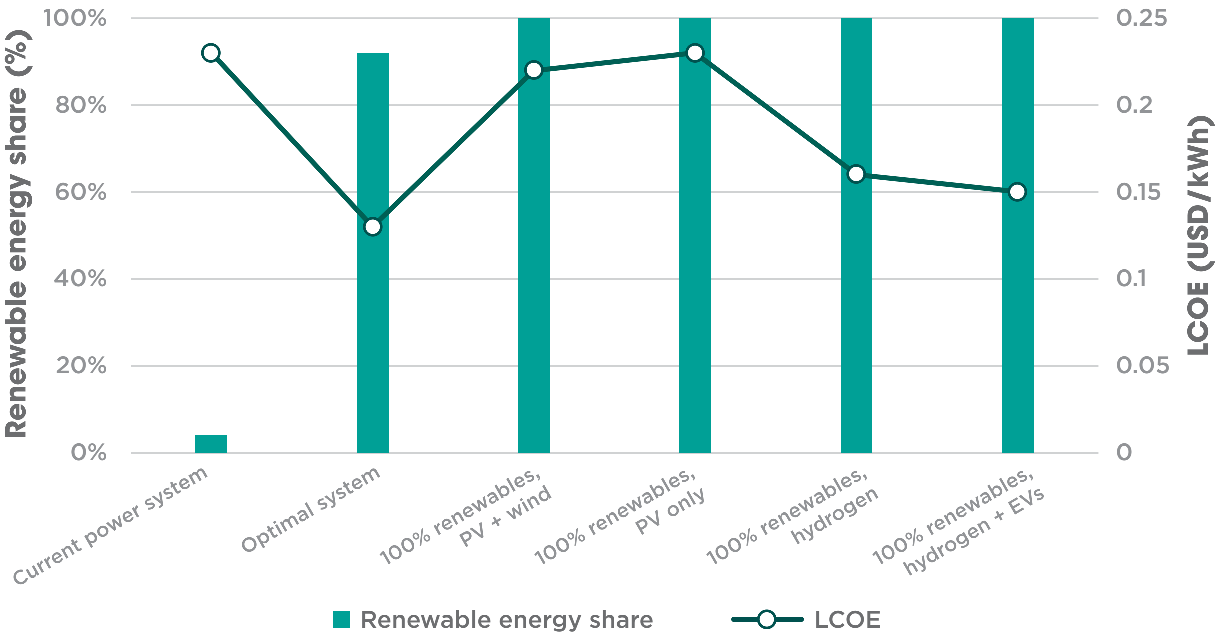
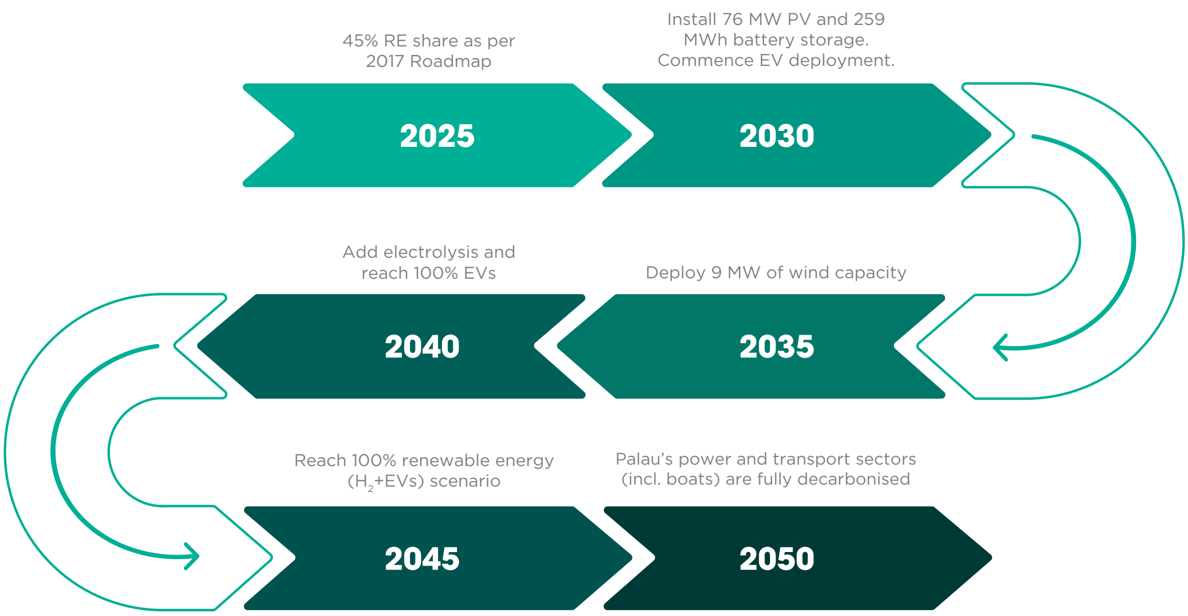


Figure 6: Palau roadmap timeline



4.1. CURRENT POWER SYSTEM

As mentioned previously, the current power system of the Republic of Palau is widely dominated by conventional fossil fuel generation. The calibration model developed has shown that currently, renewable energy generation represents only 4.03% of the total share of Palau's power sector. Therefore, there is a significant potential to increase the share taken by renewable energy in the country's energy mix and simultaneously reduce fossil fuel generation.

Palau's current power system has a total electricity demand of 89 GWh/year with no excess of electricity. Based on the optimisation results, current diesel fuel consumption was estimated at 20.5 million litres, with a daily average of 56 096 litres and an average fuel per hour of 2 337 litres. The current power system model has also shown high emission values, with CO_2 values of 54 073 tonnes/year.

With regard to the economic results of the optimisation, the LCOE for Palau's current power system was estimated to be USD 0.23/kWh. The current power system has a net present cost of USD 294 million (mostly fuel) and an operating cost of approximately USD 20.7 million/year.

Figure 7 shows the average daily dispatch for the current power system. As the name suggests, the figure illustrates the generation dispatch that occurs during an average day of the year. It shows how most of the total electricity load (the light blue dashed line) is covered through diesel generation (the black coloured area). The generators fully cover the total demand during early morning and night time hours, while throughout the day they cover most of the load. The figure also shows how the solar PV panels (yellow coloured area) generate electricity during the day (6 a.m. to 5 p.m.) to partially cover the demand. As there is no battery storage system currently present in Palau, the panels can only generate throughout the day when the sun is available, and no electricity can be stored for later use. Furthermore, the figure also confirms that Palau's current power system is widely dominated by fossil fuel generation.

Figure 8 shows the generation dispatch for a week with minimum VRE. The X-axis of the graph represents the hours of the week (168 in total). The figure clearly shows how solar PV generation occurs during daytime when the sun is shining, while during night time and early morning hours, the diesel generators are used to cover the entire electrical load. The graph also confirms the high dominance of fossil fuel generation in Palau's current power sector. Maximum solar PV generation occurs during the last day of the week, with a peak of 1.75 MW.

The week with maximum VRE generation can be seen in Figure 9. Similar to the minimum VRE week, the figure shows how most of the load is covered by the diesel generators, while the solar PV panels partially cover the demand throughout the daytime. As opposed to the minimum VRE week, however, it can clearly be seen that the solar PV generation is higher, with a peak generation of 2 MW.

Figure 7: Average daily dispatch: Current power system

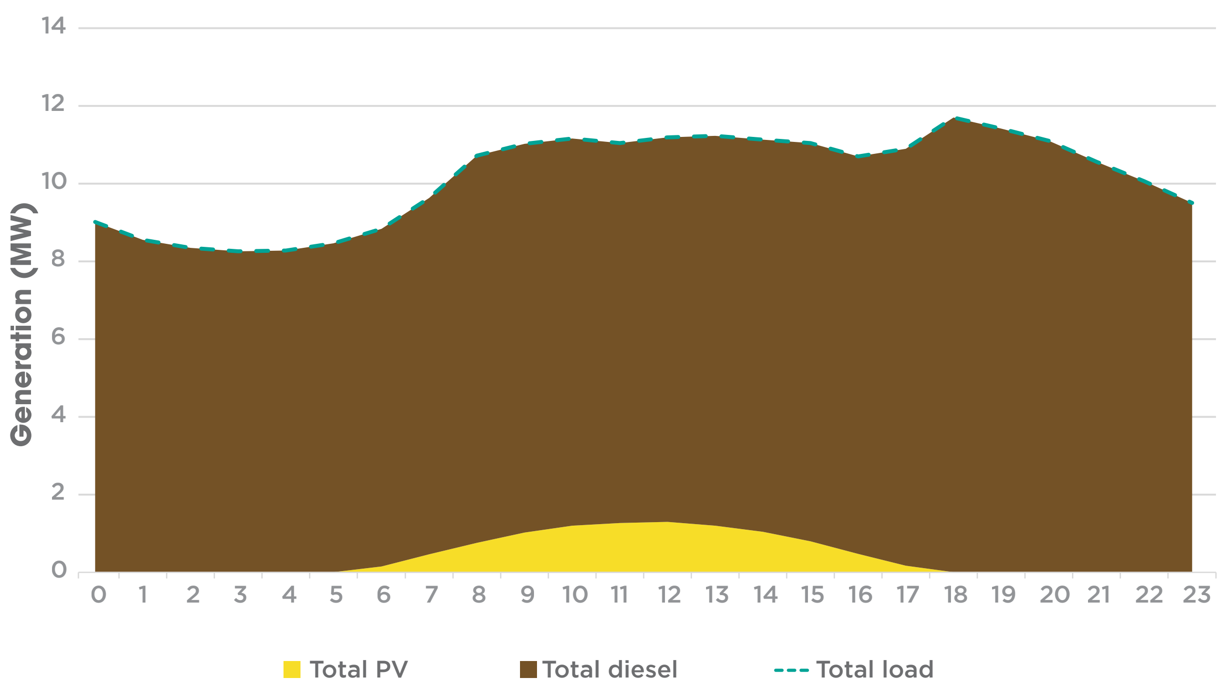


Figure 8: Minimum VRE week: Current power system

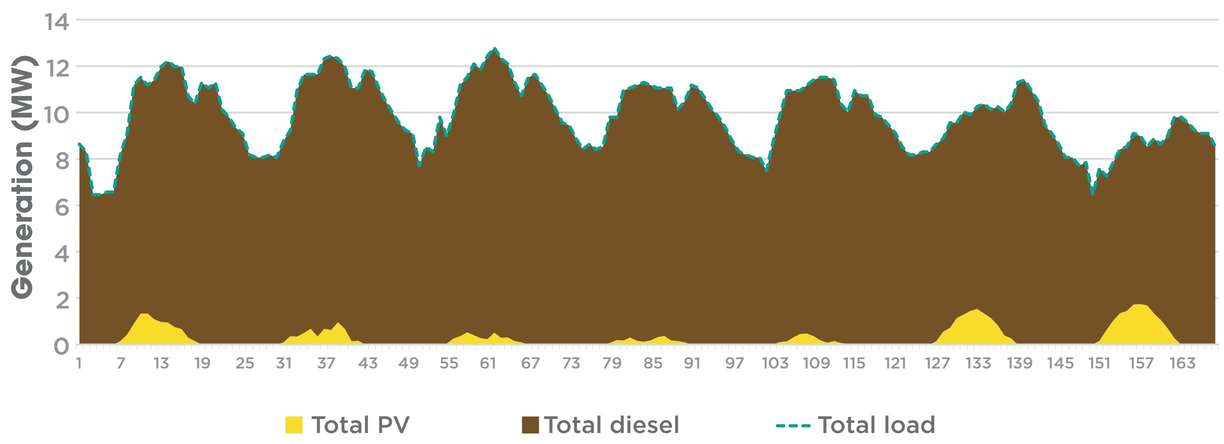
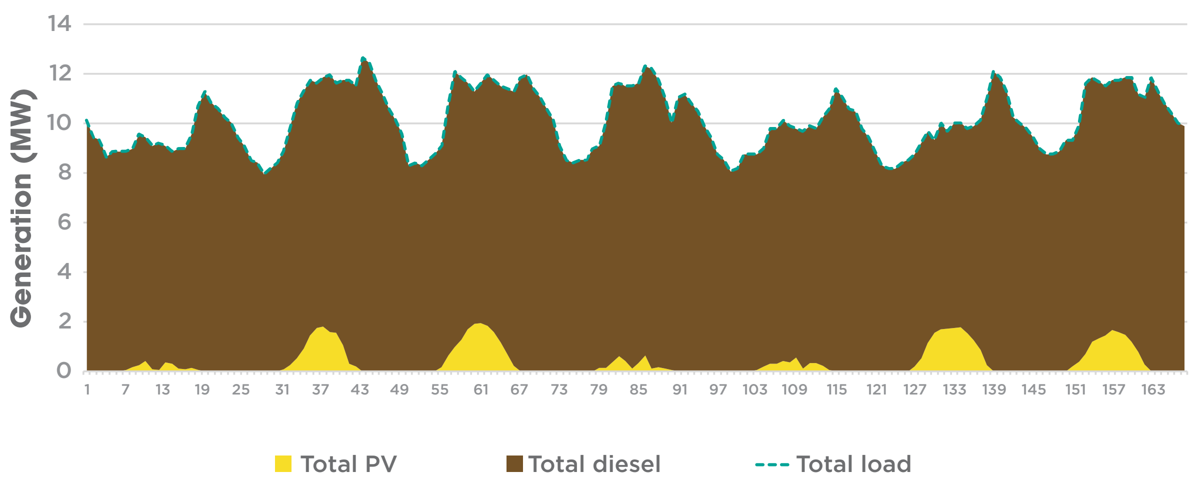


Figure 9: Maximum VRE week: Current power system



4.2. OPTIMAL SYSTEM

Once the model was calibrated in HOMER, using Palau's current power system, the first, optimal system scenario was modelled with additional renewable energy capacity added to the generation mix. The results showed that by adding solar PV and wind specifically, the Republic of Palau could significantly increase its renewable energy share from the current 4.03% to more than 92%. This could be achieved by adding 76 MW of solar PV and 9 MW of wind to the current capacity. Furthermore, to support such a system, the model's results showed that a battery storage capacity of 259 MWh and a battery inverter of 31 MW would be needed.

The results of the optimal system show that the government of Palau has the potential to come very close to achieving its proposed 100% target simply by increasing its renewable energy capacity and deploying battery storage. With a total demand of 100 GWh, the optimisation shows excess electricity of 27 GWh per year with no unmet load and capacity shortage. Total diesel fuel consumption for this scenario was estimated at 2.1 million litres, which is almost ten times smaller than the current level of 20.5 million litres. The fuel savings would then be almost USD 12.1 million, when compared to today's power system. Through the model, the average fuel per day and average fuel per hour were optimised as 5 815 litres and 242 litres, respectively.

Moreover, the optimal system also shows a significant decrease in CO_2 emissions, with these also falling almost ten times from the current level. At present, the power system emits an estimated 54 000 tonnes of CO_2/year, with this falling to around 5 500 tonnes of CO_2 per year in the optimal scenario. The remaining scenarios, being 100% based on renewable generation, bring CO_2 emissions to zero.

In terms of economics, the HOMER model estimated an initial capital cost of USD 126 million to deploy the proposed renewable energy system. The LCOE of such a system was optimised at approximately USD 0.13/kWh. When compared to the economics of Palau's current power system, there is a distinct decrease in the costs. Hence, this confirms that deploying additional renewable energy capacity, given current reductions in technology costs, makes the system more economically viable. Such a scenario would entail a net present cost of USD 188 million and an operating cost of USD 4.36 million/year.

Figure 10 shows the average daily dispatch for Palau's optimal system scenario. Unlike the current power system, the graph includes additional solar PV capacity, wind generation (the blue coloured area), battery charging (the purple coloured area) and discharging (the red coloured area), and excess electricity (the grey coloured area). From the figure, it is noticeable that the deployment of battery storage systems allows electricity to be stored and used during early morning and night time hours when the solar PV is not generating electricity. Between 6 p.m. and 6 a.m. of the next day, stored electricity is used to cover most of the load, while the remaining demand is covered using the diesel generators and the wind turbines. Between 7 a.m. and 4 p.m., all of the demand is covered by solar PV and wind, with some excess electricity being generated. By looking at the battery charging area, it can be seen that it is proportionate to the VRE generation, signifying that the excess electricity is being stored in the batteries.

Figure 11 illustrates a minimum VRE generation week for Palau's optimal system. The figure shows clearly how the various components, including the solar PV panels, wind turbines and battery storage, generate and store renewable electricity to cover the country's total load. As in the previous figure, the battery charging is proportionate to the VRE generation. Furthermore, on some days of the week, the total load is fully met by VRE generation and stored electricity from previous days. On the other hand, on some days of the week, when VRE generation is not enough to fully cover demand, diesel generators are deployed to aid in meeting the load. The figure also shows some excess electricity, with a maximum of approximately 18 MW.

The maximum VRE week for Palau's optimal system is shown in Figure 12. The graph shows a distinct difference compared to the minimum VRE week. It is noticeable that during the maximum week, there is a higher VRE generation, which also leads to more excess electricity – the maximum excess is almost 50 MW. Another difference is that less diesel generation is needed to cover the load, as most of the demand is met through renewables. Battery storage deployment allows the excess electricity from solar PV and wind to be stored and used to cover the load when needed, hence significantly decreasing diesel consumption.

Figure 10: Average daily dispatch: Optimal system

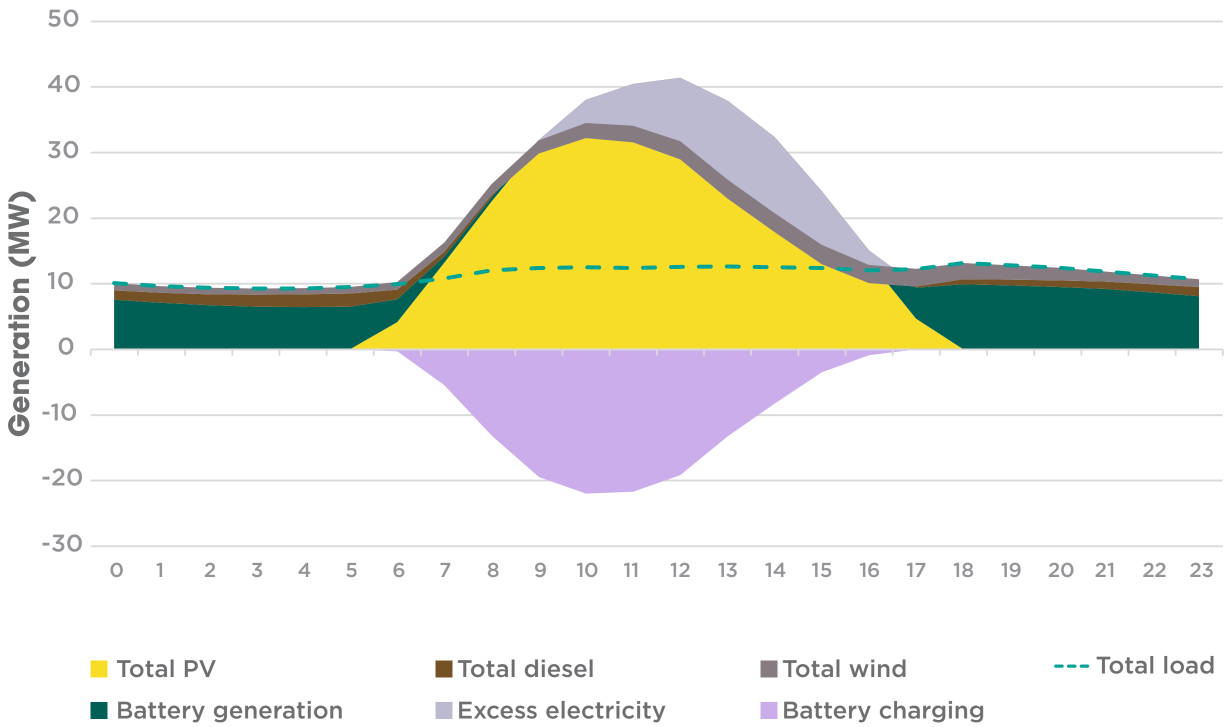


Figure 11: Minimum VRE week: Optimal system

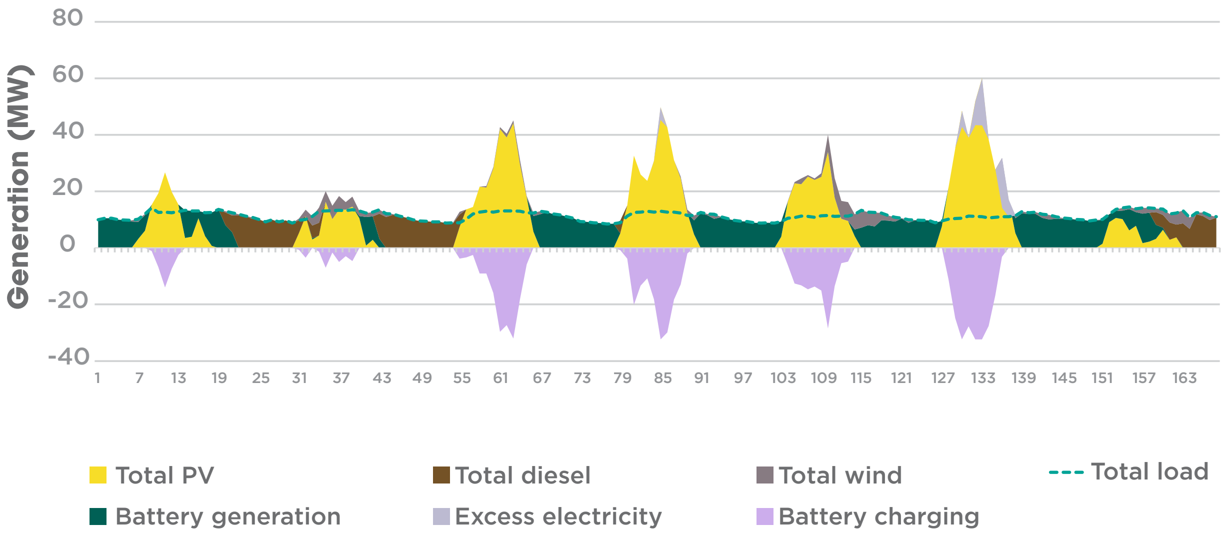
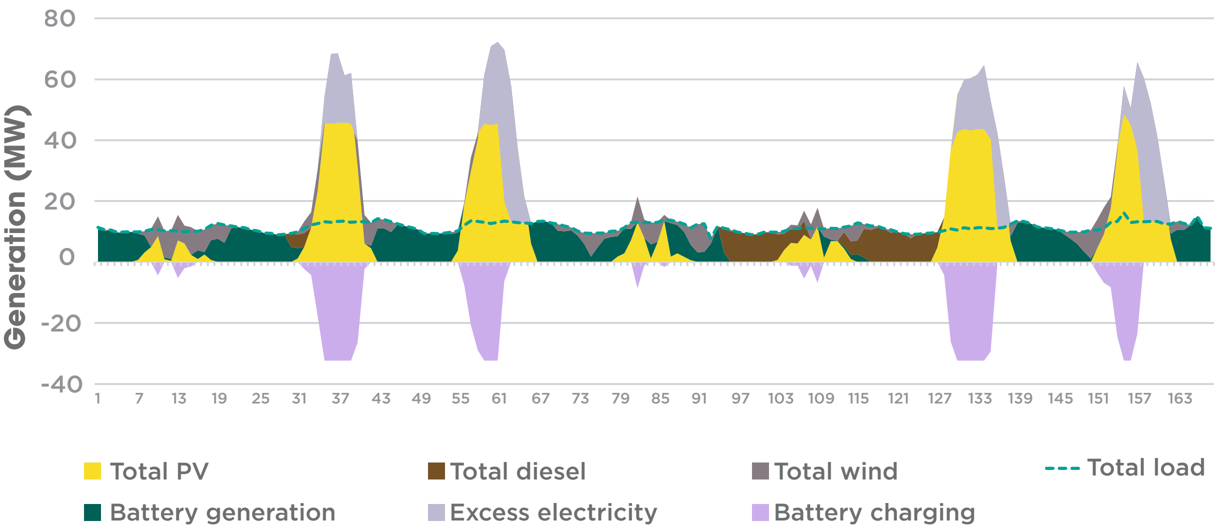


Figure 12: Maximum VRE week: Optimal system



4.3. 100% RENEWABLE ENERGY - PV AND WIND

The second scenario analysed in the roadmap is 100% renewables, with solar PV and wind. This scenario was modelled in HOMER to show that the target proposed by the government could be achieved through increased deployment of VRE and battery storage systems. The scenario did not consider any green hydrogen production, or EVs.

The results of the optimisation show that the government of Palau can achieve its 100% target by deploying an additional 190 MW of solar PV and 20 MW of wind turbines. In order to achieve the target, however, installing battery storage systems will be of utmost importance. An estimated 412 MWh of storage and 41 MW of battery inverters would be needed to support such a power system. The results also show an increase in the excess electricity generated over the previous scenario, with a total of 199 GWh/year produced. The increase in excess electricity is due to the extra renewable energy capacity being added to the system, together with the battery storage. As this scenario analysed a fully, 100% renewable energy system, no diesel generation was considered in the model.

When observing the economics of the optimisation analysis, this specific scenario had an estimated initial capital cost of USD 249 million. The LCOE for supporting such a system would be approximately USD 0.22/kWh. The net present cost and initial capital cost were optimised as USD 309 million and USD 4.3 million/year, respectively.

The average daily dispatch for the 100% scenario, inclusive of solar PV and wind, can be seen in Figure 13. The figure clearly shows how VRE generation allows Palau to meet total demand together with stored electricity in the batteries being used to cover the load when needed. Between 6 p.m. and 5 a.m., the red coloured area illustrates how stored electricity from the battery storage system is used to cover demand. Together with the batteries, some wind generation is also visible. On the other hand, between 6 a.m. and 5 p.m., electricity from the solar panels and wind turbines is able to cover the entire demand. The grey area shows all of the excess electricity being generated, with a peak of 90 MW, while the purple area shows the battery charging taking place. As mentioned previously, the excess electricity is a result of an increase in renewable energy and battery storage capacity.

Figure 14 shows the minimum VRE week for the 100% renewables, PV plus wind scenario. It also shows how the various components meet demand on different days of the week. As observed with the average daily dispatch, during the early morning hours and night time, the load is covered with stored electricity from batteries and with some wind generation. Towards the morning and afternoon hours, solar PV and wind meet the entire load while also generating some excess electricity.

The maximum VRE week for this scenario is seen in Figure 15. When looking at the graph, there is a clear and distinct difference from the minimum VRE week. The figure shows an evident increase in excess electricity, signifying also an increase in the VRE generation. The excess electricity reaches a peak of 165 MW during one day of the week. As with previous figures for this scenario, the graph also shows battery generation and charging occurring proportionate to VRE generation.

Figure 13: Average daily dispatch: 100% renewables - PV and wind

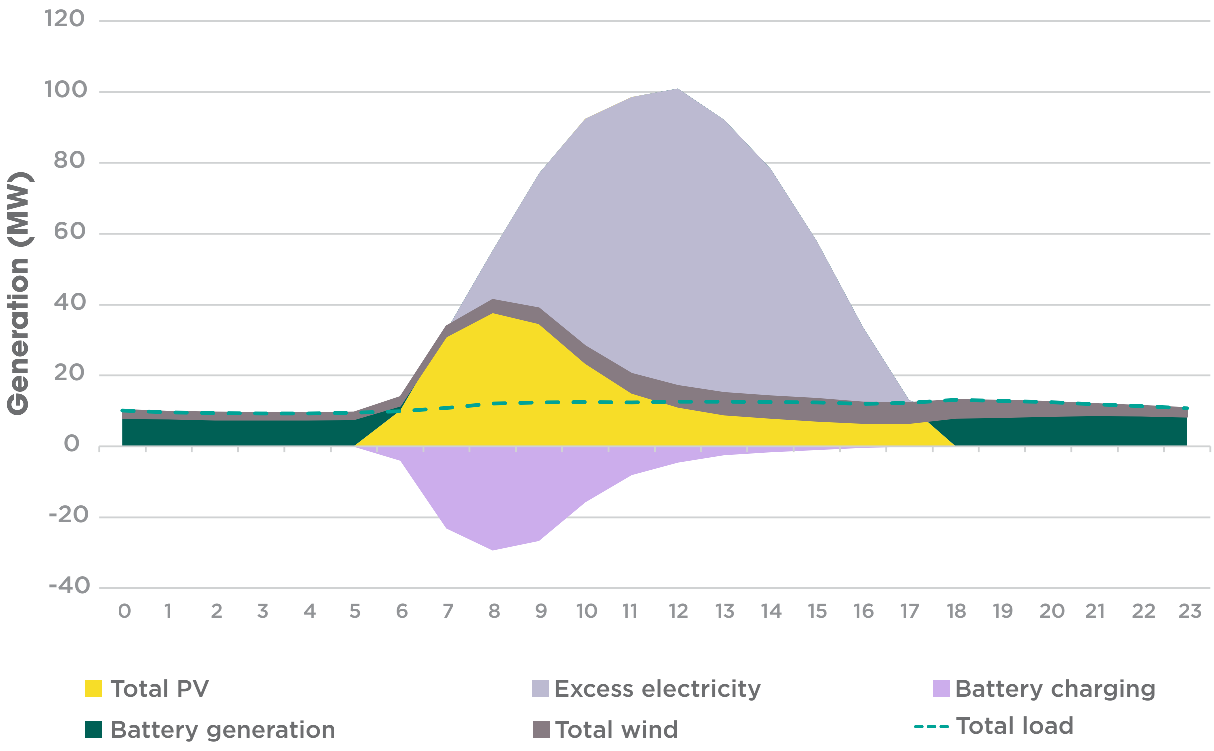


Figure 14: Minimum VRE week: 100% renewables, PV plus wind

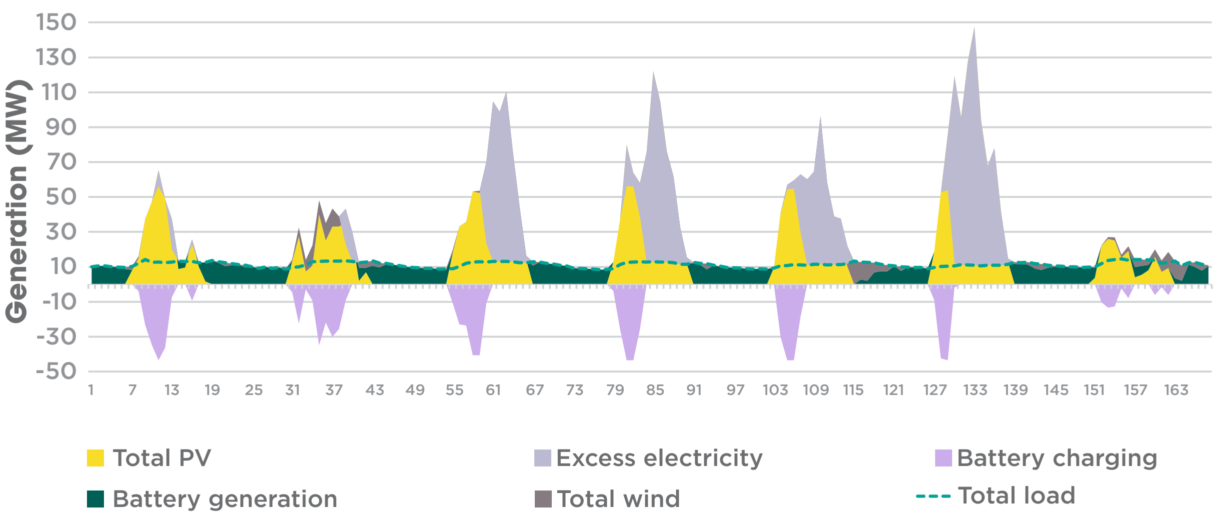
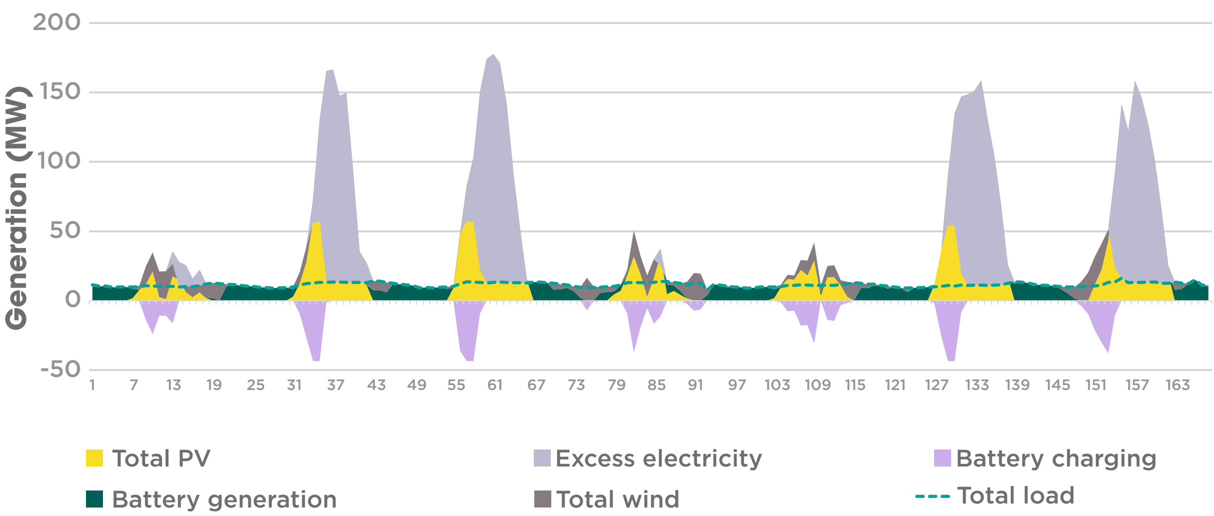


Figure 15: Maximum VRE week: 100% renewables, PV plus wind



4.4. 100% RENEWABLE ENERGY - PV ONLY

The third scenario optimised in this roadmap was the 100% renewables with solar PV only. The reason for modelling such a scenario was to show that the target could be achieved with just solar PV generation, but that this would come with different costs when compared to the 100% renewable energy scenario with both PV and wind.

The results show indeed that the Republic of Palau can achieve its 100% target by deploying 248 MW of solar PV. The results of the optimisation show that if the government decides to install solar PV alone, however, they would have to deploy an additional 58 MW to the previous scenario modelled. Therefore, in order to replace 20 MW of wind turbines, 58 MW of solar PV panels would be necessary. The results also showed battery storage and battery inverter capacities of 464 MWh and 33 MW, respectively. Compared to the previous scenario, there is an increase of 52 MWh in the optimised battery storage system. Furthermore, this scenario also shows a significant increase in excess electricity generation, with this reaching 244 GWh/year. It has also to be noted that relying entirely on one source of generation is not ideal, and complementarity with wind can reduce the need for storage and the resilience of the system to long periods of low insolation.

The results of the HOMER modelling also show an increase in economic cost when compared to the 100% renewables scenario, inclusive of solar and wind. The reason for this is the larger renewable energy capacity and batteries needed to support such a power system. The initial capital cost and LCOE were estimated at USD 266 million and USD 0.23/kWh respectively, making this scenario the most expensive one analysed in this study. The net present cost and operating cost were also increased, with the former being USD 328 million and the latter, USD 4.45 million/year.

The average daily dispatch for this scenario can be seen in Figure 16. The figure confirms the large increase in excess electricity due to larger solar PV and battery storage capacity. It also shows that between 6 p.m. and 5 a.m. the entire electricity load is met exclusively by stored electricity in batteries. The solar panels generate electricity during the day, specifically between 6 a.m. and 5 p.m., with the excess electricity being used to charge the batteries (as seen in the purple coloured area).

The minimum VRE week is illustrated in Figure 17. As with the average daily dispatch, the figure shows how in some parts of the day, solar PV is used to cover the entire load, while in others, stored electricity in the batteries meets demand. The minimum VRE week shows some days with little to no excess electricity, while on others, there are large amounts of excess electricity, peaking at 199 MW.

Figure 18 illustrates the maximum VRE week. When compared to the minimum VRE week, it is evident that there is an increase in renewable energy generation. This is also confirmed by observing the grey coloured area showing the excess electricity being generated in this scenario. Some days of the week show a significant production of excess electricity, with a peak of 218 MW. As observed in the minimum VRE week and average daily dispatch, stored electricity meets demand when the solar PV is not generating electricity.

Figure 16: Average daily dispatch: 100% renewable energy - PV only

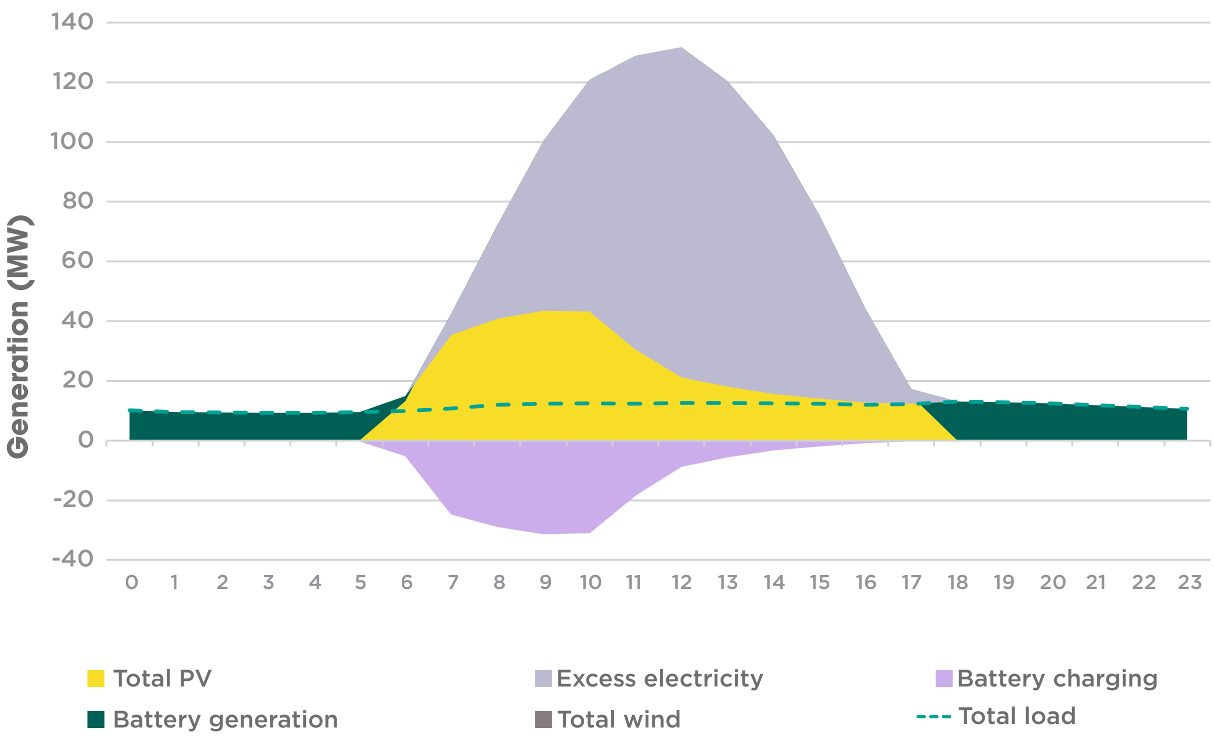


Figure 17: Minimum VRE week: 100% renewable energy - PV only

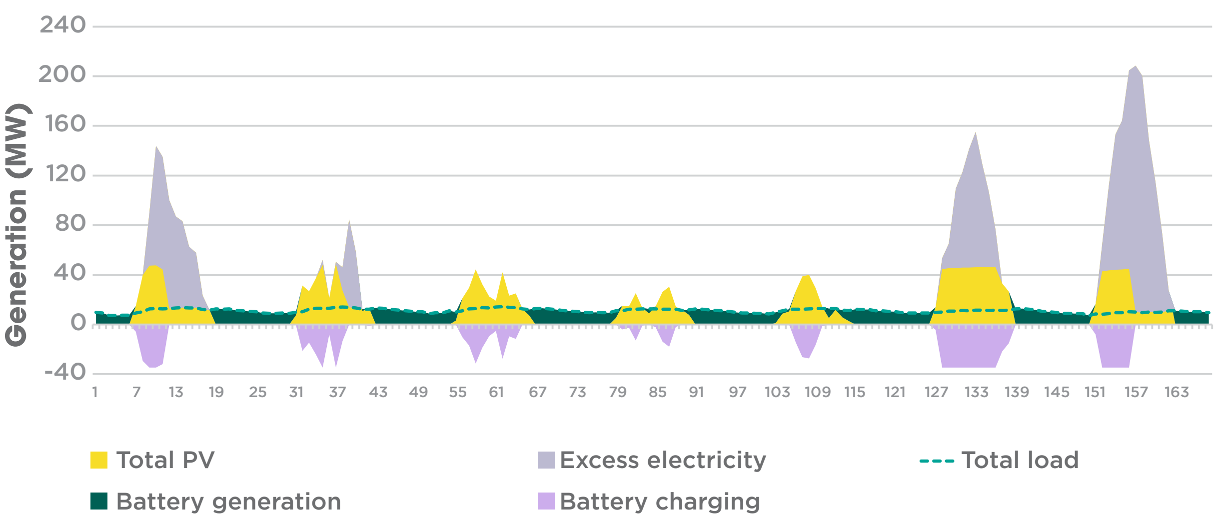
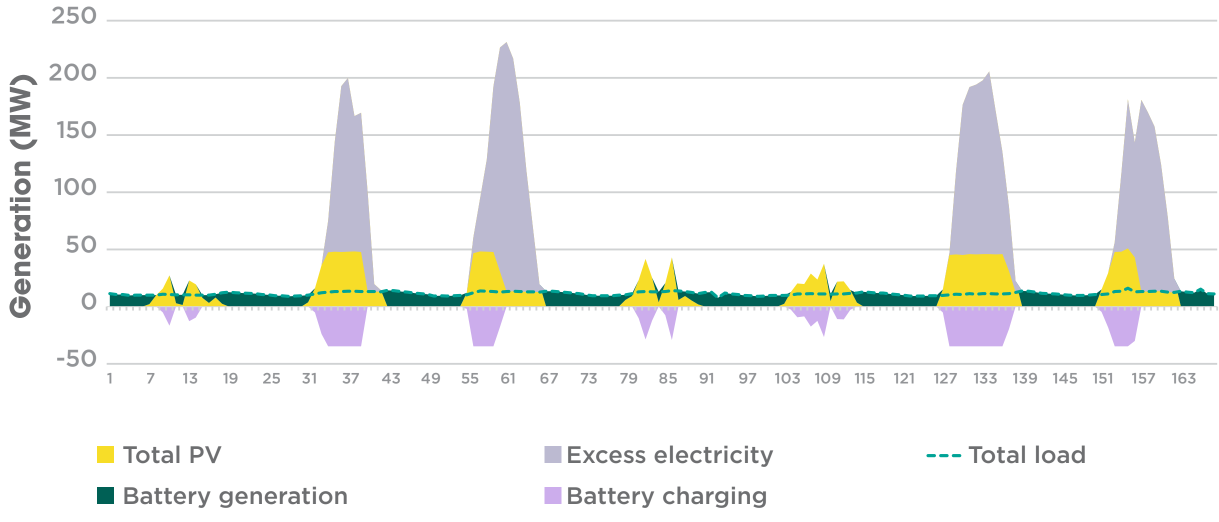


Figure 18: Maximum VRE week: 100% renewable energy - PV only



4.5. 100% RENEWABLE ENERGY WITH HYDROGEN

The fourth scenario analysed in this study is 100% renewables plus green hydrogen production from solar PV and wind. This scenario was modelled in HOMER to show how green hydrogen production can help in achieving the target set by the government and how this combination would affect the overall cost, as opposed to the other scenarios.

The results show that on top of the 2.5 MW of solar PV currently present in Palau, an additional 83 MW of solar PV and 20 MW of wind turbines would be required for such a system. Furthermore, this scenario would necessitate a battery storage system of 168 MWh and battery inverters of 34 MW. The storage and converter optimised for this scenario are the smallest when compared to the other four scenarios analysed in this study. The reason for this is the flexibility provided to the system by green hydrogen decreases the usage for batteries.

In order to model green hydrogen production in HOMER, three specific components were selected. Namely, the hydrogen tank, an electrolyser and a fuel cell. The hydrogen tank was optimised at 25 000 kilogrammes (kg), the electrolyser at 25 MW and the fuel cell at 50 MW. In this scenario, one thing to note is that green hydrogen production significantly increases Palau's total load, to approximately 120 GWh/year. The results of the optimisation have also shown that there will be excess electricity generation of 38 GWh/year, which is more than five times lower than in the previous scenario.

The economic results of the model have shown that such a system would have an initial capital cost of USD 179 million and an LCOE of USD 0.16/kWh. The net present cost would be around USD 227 million and the operating cost would be USD 3.41 million/year. When compared to the two 100% renewable energy scenarios without hydrogen, the costs are significantly cheaper. This is because once again, additional flexibility is provided to the system, decreasing not only battery storage capacity, but also the cost of electricity.

Figure 19 illustrates the average daily dispatch for the 100% renewables scenario with green hydrogen. Unlike the previous scenarios, the dispatch also shows green hydrogen production: hydrogen-to-power (green coloured area) and electrolyser output (orange coloured area). The graph shows clearly how renewable energy generation from solar and wind covers the entire load during the day, with excess electricity being used to produce green hydrogen. Between 6 a.m. and 5 p.m., renewable energy generation is consistent with the electrolyser output and the battery charging. Furthermore, between 6 p.m. and 5 a.m., most of the demand is covered by stored electricity in batteries, while a smaller amount is met by the wind turbines and hydrogen-to-power.

The minimum VRE week for this specific scenario can be seen in Figure 20. This graph shows how VRE generation covers demand during the day, with excess electricity being stored in batteries and used by the electrolyser to produce green hydrogen. There is some excess electricity occurring during four days of the week, with a peak of 30 MW. Moreover, the excess electricity generated above the total load line is proportionate to the electrolyser output and battery charging. Confirming once more that hydrogen is being produced from that excess renewable electricity.

The maximum VRE week can be seen in Figure 21. Several clear differences from the minimum VRE week can be noted. Firstly, the figure shows much more excess electricity production, with a maximum excess of 44 MW. Secondly, there is significantly more VRE generation occurring throughout the days of the week. Furthermore, there is a higher electrolyser output and level of battery charging taking place. Another major difference between the maximum and minimum VRE weeks is that in some parts of the day, more stored electricity from the batteries is used to cover electric demand.

Figure 19: Average daily dispatch: 100% renewables with hydrogen

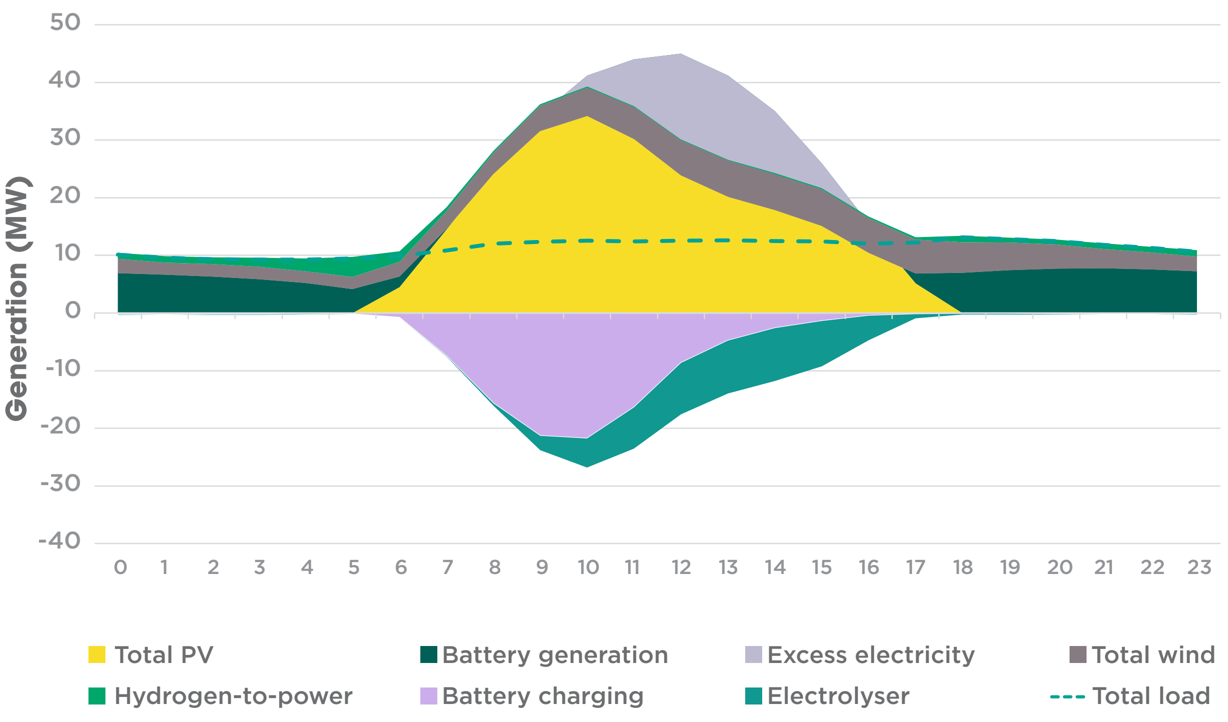


Figure 20: Minimum VRE week: 100% renewables with hydrogen

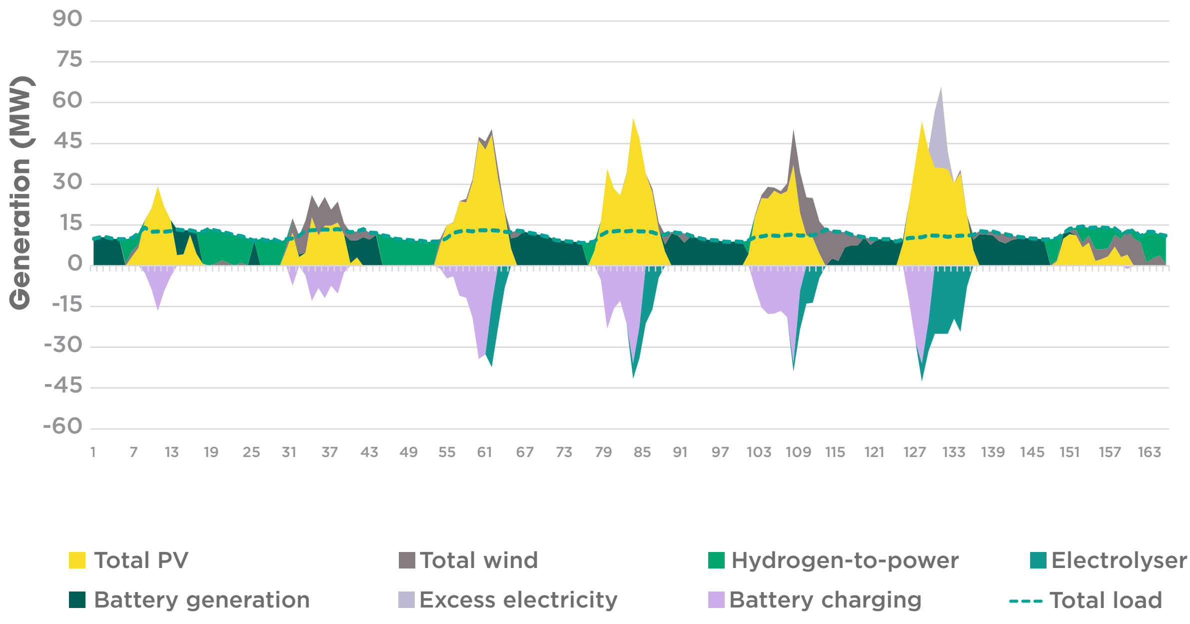
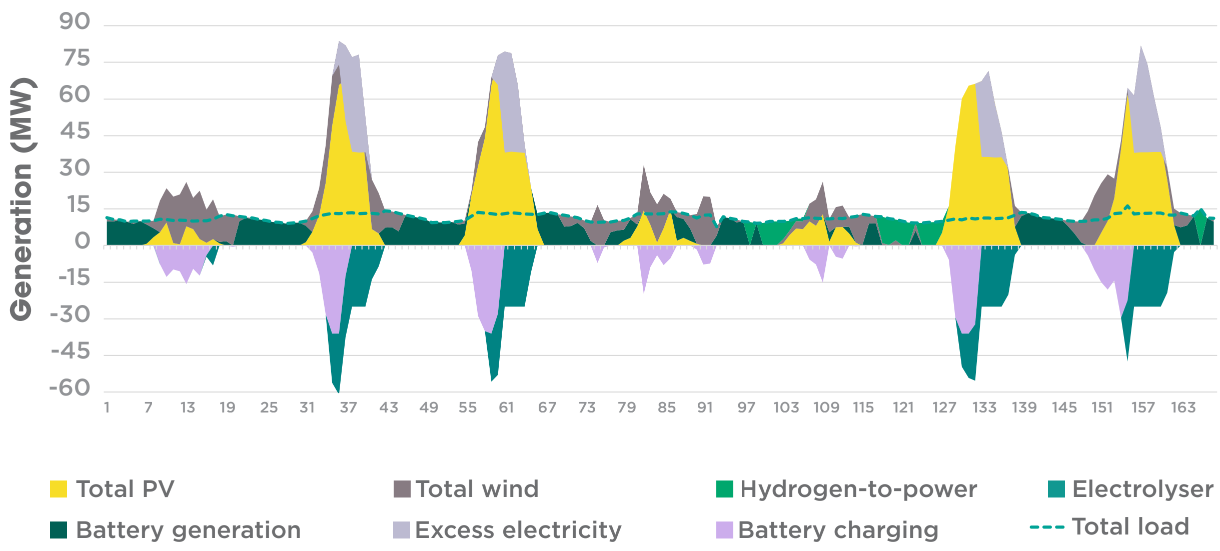


Figure 21: Maximum VRE week: 100% renewables with hydrogen



4.6. 100% RENEWABLE ENERGY WITH HYDROGEN AND EVs

The final scenario studied in the roadmap is 100% renewables with green hydrogen and EVs. This scenario was modelled to see if the proposed government target was achievable through green hydrogen production from renewables and by deploying EVs.

In order to model EVs into HOMER a deferrable load was used. The load had a scaled annual average of 26 250 kWh/day, with a storage capacity of 94 500 kWh and peak load of 8 325 kW. The EV load increased Palau's total demand even further, from 120 GWh/year in the previous scenario to 127 GWh/year. Moreover, this scenario showed excess electricity generation of 40 GWh/year. In order to support such a power system, the government would need an additional 86 MW of solar PV and 24 MW of wind turbines. The battery storage system required was estimated to be 182 MWh, while the converter system was estimated at 31 MW. For green hydrogen production, the tank was optimised at 25 000 kg, the electrolyser at 25 MW and the fuel cell at 50 MW.

The cost analysis confirms that having green hydrogen production together with full EV deployment allows the government to achieve the cheapest system, in comparison to the other 100% renewable energy scenarios. The LCOE for this combination was estimated at USD 0.15/kWh, while the initial capital cost was optimised at USD 189 million. Such a system would have a net present cost of USD 237 million and an operating cost of USD 3.42 million/year. One important thing to note here, is that EVs provide additional flexibility to the power system, which concurrently decreases the cost of electricity.

The average daily dispatch for this scenario can be seen in Figure 22. The figure shows how all the various components of the system, throughout the day, cover Palau's electricity load, with the central parts of the day showing some excess electricity. The figure also shows the EV smart charging (dark blue coloured area). Between 6 p.m. and 5 a.m., the load is covered using hydrogen-to-power, wind generation and stored electricity from the battery storage system. Throughout the day (6 a.m. to 5 p.m.) electricity generation from solar PV and wind is used to meet the demand. During peak hours, excess electricity is produced. Most of this excess electricity is then used by the electrolyser to produce green hydrogen, while the rest is stored in the batteries and used for charging the EVs.

Figure 23 shows the minimum VRE week for the 100% renewables scenario inclusive of EVs and green hydrogen. It shows how throughout the days of the week all the various components of the system are used to cover electricity demand. The figure clearly shows how the excess electricity from the renewables is used for producing green hydrogen, as well as being stored in the batteries and used for charging the EVs.

The maximum VRE week is illustrated in Figure 24. The figure shows a distinct difference from the minimum VRE week. It clearly shows higher VRE generation with higher excess electricity, which peaks at 44 MW. Furthermore, it also shows how the different components, such as solar PV, wind turbines, batteries and electrolyser, cover Palau's demand throughout the week. As mentioned earlier, with hydrogen, EVs provide further flexibility to the power system. This reduces the LCOE and makes such a system the most viable solution for the government to pursue in achieving its proposed target of 100% renewables by 2050.

Figure 22: Average daily dispatch: 100% renewable with hydrogen and EVs

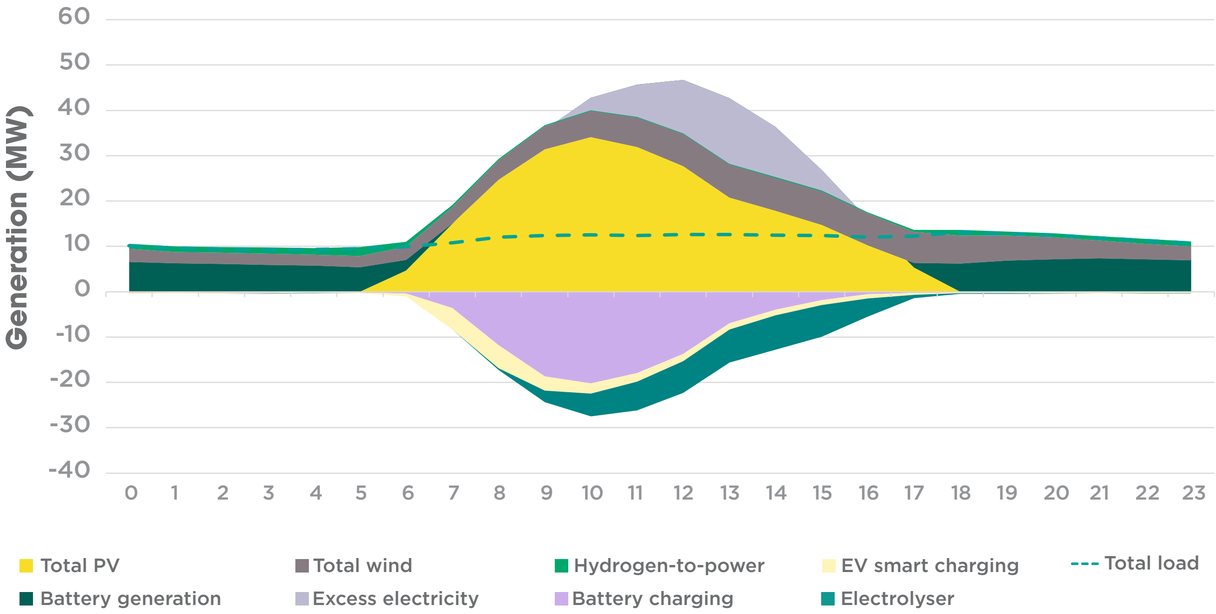


Figure 23: Minimum VRE week: 100% renewables with hydrogen and EVs

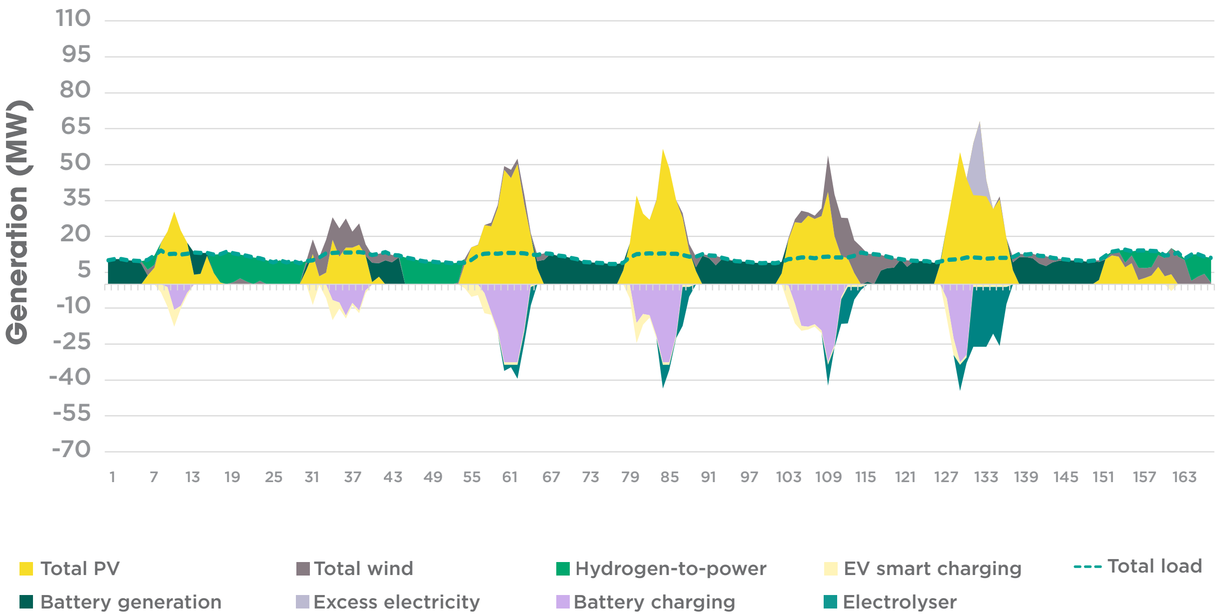
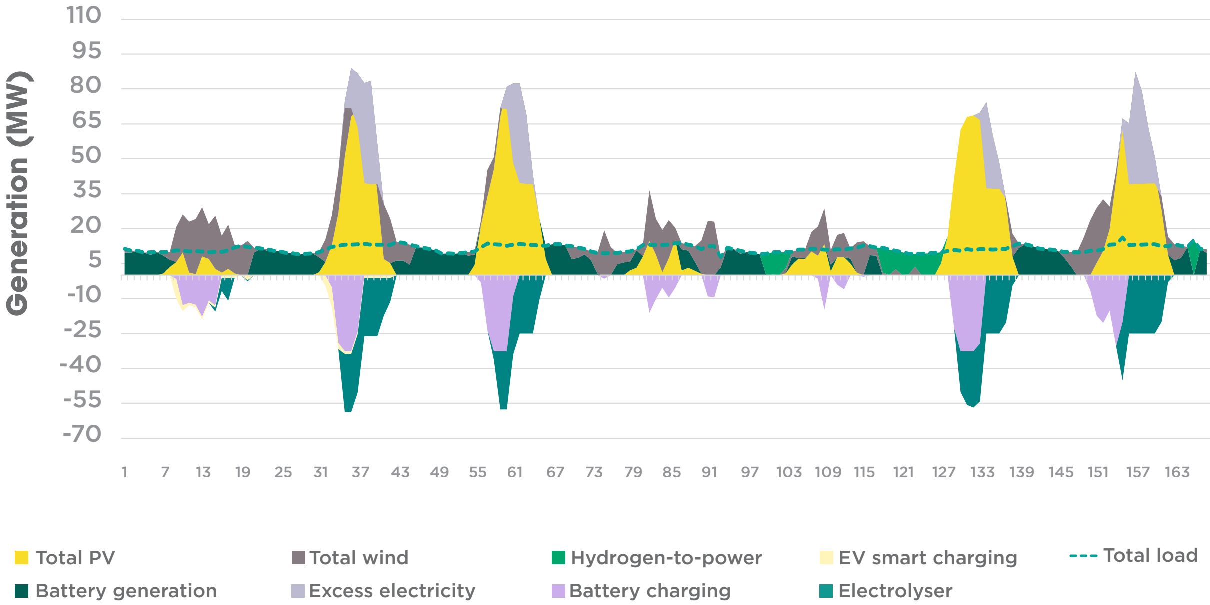


Figure 24: Maximum VRE week: 100% renewables with hydrogen and EVs



5. OUTER ISLANDS

As mentioned previously, the study focused mainly on Palau's two largest islands, namely Koror and Babeldaob. At the request of the PEA and PPUC, however, a HOMER optimisation was also performed for the outer islands of Peleliu, Angaur and Kayangel. This chapter covers the results of that analysis and discusses the possibility of deploying further renewable energy capacity on these islands as part of achieving the government's proposed 100% renewable energy by 2050 target.

5.1. PELELIU

Located southwest of Koror, Peleliu forms one of the 16 states of the Republic of Palau. The island has a population of approximately 700 people. As with Palau's other islands, Peleliu's energy production is dominated by fossil fuel generation. The island currently has a total of five diesel generators providing electricity to cover demand. The two largest generators (Yanmar 1 and 2) each have a capacity of 750 kW, with the Cummins and Wilson generators adding 275 kW of generation capacity each. Finally, the Hatz generator has a 168 kW capacity. The most used generator is the 275 kW Cummins generator, which is proportionate to the current peak load of 210 kW. Together with the high diesel generation capacity, Peleliu currently also has some solar PV generation, with a 168 kW PV plant.

Table 13 illustrates Peleliu's total power generation capacity.

In order to estimate how much additional renewable energy capacity would be required in order to achieve the government's 100% renewable energy target, a HOMER optimisation was performed for the island of Peleliu.

Similar to the main scenarios of this roadmap, a calibration model based on the current power system was first set up. From data provided by the PPUC, the electricity demand for the current power system was estimated at approximately 1.2 GWh/year. Furthermore, an additional electricity load was added to HOMER representing the water treatment facility currently on Peleliu for water desalination (increasing the total demand to 1.3 GWh/year). Once electricity demand had been inputted into the model, the generation capacity was included. A solar PV plant of 168 kW was also added, representing the current installed solar PV capacity. With regard to diesel generation, the study only considered the Cummins generator (currently under major overhaul) and the two Yanmar generators.

The results of the calibration model confirmed the dominance of diesel generation in Peleliu's power system. Yet, they also showed that some of the total demand was being covered by the solar PV plant, giving renewable energy a 17.7% share of the total. This is still far from the overall government target, however, and thus additional renewable energy capacity would be required. In terms of costs, the LCOE of the current power system was estimated at USD 0.25/kWh, with a net present cost of USD 4.59 million and an operating cost of USD 326 138/year.

The government of Palau has a planned, 206 kW solar PV project for Peleliu. Therefore, an additional scenario was developed on top of the calibration model to show how much the share of RE would increase once this new project has been completed. The planned project will also have a battery storage system of 787 kWh and a battery inverter system of 250 kW.

The results of the optimisation show that with an additional 206 kW of solar PV, Palau can increase the share of renewables to approximately 35.2%. The results also show that the cost of electricity would decrease to USD 0.166/kWh, with a net present cost of USD 3.05 million and an operating cost of USD 0.2 million/year. Deploying additional solar PV capacity would allow the government to reduce their costs and increase the share taken by renewables. The government would, however, still be far from the 100% target, and thus further renewable capacity and battery storage should be considered.

Table 13: Generation capacity of Peleliu

NAME	TYPE	CAPACITY (kW)
Yanmar 1	Diesel	750
Yanmar 2	Diesel	750
Cummins	Diesel	275
Hatz	Diesel	168
Wilson	Diesel	275
Solar PV Plant	Solar PV	168

Source: PPUC and PEA data (n.d.).

Results

Once the calibration model representing the current power system of Peleliu and the planned, 206 kW government project was prepared, additional RE capacity – in terms of solar PV generation – was added to the model to observe how much the share of renewable energy could be increased. The HOMER optimiser was used to size the ideal additional solar PV capacity needed. Furthermore, a battery storage system and a battery converter were also added, as they are crucial components required not only to increase the share of renewable energy, but also to provide flexibility to the power system. Both of these components were also sized using the optimiser. Table 14 shows the main results of the optimisation performed for Peleliu's optimal power system.

Table 14: Peleliu overall results

MODEL/SCENARIO	CURRENT POWER SYSTEM	CURRENT POWER SYSTEM + PELELIU PROJECT	OPTIMAL SYSTEM
Electricity demand (GWh/year)	1.3	1.3	1.3
Excess electricity (GWh/year)	0.04	0.07	0.45
Old PV (MW)	0.168	0.374	0.374
New PV (MW)	0	0	0.718
Wind (MW)	0	0	0
Hydrogen tank (tonnes)	0	0	0
Electrolyser (MW)	0	0	0
Fuel cell (MW)	0	0	0
Diesel (MW)	1.78	1.78	1.78
Storage (MWh)	0	0.788	3.3
Battery inverter/rectifier (MW)	0	0.250	0.44
Renewable energy share (%)	17.7	35.2	93.1
Levelised cost of electricity (USD/kWh)	0.25	0.166	0.09
Initial capital cost (USD millions)	0	0.219	1.28
Net present cost (USD millions)	4.59	3.05	1.72
Operating cost (USD million/year)	0.3	0.2	0.03

The results showed that with an additional 718 kW of solar PV capacity, a battery storage system of 3.3 MWh and a converter of 440 kW, Peleliu's power system could reach a 93.1% renewable energy share. This is a significant increase from the current 17.7%. Together with this, Peleliu would also require less diesel generation capacity, with just the Cummins generator being enough to support the system. The results show excess electricity generation of 0.45 GWh/year, with no unmet load and no capacity shortage.

In terms of economic costs, the optimisation for Peleliu's optimal system shows a significant decrease in the levelised cost of electricity, from the current power system's USD 0.25/kWh to USD 0.09/kWh. This shows that with current renewable energy technology costs decreasing, a power system widely dominated by renewables becomes more viable. The initial capital cost for this would be around USD 1.28 million. The net present and operating costs also show a significant decrease, compared to the current power system, at USD 1.72 million and USD 0.03 million/year, respectively.

The average daily dispatch for Peleliu's optimal power system can be seen in Figure 25. The figure illustrates how the various components would cover daily electricity demand for the island. From 6 p.m. to 5 a.m., most of the electricity load is covered by stored electricity in the batteries, while a smaller part is covered using the diesel generator. Throughout the day, however, the solar PV system is able to cover the entire load while also producing excess electricity, hitting a peak of 270 kW. The graph also shows how between 7 a.m. and 4 p.m. the excess electricity is being stored by the battery storage system (see purple coloured area).

Figure 26 shows the minimum VRE generation week for Peleliu's optimal power system. It clearly shows how the different technologies assist in meeting the total load. During some days of the week, the electricity generated from the solar panels and stored in the batteries is enough to cover the island's entire demand. On other days of the week when there is higher demand, however, the diesel generator is needed to partly cover the load. The figure also shows some excess electricity production on some days, with this then stored in the batteries.

The maximum VRE week for Peleliu can be seen in Figure 27. There is a clear difference between this and the minimum VRE week. Firstly, the graph shows a significant increase in solar PV generation and excess electricity. Secondly, the figure shows less diesel generation than in the minimum week, signifying that when peak VRE generation occurs, stored electricity in the batteries covers the electricity load that the PV cannot serve during night time hours. The maximum VRE week also shows the excess solar PV generation is proportionate to the battery charging.

Figure 25: Average daily dispatch: Peleliu optimal system

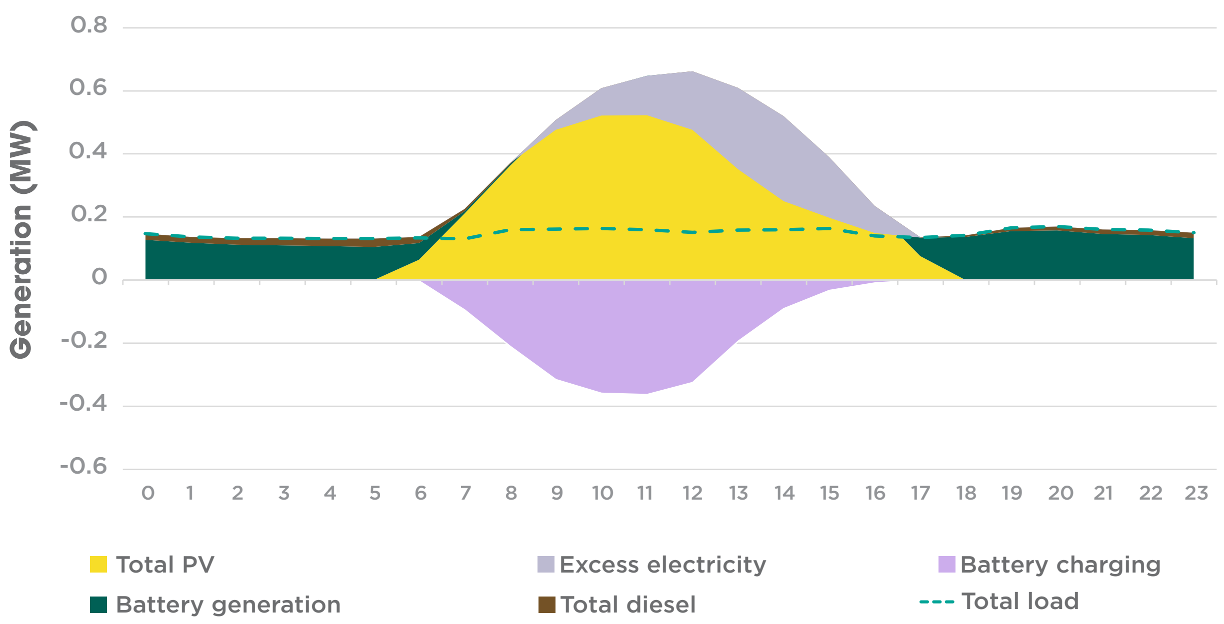


Figure 26: Minimum VRE week: Peleliu optimal system

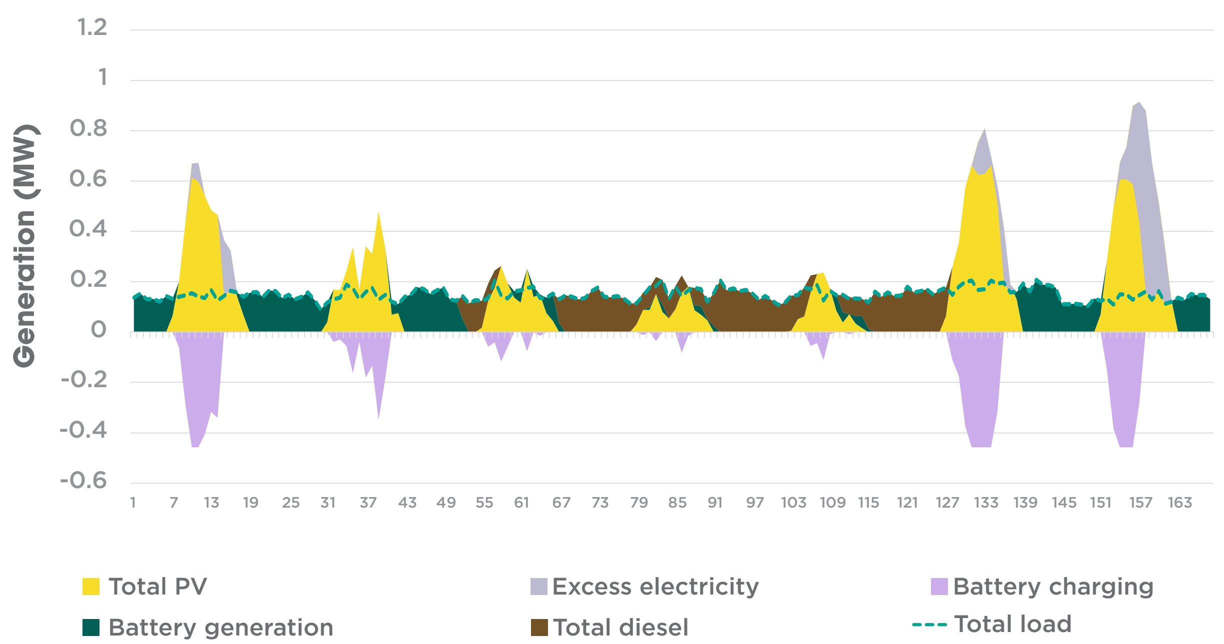
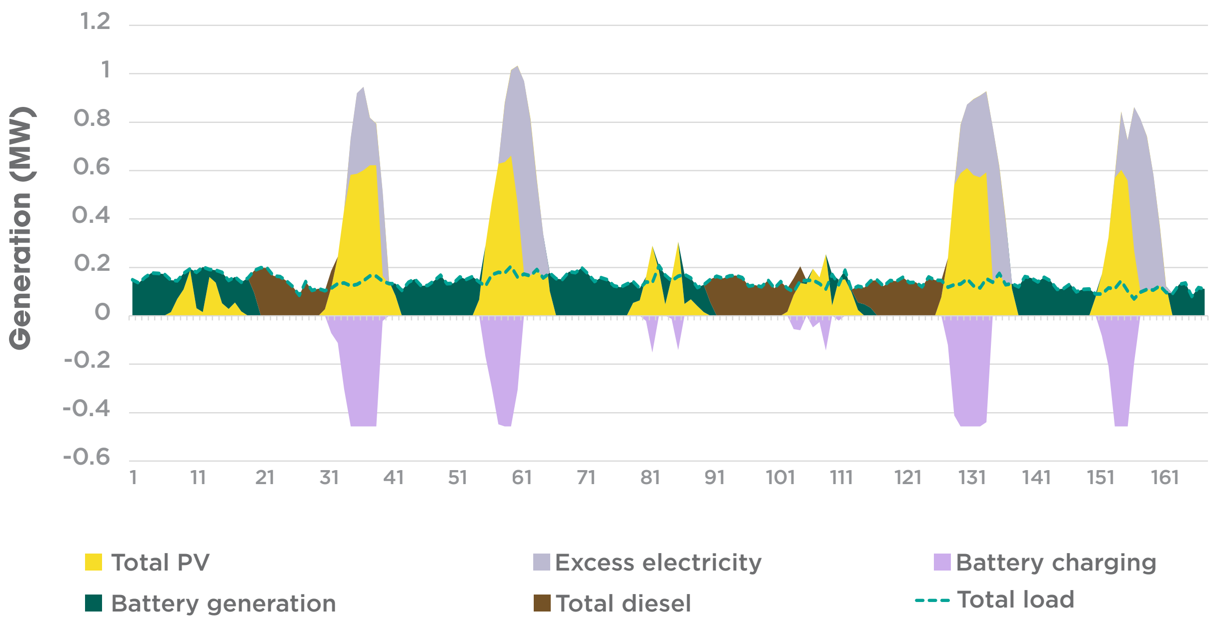


Figure 27: Maximum VRE week: Peleliu optimal system



5.2. ANGAUR

Located southwest of Peleliu and with a population of approximately 200, Angaur is another outer island of the Republic of Palau with a high dependence on fossil fuel for power generation. The island's generation capacity includes seven diesel generators, which provide enough electricity to cover total demand. The largest generator is the Cummins 5, with a 150 kW capacity, followed by the Cummins 4 and Perkins 2, with capacities of 120 kW each. All three of the aforementioned generators are currently being used as a standby, however. The main generators which are currently operational and providing electricity to Angaur are the four Hatz units, which have a total capacity of 112 kW. Together with the high level of diesel generation, Angaur presently also has some renewable generation, with a 100 kW solar PV system. The total generation capacity of the island of Angaur can be seen in Table 15.

Angaur's current generation capacity was added to HOMER in order to develop a calibration model. Based on data provided by the PPUC, the total electricity demand for the island's power system was estimated at 340 MWh/year.

The results of the calibration model show that Angaur is widely dependent on diesel generation, but that it also has a 19.1%. renewable energy share. This is still far from the proposed government target, however, and thus additional renewable energy capacity needs to be deployed. With regard to the economic costs, the current LCOE was estimated at approximately USD 0.30/kWh. The net present cost and operating cost of the current power system were estimated at USD 1.45 million and USD 0.1 million/year.

Table 15: Generation capacity of Angaur

NAME	TYPE	CAPACITY (kW)
Cummins 4	Diesel	120
Cummins 5	Diesel	150
Perkins 2	Diesel	120
Hatz units	Diesel	112
Solar PV plant	Solar PV	100

Source: PPUC and PEA data (n.d.).

Results

After calibrating the model to represent Angaur's current power system, additional renewable energy capacity was added in order to observe the change in overall share. The HOMER optimiser was used to estimate the ideal solar PV capacity, the battery storage system and the battery inverter.

Table 16 shows the overall results for Angaur's optimal system.

The results of the optimisation show that the Government of Palau can significantly increase Angaur's renewable energy share from the current 19.1% to more than 86%. This is a substantial increase and would bring Palau closer to its 100% target. For such a power system, the government would have to deploy an additional 260 kW of solar PV to the existing 100 kW. Furthermore, a battery storage system of 1 MWh with a battery inverter of 160 kW would also be required. The results also show excess electricity generation of 195 MWh/year.

Table 16: Angaur overall results

MODEL/SCENARIO	CURRENT POWER SYSTEM	OPTIMAL SYSTEM
Electricity demand (GWh/year)	0.34	0.34
Excess electricity (GWh/year)	0.079	0.195
Old PV (MW)	0.1	0.1
New PV (MW)	0	0.26
Wind (MW)	0	0
Hydrogen tank (tonnes)	0	0
Electrolyser (MW)	0	0
Fuel cell (MW)	0	0
Diesel (MW)	0.5	0.5
Storage (MWh)	0	1
Battery inverter/rectifier (MW)	0	0.16
Renewable energy share (%)	19.1	86.2
Levelised cost of electricity (USD/kWh)	0.30	0.13
Initial capital cost (USD million)	0	0.422
Net present cost (USD million)	1.45	0.6
Operating cost (USD million/year)	0.1	0.01

Regarding the economic costs, the results of the optimisation in HOMER show a significant decrease in the LCOE of Angaur's power system, from USD 0.30/kWh to USD 0.13/kWh. With an initial capital cost of USD 0.42 million, the net present cost and operating cost would also decrease to USD 0.6 million and USD 0.01 million/year, respectively.

Figure 28 illustrates the average daily dispatch for Angaur's optimal power system. The dispatch graph shows how the different components provide electricity to cover the total demand of the island. From 6 p.m. to 5 a.m., most of the load is covered by electricity stored in the batteries, while a small part is covered by the diesel generator. During the day, the solar PV panels generate excess electricity, which is then stored in the battery storage system for later use

The minimum VRE week for Angaur's optimal system can be seen in Figure 29. This shows how, on most days of the week, solar PV panels and battery-stored electricity covers the entire electricity load of the island. It should also be noted, however, that on some days of the week, during peak load, diesel generators are required to meet demand and also charge the batteries. The graph also shows how electricity from the solar panels and diesel generators is used for charging (the purple coloured areas).

Figure 30 shows the maximum VRE week for Angaur's optimal system. When compared to the minimum VRE week graph, several differences are noticeable. Firstly, more excess electricity generation is visible, signifying that indeed the figure represents the maximum VRE week. Secondly, the figure shows fewer days where the diesel generators are used for charging the batteries, with the solar PV and stored electricity in the batteries covering the majority of the demand during the week.

Figure 28: Average daily dispatch: Angaur optimal system

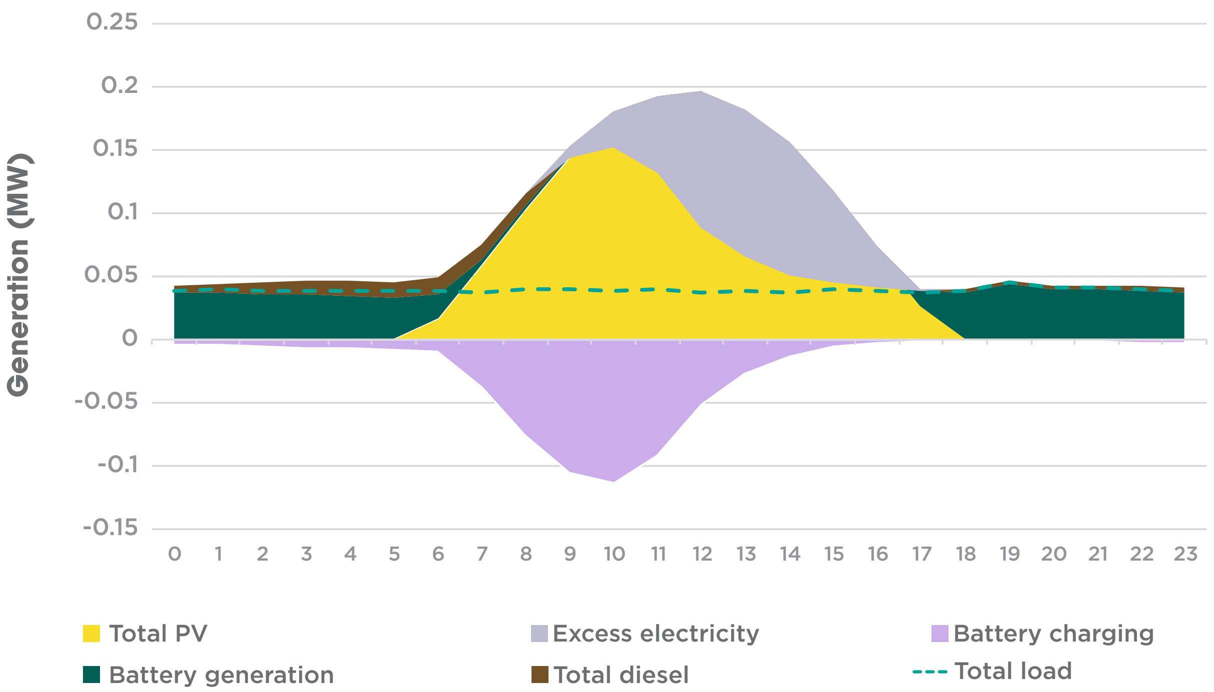


Figure 29: Minimum VRE week: Angaur optimal system

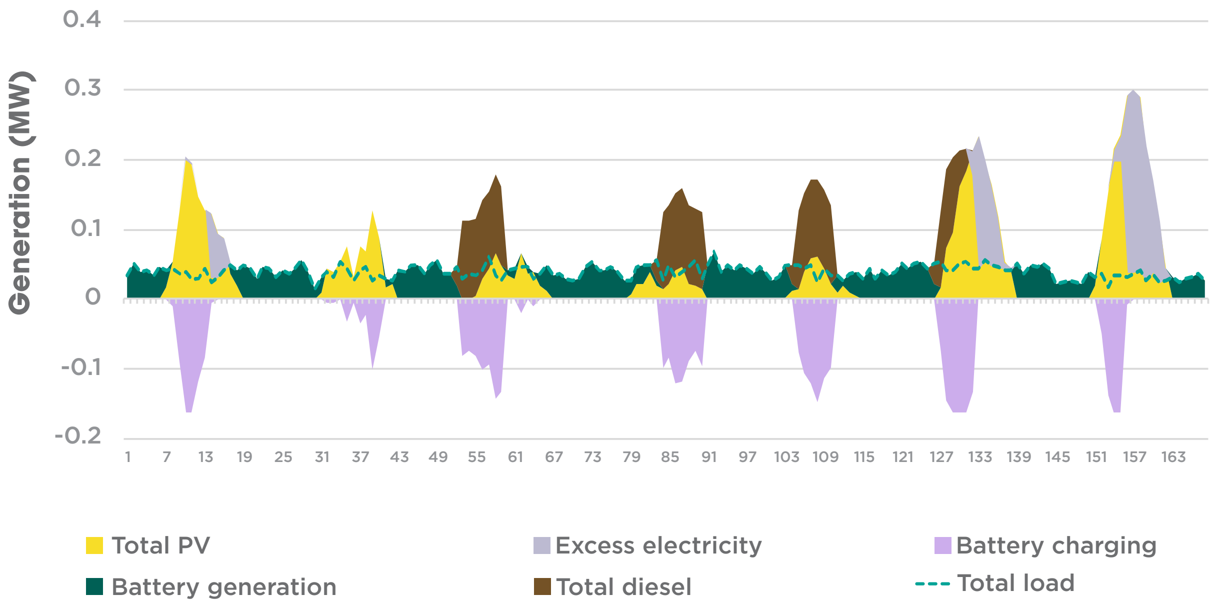
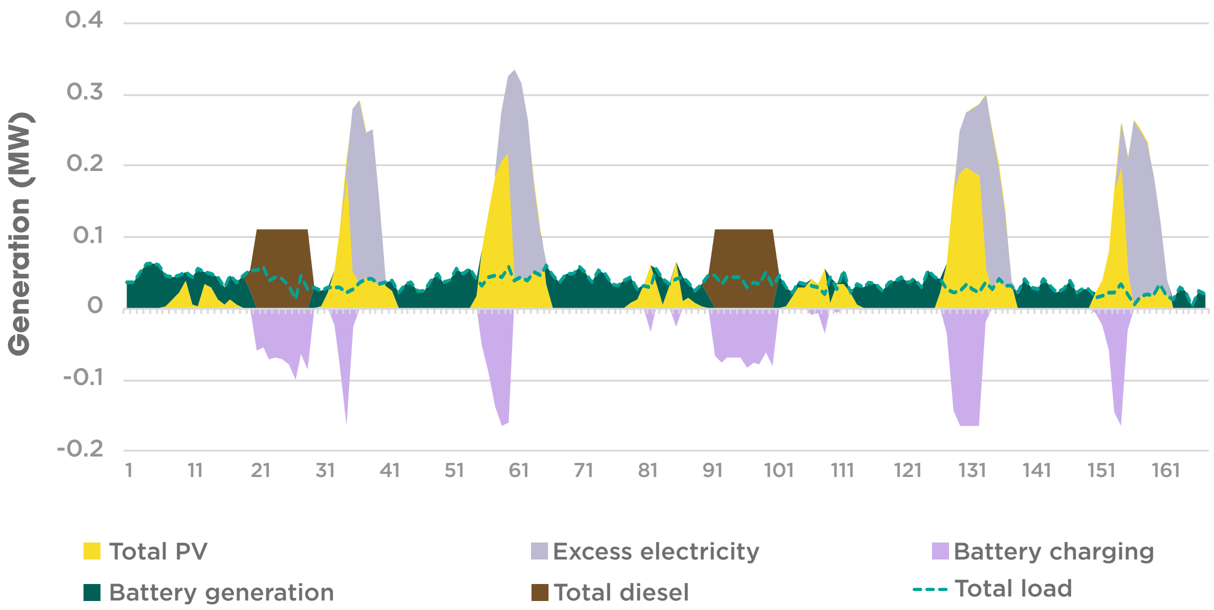


Figure 30: Maximum VRE week: Angaur optimal system



5.3. KAYANGEL

Located approximately 24 km north of Koror, Kayangel is the northernmost state of Palau and has a population of around 200 people. As on Palaus's other outer islands, Kayangel's power grid is heavily dependent on fossil fuel generation. The current power system includes a total of three diesel generators. The largest of these is Cummins 7, with a capacity of 120 kW, followed by Cummins 8, with 100 kW and Cummins 6, with 90 kW. Some renewable energy capacity is also present in Kayangel, with a 63 kW solar PV plant auto-operated with a battery storage system of 175 kWh.

Table 17 shows the total generation capacity of Kayangel's current power system.

Using data provided by the PPUC, a calibration model representing Kayangel's current power system was developed. Total electricity demand was estimated at approximately 154 MWh/year. For the model, the Cummins 6 (90 kW) generator was not considered, as it is currently undergoing maintenance.

The results for the current power system confirmed the heavy dependence on diesel generation. The results also show, however, a 36.1% renewable energy share in power generation. The current power system's LCOE was estimated at USD 0.20/kWh, with a net present cost of USD 0.44 million and an operating cost of USD 0.03 million/year.

Table 17: Generation capacity of Kayangel

NAME	TYPE	CAPACITY (kW)
Cummins 6	Diesel	90
Cummins 7	Diesel	120
Cummins 8	Diesel	100
Solar PV plant	Solar PV	63

Source: PPUC and PEA data (n.d.).

Results

Additional renewable energy capacity was added to Kayangel's calibration model in order to estimate how large a share could be achieved for renewable energy. The overall results for Kayangel's optimal power system can be seen in Table 18.

The results show that with an additional 121 kW of solar PV, the share taken by renewable energy could potentially increase from the current 36.1% to 89.1%. In order to achieve such a high share, however, deploying further battery storage capacity would be essential. The results estimate that the government would require an additional 336 kWh of batteries with an additional 7 MW of battery inverters. The excess electricity was estimated at 114 MWh/year.

When observing the economic costs of the optimisation, the LCOE significantly decreases from its current level of USD 0.20/kWh to USD 0.14/kWh. The net present cost and operating cost also decrease, to USD 0.3 million and USD 6 000/year respectively.

The average daily dispatch for Kayangel's optimal system can be seen in Figure 31. The graph shows how during the day, the solar PV panels are able to cover the entire electricity load, in addition to producing excess electricity which is subsequently stored in the batteries (see purple coloured area). Between 7 p.m. and 5 a.m., the majority of the demand is covered by stored electricity in the storage system, with some diesel generation also being used to cover some of the load.

Table 18: Kayangel, overall results

MODEL/SCENARIO	CURRENT POWER SYSTEM	OPTIMAL SYSTEM
Electricity demand (GWh/year)	0.154	0.154
Excess electricity (GWh/year)	0.02	0.114
Old PV (MW)	0.063	0.063
New PV (MW)	0	0.121
Wind (MW)	0	0
Hydrogen tank (tonnes)	0	0
Electrolyser (MW)	0	0
Fuel cell (MW)	0	0
Diesel (MW)	0.22	0.22
Storage (MWh)	0.175	0.511
Battery inverter/rectifier (MW)	0.078	0.085
Renewable energy share (%)	36.1	89.1
Levelised cost of electricity (USD/kWh)	0.20	0.14
Initial capital cost (USD millions)	0	0.206
Net present cost (USD millions)	0.44	0.3
Operating cost (USD million/year)	0.03	0.006

The minimum VRE week dispatch of Kayangel's optimal system can be seen in Figure 32. It shows that for two days of the week, diesel generators are used to charge the battery storage systems, while for the rest of the week, solar panels and electricity stored in the batteries are enough to cover the entire demand. The figure also shows how battery charging is proportionate to the excess electricity produced by the solar PV panels.

Figure 33 illustrates the maximum VRE week for Kayangel's optimal system. When compared to the previous graph, it is clear that the maximum VRE week generates far more excess electricity than the minimum VRE week. Furthermore, the figure also shows more days of the week where the diesel generators are needed to cover demand and also charge the batteries. For most days of the week, however, the solar PV and electricity stored in the batteries are enough to meet Kayangel's total electricity demand.

Figure 31: Average daily dispatch: Kayangel optimal system

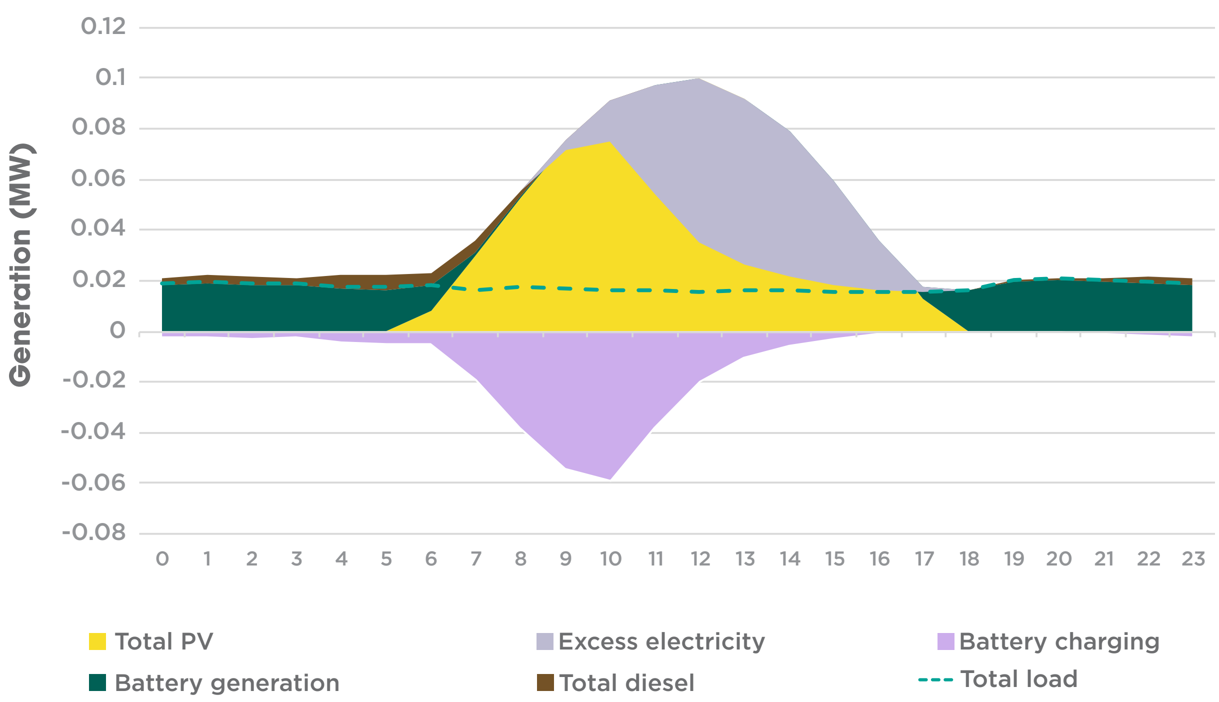


Figure 32: Minimum VRE week: Kayangel optimal system

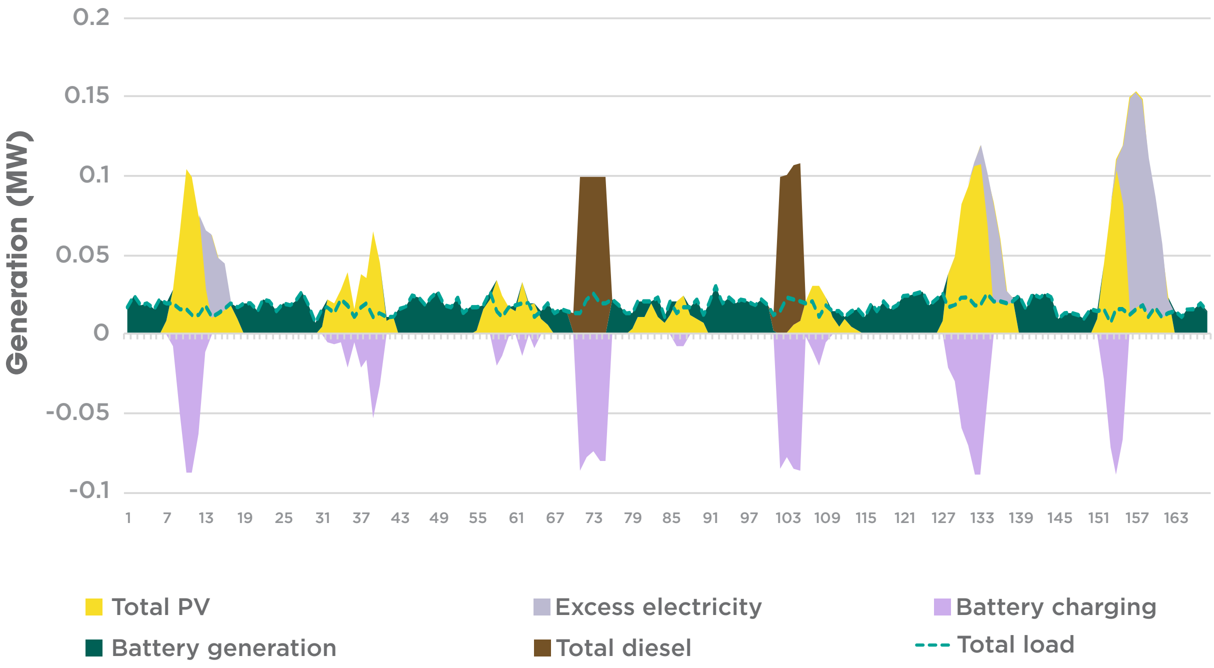
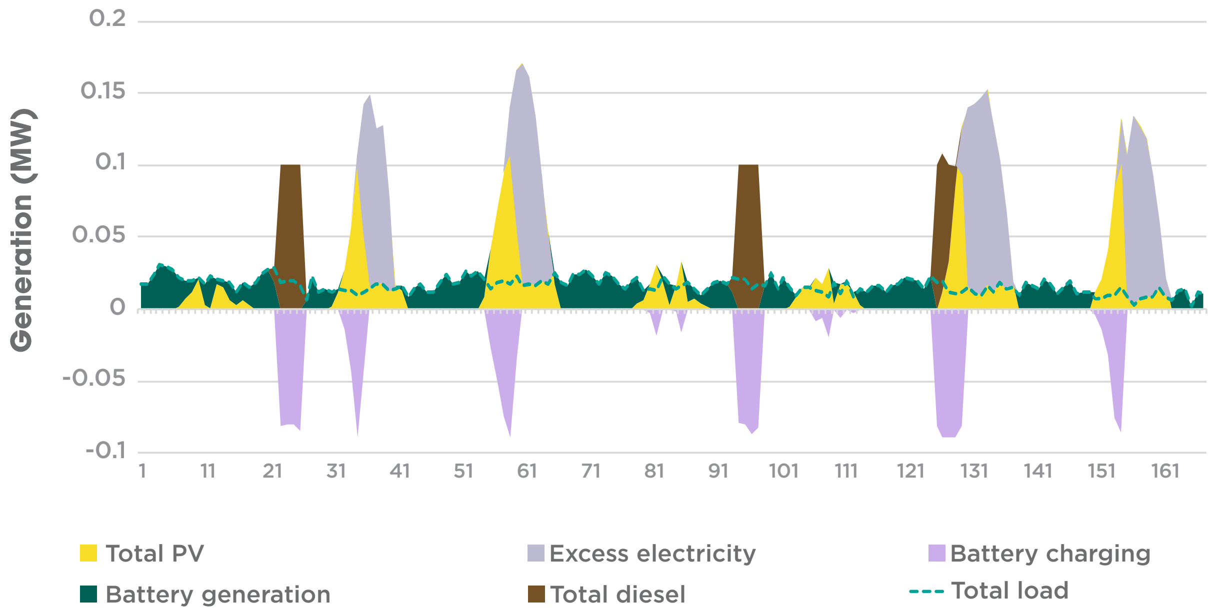


Figure 33: Maximum VRE week: Kayangel optimal system



6. RECOMMENDATIONS AND CONCLUSIONS

This roadmap concludes that deploying additional renewable energy capacity through a mixture of solar PV, wind turbines and green hydrogen production across Palau is both feasible and cost-effective.

The recommended path forward for the government of Palau is that it follows the optimal system scenario analysed in this study. Following this scenario would allow the current share of renewable energy to significantly increase, rising from 4.03% to 92.1%. The final 8% can then be reached by exploring green hydrogen production from solar PV and wind, as analysed in the 100% renewables, with hydrogen scenario. Full deployment of EVs can also be achieved cost-efficiently by 2050, also increasing the share of renewables in the transport sector.

The following chapter includes the roadmap's key recommendations and conclusions for study. It encompasses a series of policy recommendations which would be crucial to implement and take into consideration in order for the Republic of Palau to achieve its proposed target of 100% renewable energy in the power sector by 2050.

6.1. RECOMMENDATIONS

The results of the roadmap show that the government of Palau can achieve the proposed 100% renewable energy target by 2050 via increased deployment of renewable energy technologies. Installing additional solar PV and wind turbines, in addition to battery storage systems, will definitely aid the government in increasing the share of renewable energy to 92% in a cost effective manner. To achieve a fully decarbonised power system, flexible green hydrogen production and power generation using this is the most cost-effective next step to provide system adequacy.

As previously mentioned, the optimal power system scenario is the recommended next step on the path to 100% renewable energy for the Republic of Palau, with such a system requiring an initial capital cost of USD 126 million. When adding green hydrogen production and EVs to the power system, the initial capital cost for the government would increase to USD 189 million. The additional flexibility provided through green hydrogen and EVs would also aid in decreasing the LCOE to USD 0.15/kWh, making such a system viable and cost-effective. It could also assist in decarbonising road transport at the same time, with an additional upfront investment of USD 10 million – a figure estimated to be less than two years of fossil fuel costs for road transport.

A key recommendation for the government of Palau, in order for it to decrease costs and emissions due to high fossil fuel consumption and increase the share of renewables, is to **accelerate solar PV and battery storage deployment**. This should be the first step for the Republic of Palau in order for it to achieve a fully decarbonised power system. Recent advancements in technology, coupled with a constant decrease in costs for both solar PV and batteries, has made this into the most cost effective solution.

The results of the 100% renewables scenario with only solar PV also confirm that indeed Palau could achieve the 100% target with increased deployment of solar PV and storage. However, although this would decrease the operating cost of the current power system significantly, to USD 4.45 million/year, the results of the roadmap show the benefit of differentiating from PV-only, with some wind capacity being complementary to PV. Indeed, adding some wind capacity would help in decreasing the cost of electricity even further.

This then leads to the next recommendation for the government of Palau, which is to **ensure that identified locations for solar and wind farms are aligned with grid development**. This would be essential in order to ensure that all the power generated from these facilities can be delivered to cover Palau's electricity load. Identifying the land for those projects should be done keeping in mind where the current grid infrastructure is currently able to host solar PV or wind farms with minimal upgrades, and – especially for wind – where the resource is best. Keeping grid models up to date, such as those developed with support from the Japan International Co-operation Agency (JICA) in 2019 (JICA, 2019), is an important element in understanding the hosting capacity of the grid in different areas. It can also help identify sites that can be used for PV or wind deployment with or without upgrades and determine those sites' limitations.

The government should **link the 2025 goal with short term projects and continue with the same strategy (PV + storage and an exploration of wind)** until approximately 90% of electricity is produced from renewables. Furthermore, they should also **identify a suitable mix of grants, soft loans and independent power producers (IPPs), supported by climate finance**, to achieve the minimum weighted average cost of capital (WACC) to finance Palau's energy transition.

Another important recommendation that should be considered is to **ensure that the PPUC can get acquainted with the technologies** that are to be put in place in Palau before scaling-up. That includes EVs, solar PV, wind turbines, battery storage systems, electrolysers, hydrogen tanks and hydrogen fuel cells. In order to do this, it is of the utmost importance to **start small grant-funded pilot projects** on wind, as well as EVs for public services. This does not only apply to individual technologies, *e.g.* learning how to maintain wind turbines and how to secure them before a hurricane strikes. It also applies to learning to operate a combination of solar, wind, storage and – later in the transition – hydrogen electrolysers. It also means piloting, in the outer islands, for instance, the operation of the power system based on grid forming inverters connected to battery energy storage systems, rather than synchronous generators. Palau is in the unique position of having some of those systems in place in Kayangel and soon in Pelelieu. It can therefore learn to operate such systems on a smaller scale before moving to a larger system, like the one serving Koror and Babeldaob. There, additional issues, such as protection co-ordination and fault clearance, would have to be adjusted in the absence of synchronous machines operating and providing services like, for example, high short circuit currents to clear faults.

The roadmap has also analysed green hydrogen production in order to achieve the 100% target at lower cost than using just solar, wind and battery storage.

To model green hydrogen production, various technologies/components had to be considered, including hydrogen tanks, fuel cells and electrolysers. The latter should ideally be connected to large-scale water desalination plants so that they can provide additional fresh water to the Republic of Palau. For power generation from hydrogen, either fuel cells or modified diesel generators are expected to be available in the near future and can be used to provide dispatchable renewable energy generation, to complement solar and wind. As a later step, the government of Palau should **consider pilot projects for hydrogen boats**, once some local green hydrogen production can be made available beyond the power sector, and maintenance of such boats can be provided in Palau. This would be one of the few solutions possible to decarbonise speedboats, where direct electrification is still challenging. Battery technologies keep making progress, however, potentially enabling innovative speedboat designs that might be compatible with battery-electric drives.

Finally, by 2050, having done the necessary pilots, replaced all cars and road vehicles with battery EVs and decarbonised the last 8% of the power sector through locally-produced green hydrogen, Palau would be able to achieve full decarbonisation in its power and transport (road and marine) sectors.

6.2. CONCLUSIONS

The renewable energy Roadmap for the Republic of Palau charts the way forward to 2050 for the country's power and transport sectors. It looks in detail at the current power sector and provides a pathway for achieving a fully decarbonised, least-cost power system, with intermediate milestones. Additionally, it also encompasses renewable energy options for the marine and road transport sectors. The results of the analysis have shown that the government of Palau can successfully achieve its proposed target of 100% renewable energy in the power sector by 2050. Currently only accounting for 4%, this share is still distant from the government's proposed target. Hence, new, large-scale PV projects with battery storage systems are crucial to increase the share of generation taken by renewable energy even towards its 2025 target of 45%. The results of the roadmap show that Palau could continue with the same modular approach towards a power system with a renewable energy share of more than 92%. To achieve such a percentage, additional deployment of solar PV and battery storage systems is still the recommended approach, complemented by one or two wind farms.

The roadmap also analyses four specific options for reaching the 100% target for Palau's power sector. The most cost-efficient scenario observed was the scenario that involves green hydrogen production from solar PV and wind. In this scenario, we also consider the possibility of gradually replacing all the current stock of vehicles with EVs. The flexibility provided by EVs and green hydrogen production reduces the cost of electricity from the current USD 0.23/kWh to USD 0.15/kWh, in a scenario with 100% renewable power and road transport.

As a next step, IRENA will conduct a cost-benefit analysis of power sector mitigation options, with a particular emphasis on renewable energy technologies. This analysis will be conducted by comparing various mitigation alternatives to determine which technology options have the greatest potential for reducing GHG emissions while remaining economically viable, and thus provide information for NDC implementation plans. As a result of this analysis, national stakeholders will gain a better understanding of the requirements inherent in each technology and will be able to design efficient implementation pathways for achieving their NDC targets

In conclusion, it must also be noted that in order to achieve the proposed target and implement the scenarios analysed in this study, policies, regulations and financing are essential building blocks to enable the energy transition in Palau.

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ANNEX

Table 19 shows the current power system for all the main islands of the Republic of Palau, including the outer islands of Peleliu, Angaur and Kayangel.

Table 19: Overall current power system for Palau

MODEL/SCENARIO	CURRENT POWER SYSTEM KOROR/ BABELDAOB	CURRENT POWER SYSTEM PELELIU	CURRENT POWER SYSTEM ANGAUR	CURRENT POWER SYSTEM KAYANGEL
Electricity demand (GWh/year)	89	1.3	0.34	0.154
Excess electricity (GWh/year)	0	0.04	0.079	0.02
Current PV (MW)	2.5	0.168	0.1	0.063
New PV (MW)	0	0	0	0
Wind (MW)	0	0	0	0
Hydrogen tank (tonnes)	0	0	0	0
Electrolyser (MW)	0	0	0	0
Fuel cell (MW)	0	0	0	0
Diesel (MW)	20	1.78	0.5	0.22
Storage (MWh)	0	0	0	0.175
Battery inverter/ rectifier (MW)	0	0	0	0.078

Renewable energy share (%)	4.03	17.7	19.1	36.1
Levelised cost of electricity (USD/kWh)	0.23	0.25	0.3	0.2
Initial capital cost (USD millions)	0	0	0	0
Net present cost (USD millions)	294	4.59	1.45	0.44
Operating cost (USD million/year)	20.7	0.3	0.1	0.03

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