



CATALOGUE OF CASE STUDIES AND BEST PRACTICES

This catalogue strives to serve as a repository of case studies, aiming to facilitate knowledge transfer, identify best practices, and highlight significant developments related to renewable energy production and integration in non-interconnected island grids. The catalogue presents 11 case studies, touching both Overseas Countries and Territories (OCTs) and other island countries and regions, illustrating technological and administrative solutions on the way for a fully sustainable and secure energy supply.

RENEWABLE ENERGY INTEGRATION

Colophon

Title	Catalogue on renewable energy integration
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Author	Green Overseas Hands across oceans.. a collective approach towards sustainability www.green-overseas.org
Written by	Riccardo Novo (3E), Martina Cannata (3E)
Reviewed by	Green Overseas islands
Graphic design	Francesca Van Daele (Th!nk E)

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Acronyms

BESS	Battery Energy Storage System
BoL	Beginning of Life
DSO	Distribution System Operator
PPA	Power Purchase Agreement
IPP	Independent Power Producer
PV	Photovoltaic
REC	Renewable Energy Community
RES	Renewable Energy Sources
TSO	Transmission System Operator



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INTRODUCTION

Overview

This catalogue serves as a repository of case studies, aiming to facilitate knowledge transfer, identify best practices, and highlight significant developments related to renewable energy production and integration in non-interconnected island grids. The catalogue presents 11 case studies, touching both Overseas Countries and Territories (OCTs) and other island countries and regions, which illustrate technological and administrative solutions on the way for a fully sustainable and secure energy supply. The structure of the catalogue is organised into four main pillars:

RENEWABLE POWER GENERATION

The selected case studies highlight good practices of power generation from Renewable Energy Sources (RES), namely solar, wind and hydro, focusing on planning challenges as well as on the need to increase the flexibility of existing assets to favour the penetration of non-dispatchable, intermittent renewable power from solar photovoltaics (PV) and wind farms).

BATTERY STORAGE & GRID STABILITY

Case studies present interventions on power networks to ensure grid stability and provide grid services through the deployment and operation of Battery Energy Storage Systems (BESS).

HYBRID POWER PLANTS

Case studies refer to those solutions where power generation from a certain source is integrated with power generation from other sources and/or energy storage systems.

ELECTRICITY SYSTEM REGULATION

The case studies present the laws and regulations implemented in different territorial contexts to promote the generation of electricity by Independent Power Producers (IPPs) and small producers/prosumers, while ensuring the overall stability of the electricity grid.

Case studies

The case studies are presented with a short description of the electricity system in which they were developed, a description of the case study itself, an analysis of the impacts and, finally, a list of lessons learned for potential replication. For each case study, the sources used and other material for further reading are also provided.

RENEWABLE POWER GENERATION

- Wind energy exploitation in **Curaçao**.
- Solar and hydroelectric generation in **Tahiti**.

BATTERY STORAGE & GRID STABILITY

- Grid services through BESS in **New Caledonia**.
- BESS and synchronous condensers to support large wind power integration in the **Faroe Islands**.
- Grid stability and load shifting through BESS in **Tonga**.

HYBRID POWER PLANTS

- **Bonaire**'s Hybrid Hub.
- Hybrid PV-BESS power plant in **Sint Eustatius**.
- Hybrid PV-Wind-BESS power plant in **Saba**.
- Wind generation and hydro storage in **El Hierro**.

ELECTRICITY SYSTEM REGULATION

- The grid code of the Autonomous Region of **Madeira**.
- Feed-in tariffs and Power Purchase Agreements in **Bermuda**.

Key challenges

The reduction of fossil fuel-based power generation through the increase of renewable energy production can bring considerable advantages for islands, including greater energy self-sufficiency, lower dependence on oil market fluctuations, and generally lower costs associated to the electricity supply.

Nevertheless, OCTs and other islands that strive to increase renewable power generation also face significant challenges related to their environmental and socio-economic conditions, as well as technical challenges related to the operation of non-interconnected electricity systems with high shares of non-dispatchable generation. Below are some of the key challenges that islands can encounter in the decarbonisation of their electricity supply:



Variability

Island power systems are typically characterised by highly variable loads. Because of the low load aggregation, generally low industrial production (with a few exceptions, e.g. New Caledonia), and seasonal tourist fluxes, the power load is very variable both on a daily and monthly basis. In such a framework, diesel and fuel oil power plants offer a flexible way of producing electricity, with capability of quickly adapting the generation to match the power demand. Non-dispatchable RES, such as wind and especially solar energy, are instead intermittent and hard to predict. Matching a variable power demand with varying resources is a key challenge, which on islands result to be even more challenging than on the mainland.



Reliability

Island grids are often characterised by a higher number and duration of power interruptions and outages than interconnected networks. These power interruptions are related to grid instabilities, as well as to the vulnerability to extreme weather conditions (e.g., storms, high temperatures causing fires). The connection of intermittent power generation from renewables in such grids, and especially the targeted shutdown of portions of conventional power plants, risks to further reduce the reliability of the electricity supply, if not suitably mitigated. A sometimes-necessary last resource mitigation is the curtailment of renewable energy, i.e. a reduction of the renewable power plants output to maintain grid stability. However, when applied at large scales, curtailment can put at risk the economic sustainability of renewable power generation.



Controllability

In many medium- and large-sized territorial contexts, the transition to renewable power generation entails a decentralisation of the energy system, with multiple plants at different locations supplying electricity to the grid. Whereas utility-scale plants are normally equipped with technology for control by grid operators, small-scale renewable systems – such as rooftop-mounted PV – are scarcely controllable, potentially causing instability issues to the power grid.



Spatial planning

Islands host unique environmental and landscape heritage, which must be appropriately protected. On top of that, land use on islands often is a delicate matter, because of the limited space available and sometimes high population density. Allocating the right areas for the installation of renewable energy and storage systems can be particularly challenging, with wind farms raising concerns for their visual impact and potential effects on birds and bats, and ground-mounted solar PV and BESS requiring significant land use.



Financial resources

Although characterised by lower operating costs, the installation of renewable energy systems, as well as the deployment of storage facilities, requires typically higher investments than fossil fuels power plants. The energy transition therefore requires large capital expenditures, which are then typically offset by the avoided fossil fuel consumption. Securing large capital investments for power generation in small countries and territories is often not straightforward.

Possible solutions

As demonstrated by the remarkable case studies in this catalogue, technical and administrative solutions exist to successfully tackle the energy transition of islands. Although specific solutions should be sought according to the local characteristics, it is possible to identify some general approaches that demonstrated to date to be beneficial in different territorial contexts.

Alternative means of providing grid services

Storage facilities can increase the operational flexibility of the grid and improve the security and quality of the electrical supply. BESS equipped with grid-forming inverters, which operate as voltage source for the grid, have attracted particular interest in recent years. Hybrid plants have the potential to enable switching off the conventional power plants, reducing operating costs and maximising the value of renewable energy. In addition, also facilities with rotating masses such as synchronous condensers or hydro plants (with or without pumping) can contribute to the system stability and enable a reduction in the use of fossil fuel power plants.

Hybrid power plants

Hybrid power plants consist of electricity generation from a certain source integrated with generation from other sources and/or energy storage. They result to be particularly effective on island power systems since they enable an optimised use of the available connection capacity, an optimal use of the available land, and generally higher flexibility and/or lower variability. Hybrid power plants with storage have the potential to provide energy time-shift services, to avoid curtailment of RES generation, or even support the grid with peak shaving and energy arbitrage.

Electricity system regulation and grid codes

Developing an advanced regulatory framework of electricity-supply services (production, storage, transmission/distribution, retail) is a key step to ensure fair competition and protect customers. Regulation, which can be effectively developed through the establishment of an independent regulatory authority, should include provisions for the distributed generation of electricity and for a fair remuneration of prosumers injecting electricity into the grid. A clear and stable regulatory framework can also be a key factor to attract private investments in larger renewable generation and storage plants. In addition, the elaboration of grid connection codes has the potential to provide system operators with certainty on the minimum characteristics that generation equipment from third parties should have.

Mobilising private and institutional capital

There are various options available for the construction and operation of renewable energy and storage assets. Investments by local utilities, whether public or private, can be facilitated by the development of a clear regulatory framework, which is often required for a straightforward access to finance. If the local utility companies are too small to make the investments or do not have sufficient experience in developing and operating those assets, third-party capital from Independent Power Producers (IPPs) may be attracted. In such a case, a suitable regulatory framework for the establishment of Power Purchase Agreements (PPAs), i.e. long-term contracts between the IPP and the system operator, is required to reduce risks and attract investors, together with eventual government guarantees. Finally, for those countries and territories benefiting from sources of subsidies to mitigate the final price of electricity, the progressive transitioning of those subsidies to capital investments can represent a potential win-win situation both for the supporters and the territories and countries themselves.

RENEWABLE POWER GENERATION

Wind energy exploitation

CURAÇÃO

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island(s)	Curaçao
Country / Territory	Curaçao
Area	444 km ²
Population (2023)	155 826
Annual electricity consumption (2023)	635 GWh/year
Generation plants	<ul style="list-style-type: none"> • Thermal (diesel): 135 MW • Wind: 70 MW (2025) • Distributed solar PV: 17 MW
Energy storage	BESS (under development): 25 MW / 45 MWh
RES penetration (2023)	~30% (expected 50% in 2025)



Curaçao is a constituent island country within the Kingdom of the Netherlands. It has an area of 444 km² and a population of about 156 000 inhabitants.

Curaçao's electricity landscape has undergone deep changes in recent years. From a mere 9% renewable generation share in 2012, the island has reached 20% in 2023. Through the installation of a new wind farm and a BESS facility, Curaçao is foreseen to cover at least half of its electricity demand with renewables by 2025 and up to 70% by 2027.

As of now, Curaçao still relies for the majority of its electricity on the thermal generation of the oil-fired combustion engines at the Dokweg site and on the diesel-operated one at the Isla oil refinery, both operated by Aquaelectra. On the renewables front, Curaçao's facilities count on four wind farms of overall 69.8 MW (described in the case study below) and about 20 MW of registered distributed PV, including rooftop solar on schools and industrial buildings. Non registered distributed PV is estimated to be between 5 and 10 MW.



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CASE STUDY

Main Contributors	NuCapital, Aspiravi, Aquallectra Utility
Type of installation	Wind farms
Installed capacity	47.4 MW (32.245 MW + 15.0 MW)
Commissioning date	1993 / 2012 / 2017
Share of total electricity production	19%

Curaçao has 4 wind farms: the Tera Korá I and Tera Korá II, the Playa Kanoa, and the NuKoraal Tabak. All of them are located on the eastern coast of Curaçao, to take advantage of the strong winds touching the island from the Eastern sector.

The first turbines of the Tera Korá wind farm were built in 1993 and totalled an installed capacity of only 3 MW, through 12x250 kW turbines. The plant underwent a complete repowering in 2012 to reach an installed capacity of 15.0 MW (Tera Korá I) thanks to the installation of 5x 3 MW Vestas V90/3000 turbines. Finally, an extension of the wind farm with 17.3 MW was realized in 2017 (Tera Korá II) with 5x 3.45 MW Vestas V117/3450 turbines installed. Important from an energy system point of view, the Tera Korá Wind Farm regularly operates as a baseload power generator, with very high capacity and power penetration factors.

The Playa Kanoa wind farm was built in 2012, at the same time of the Tera Korá I, and also consists of 5x 3 MW Vestas V90/3000 turbines. With a total installed capacity of 15 MW, the Playa Kanoa wind farm generates around 36 GWh/year, enough to power around 10 000 homes and supply roughly 7% of Curaçao's average electricity demand.

The most recent wind farm is the Koraal Tabak. It was commissioned in 2024, and it consists of 5x 4.5 MW Vestas V150/4.5MW. The total installed capacity amounts to 22.5 MW.

The investment in the wind farms was made by NuCapital and Aspiravi. A PPA regulates the remuneration of the electricity by the offtaker, Aquallectra, which is the DSO and utility company of Curaçao.

IMPACT

The Tera Korá I, Tera Korá II and Playa Kanoa wind farms, which total an installed capacity of 47 MW, yield an annual output of around 150 – 160 GWh combined, corresponding to 20 to 30% of the island's annual electricity demand. Since 2017, the start year of operation of the full-scale plants, an estimated 100 000 metric t of CO₂/year have been avoided thanks to wind energy. The commissioning in 2024 of the new Koraal Tabak wind farm will ensure the achievement of even higher renewable penetration targets (expected: 50%).

Additionally, thanks to the steady, high-speed winds of which the farm's site benefits all year-round, the Tera Korá plant shows outstanding baseload capabilities. Operating with a high capacity factor, it occasionally supplies more than 40% of the demand during low-load periods, making it one of the few baseload-capable wind farms globally.

Thanks to the progressive reduction of dependence on fuel, Aqualectra is also in the process of structurally lowering its electricity tariffs, aiming at a reduction between 10%-20% in the period 2012-2027.



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LESSONS LEARNT

- ✓ Depending on the local availability of the resource, the exploitation of wind energy on islands can bring significant contributions to the power mix.
- ✓ Wind energy can provide quite stable baseload production for significant periods of time. This brings benefits in terms of the efficient functioning of the thermal power plants.
- ✓ Spatial planning can lead to the identification of suitable areas for wind farms installation on islands, respecting safety and annoyance buffers from houses and other infrastructure. Landscape modifications of coastal areas can be acceptable when careful planning is put into place.
- ✓ PPA schemes can be beneficial for OCTs/OTs and their utility companies. On the one hand, they ensure the attraction of private capitals, as well as of companies with experience in the construction and operation of RES power plants. On the other hand, PPAs also ensure a stable cost of electricity for a long time frame, reducing market oscillations and favouring the reduction of electricity tariffs.



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RENEWABLE POWER GENERATION

Solar and hydroelectric generation

TAHITI

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island(s)	Tahiti
Country / Territory	French Polynesia
Area	1 044 km ²
Population (2024)	281 800
Annual electricity production (2024)	501 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Thermal (diesel): 121 MW + 12 MW • Hydropower: 48 MW • Solar PV: 58 MW
Energy storage	Centralised BESS: 15 MW / 10 MWh
RES penetration (2024)	45.7%

In December 2024, 30 MW PV plants were connected (ground-mounted or agri PV), with a storage of 29.6 MW / 44.6 MWh. These are not accounted for in the table and charts above.



Tahiti is the largest island of French Polynesia, an overseas collectivity of France. It has an area of 1 044 km² and a population of about 281 800 inhabitants.

Over the past 10 years, Tahiti's electricity mix has been dominated by fossil fuels and hydro generation, with a constant trend towards higher RES penetration. The RES penetration on the island has been oscillating between 34% and 46% over this period, mainly due to the large interannual variability of water availability in the hydropower plants. In the last years, hydro power has been supplemented by solar PV plants, mostly installed on rooftops, which now contribute to the final mix with about 11% of the total production. More details on these energy sources are given in the case study below.

Tahiti's thermal generation includes 8 diesel units located in the Punaruu Valley industrial zone of Punaauia and implemented by a diesel combustion turbine, with a total capacity of about 133 MW. These are responsible for maintaining the baseload, providing ancillary services and complementing the renewable generation. Additionally, Tahiti added a large-scale 15 MW /10 MWh lithium-ion battery equipped with a virtual synchronous generator system, named Putu Uira (which means 'energy reserve'). Equipped with a "grid-forming" inverter, this electrochemical storage system helps maintaining the frequency and voltage of the system when renewables are fluctuating, critical for high renewable penetration.



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CASE STUDY

Main Contributors	Marama Nui (EDT Engie, Government of French Polynesia), Private developers (solar), TEP
Type of installation	<ul style="list-style-type: none"> • Hydropower plants • Solar PV plants
Installed capacity (2024)	<ul style="list-style-type: none"> • Hydropower plants: 48 MW • Solar PV plants: 58 MW
Commissioning date	<ul style="list-style-type: none"> • Hydropower plants: from 1981 until 2018 • Solar PV plants: from 2009 to 2024
Share of total electricity production	<ul style="list-style-type: none"> • Hydropower plants: 25% to 40%, depending on precipitations • Solar PV plants: 11% in 2024



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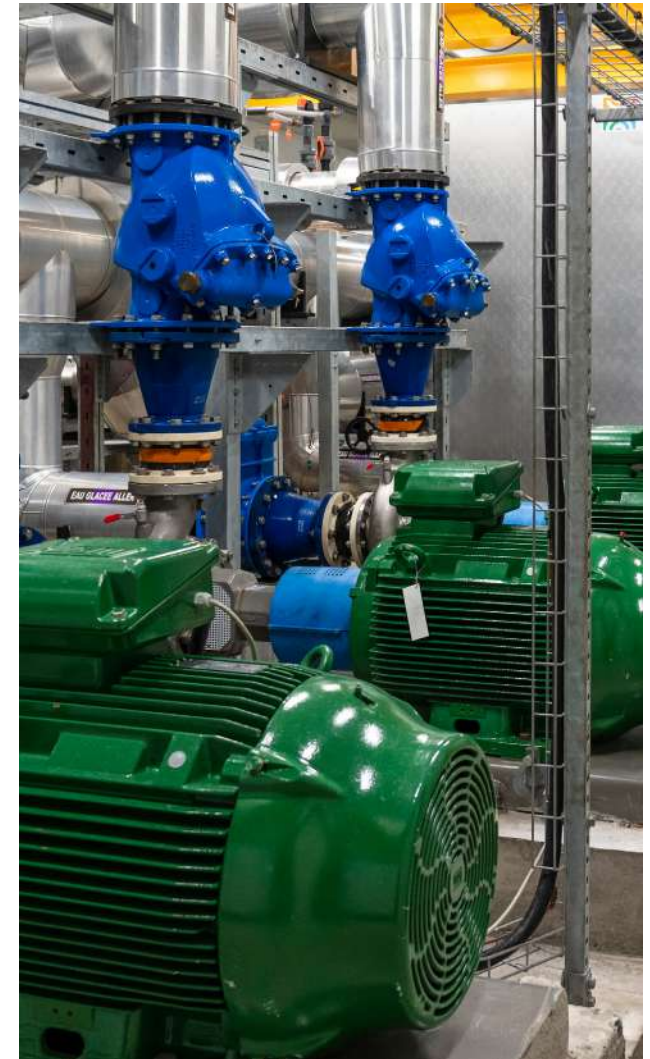
The island of Tahiti counts with 18 hydroelectric power plants spread over five valleys (Papeno'o, Fa'atauti'a, Vaihiria, Tita'aviri and Vaite). These sites benefit from abundant rainfall and great head heights, which constitute ideal conditions for stable and reliable electricity production throughout the year. With an installed capacity of 48 MW, such facilities can cover up to 40% of Tahiti's electricity demand (with variability year by year depending on the amount of rainfall precipitation). More in detail:

- Papenoo – Total installed capacity: 28.8 MW; Construction/expansion date: 1991, 2018.
- The largest valley in all French Polynesia, with its 91 km², it has the largest watershed on the island and a 370 m of gross head. Papenoo represents 61% of Tahiti's hydro generation. The installation counts 4 power plants with a total of 9 turbines (5 Francis turbines, including 4 of 4 000 kW; 3 Pelton turbines of 4 000 kW; 1 very low head turbine of 230 kW), and 5 dams of overall 1 308 000 m³.
- Faatautia – Total installed capacity: 7.6 MW; Commissioning date: 1988.
- With 750 m of gross head and 11 m of annual rainfall, Faatautia represents 16% of Tahiti's hydro generation. It counts 4 power plants with 6 turbines (3 Pelton turbines, 2 of which of 3 000 kW, and 3 Francis turbines, of which 1 of 1 000 kW) and 4 dams of overall 725 000 m³.
- Vaihiria – Total installed capacity: 4.8 MW; Commissioning date: 1985.
- Vaihiria represents 10% of Tahiti's hydro generation. It counts 3 power plants with 3 Francis turbines of 2 000 kW, 1 500 kW and 1 300 kW, 2 dams of 90 000 m³ and 1 natural lake of 2 000 000 m³.
- Tita'aviri – Total installed capacity: 4 MW; Commissioning date: 1993.
- Responsible for 8% of Tahiti's hydro generation, Tita'aviri counts 3 power plants with 3 Francis turbines, 2 of 2 200 kW and 1 of 1 250 kW, and 2 dams of overall 590 000 m³.
- Vaite – Total installed capacity: 2.4 MW; Year of commissioning: from 1981 to 1987.
- The first hydro installation of Tahiti, representing now 5% of the island's hydro generation, Vaite counts 2 power plants with 2 Francis turbines, 1 of which is 1 800 kW, and 2 dams of 470 000 m³.

Alongside hydro generation, solar power has been playing a growing role in Tahiti's electricity landscape since 2009. A significant increase in the PV generation fleet was achieved thanks to the implementation of several local financial measures and incentives and the reduction in the cost of PV equipment worldwide. In addition, in 2021, with the aim of encouraging the establishment of large-scale production sites at a competitive price, the government launched a call for projects for PV installations with storage in Tahiti. The cumulative capacity of the four projects selected in 2022 is 30.4 MWp, all commissioned in December 2024:

- The Manasolar solar farm, developed by the Moux Group, equipped with 10.8 MWp/17 MWh BESS.
- The two solar farms Fare Meri and Fare Gouwe, developed by Ito Nui, respectively equipped with 6 MWp/9.7 MWh and 3 MWp/4.9 MWh BESS.
- The Mahana O'hiupe solar farm, developed by the Siu Group, equipped with 10.7 MWp/13 MWh BESS.

In addition to the the newly installed solar PV plants in exclusive production mentioned above, most of the installations are used for self-production (with injection of the surplus into the grid), installed on rooftops and connected to the distribution network. Some solar PV installations can also be found in isolated sites and are devoted only to self-consumption, i.e. not connected to the grid (less than 200 kW).



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IMPACT

The combination of hydro and solar generation, paired with BESS, is allowing Tahiti to decarbonise its electricity sector at a remarkable pace. The flexibility of hydro power generation makes space to solar energy during sunny days, shifting hydro generation to the night mostly. Whereas historically most of the hydro power plants were running most of the time, some of them are now operated in complementarity with solar production. These two technologies, when jointly operated, showcase complementary generation profiles. The Putu Uira centralised BESS system compensates for the variability and unpredictability of photovoltaic energy production, aided by thermal production facilities.

In 2022, hydro power in Tahiti has hit a record of 193 GWh, enabled by high rainfall and grid modernization, covering about 38% of total electricity consumption. Combined with battery storage (Putu Uira lithium-ion storage) and integrated with solar generation, it has allowed EDT to reduce diesel generators use and, at times, operate the island at up to 100% renewable electricity for short periods. The hydro power plants on Tahiti contribute on average to 55 000 t of avoided CO₂ emission annually, leaving between 15 and 18 million liters of diesel unburnt.

From an economic perspective, hydroelectric power generation is generally characterised by large initial capital expenditures (CapEx) and low operational expenditures (OpEx). Its convenience is particularly evident in locations where fossil fuel supply is very expensive, such as the islands in the Pacific region.

At the time of writing, Marama Nui is working – together with the other actors, primarily the Transmission System Operator (TSO) TEP – to upgrade some of the hydro power plants with pumping equipment, in order to further increase the flexibility of hydroelectric facilities and enable the exploitation of dams for storing the excess electricity generated by solar PV. The first pumped hydro power plant will be the Titaaviri plant, with an initial pumping power of 2 MW. The learnings from this pilot project will be used for replication at larger scale on the same and other sites.

LESSONS LEARNT

- ✓ Reliability and flexibility: hydro power can provide 24/7 dispatchable power, mitigating the risk of blackouts. However, its generation yield is dependent on rainfall conditions, and large interannual variations should be expected.
- ✓ Hydro projects, despite a high initial CapEx and a complex civil design, yield low operating costs and can ensure long-term energy security. If compatible with the orographic and environmental conditions of the island, hydro power has to be prioritised.
- ✓ The combination of hydro + solar + BESS is able to cover a part of the island electrical demand with a virtually uninterrupted green electricity supply. The upgrade of hydro power plants with pumping equipment and lower storage – or the use since the beginning of a reversible hydro plant – can provide a storage facility with relatively low investment cost and environmental cost, and play a strategic role in the decarbonisation of the energy system.



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BATTERY STORAGE & GRID STABILITY

Grid services through BESS

NEW CALEDONIA

RENEWABLE POWER GENERATION

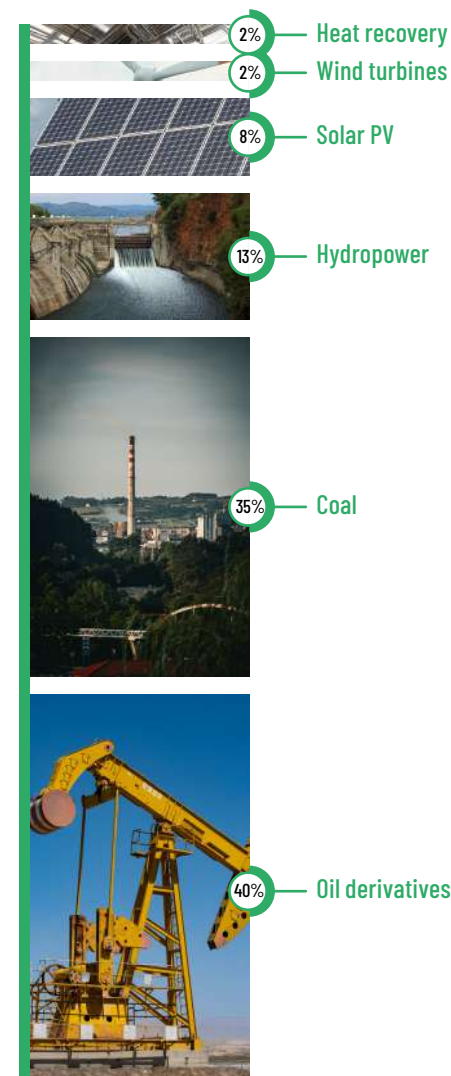
BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island(s)	Grande Terre, Loyalty Islands (Lifou, Maré, Tiga, Ouvéa, Mouli et Faiava), Bélep Islands (Art and Pott islands), Isle of Pines.
Country / Territory	New Caledonia
Area	18 575 km ²
Population (2024)	292 639
Annual electricity consumption (2023)	2.93 TWh/year (of which 795 GWh/year for the public distribution, 2130 GWh/year for the heavy industry)
Generation plants and contribution to the electricity mix (2023)	<ul style="list-style-type: none"> • Oil derivatives (diesel, fuel-oil and kerosene): 40.2% • Coal: 34.7% • Hydro: 12.3% • Solar: 8.3% • Wind: 2.3% • Heat recovery: 2.1%
Energy storage	<ul style="list-style-type: none"> • Hélio Boulouparis hybrid BESS (10 MW / 10MWh) • Wi-Hâche Ouatom hybrid BESS (7 MW / 7 MWh) • Tadine hybrid BESS (0.8 MW / 3.2 MWh) • Lifou Island Microgrid (5.4 MW / 5 MWh) • Comagna BESS (0.9 MW / 3.6 MWh) • Nepoui BESS (25MW / 38 MWh)
RES penetration in the electricity mix (2023)	24%



New Caledonia has a particularly articulated electricity system, due to its large dimensions and to the presence of energy-intensive productive activities. There are several institutional and private electricity producers, who inject electricity into the transmission grid operated by ENERCAL (TSO) or provide it directly to the industrial plants. The distribution grid is operated by two separate Distribution System Operators (DSOs) – ENERCAL in 25 municipalities, EEC in 8 municipalities. The electricity mix of New Caledonia is heavily dominated by fossil fuel generation (70%) through 11 production units. Of these, 8 are facilities mainly operated by ENERCAL for the supply of the public grid and the other 3 power stations supplying the heavy industry (especially metallurgic sector specialised in nickel refining).

The thermal power plants are mostly supplied with coal and oil derivatives (kerosene, diesel). The main plants are:

- The Ducos TAC I and II has been in operation since 1973 on Grande Terre and operates burning kerosene. It has a capacity of 43 MW and injects electricity in the transmission grid.
- The Jacques Lékawé de Népoui fuel oil power plant is in operation since 1993 on Grande Terre and was conceived as the main generation facility of the archipelago, role that it maintained until 2008. It has a capacity of 55 MW.
- The Karadeniz Powership “Orhan Bey” is a floating oil-fired power ship with an installed capacity of 202 MW, located near the SLN nickel smelter in Doniambo (Nouméa). It was installed in 2022 to temporarily supply the nickel refinery, replacing older diesel plants and reducing CO₂ emissions.
- The Koniambo plant is equipped with a coal-fired steam-turbine with an installed capacity of 270 MW. It serves the KNS nickel refinery, located in the North Province.
- The SLN Doniambo Plant burns heavy fuel oil (and diesel) and makes part of the SLN refinery infrastructure. It constitutes the main power supply for SLN and the local grid.

The other thermal generation facilities include two emergency groups on Grande Terre, a biomass/diesel hybrid plant, a micro hydro/thermal hybrid plant, and other independent units located on the smaller islands.

Besides the traditional fossil fuel-based generation, New Caledonia counts with several small scale non-reversible hydro-electric plants and several hybrid (solar + BESS) facilities which are able to cover about 24% of the country's electricity demand.

The main hydroelectric power plants are:

- The Yaté Dam power station has been in operation since 1959. With a capacity of 68 MW, it achieves about 307 GWh of annual generation.
- The Neaoua hydroelectric plant has been supplying the public grid since 1982. With a capacity of 7.2 MW it achieved an annual output of 30 GWh.
- La Tôû is a small hydroelectric station, with a capacity of 2.2 MW and an annual output of 7 GWh.
- On top of that, there are a number of mini- and micro-hydro power plants, mostly in Grande Terre.

The main solar PV plants are:

- The Népoui solar plant has been operational since 2023 and was intended to replace the gradual phase-out of the Jacques Iékawé de Népoui thermal plant. It has an installed capacity of 30 MW and an annual output of 49 GWh.
- The Hélio Boulouparis solar park has a capacity of 16 MW and is paired with a 10 MW / 10 MWh lithium-ion battery storage system utilised to stabilise the grid by time-shifting solar generation.
- The Wi Hâche Ouatom hybrid plant, which was the first solar + storage facility in New Caledonia and the Pacific. Operational since 2019, it has installed PV capacity of 10 MW paired with a 7 MW / 7 MWh Lithium-ion BESS.
- Agrivoltaic sites: Ouaco (5 MW), Focola (1.7 MW), and Kwita Wije (6 MW / 3 MWh storage).

In addition to this, ENERCAL – at the time of writing – is developing the Poya Solar PV Park with a capacity of 30 MW ground-mounted PV. The plant is expected to be operational by 2025. Multiple other smaller PV facilities are also present on the different islands.

New Caledonia also hosts a number of small- and medium-sized wind farms. Eight of them are located in Grande Terre, and one in Lifou. The largest wind farm is the Eole Yaté of 20.4 MW, operated by Total Energies.

New Caledonia has been a frontrunner in the deployment of energy storage, with the first hybrid (solar + BESS) facility in the Pacific set in operation in 2019 (Wi Hâche Ouatom). Several operational solar plants are already paired with BESS systems to fully harness the solar potential and provide grid services. Especially, ENERCAL operates three electrochemical storage systems: Tadine, Comagna, and Népoui; this last one is described in detail as follows as a case study.

Other projects of energy intensive electrochemical storage (batteries), as well as a pumped-hydro storage facility, are currently under development to further support the decarbonisation of the New Caledonian energy system.



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CASE STUDY

Name of the plant	Népoui BESS
Main Contributors	ENERCAL (TSO), RTE (Réseau de Transport d'Electricité), Enercal Energies Nouvelles
Type of installation	Standalone BESS
Installed capacity	25 MW / 38 MWh
Commissioning year	2023

The Népoui storage system consists of a 25 MW / 38 MWh lithium-ion battery supporting the transmission grid of Grande Terre. Its main role is to provide ancillary services to the electricity system, namely frequency and voltage regulation. The plant took over some of the key services traditionally provided by fossil fuel power plants, and in particular, it reduces the required amount of operating reserve from other plants. Beside increasing the reliability of the grid, the Népoui BESS enabled to switch off an increasing number of fossil fuel generation systems during periods of large RES production, thus reducing the overall operating costs of the electricity system. At the moment the system operates in parallel with the Népoui power plant, showing its efficiency in facing the perturbations introduced by the oscillation of renewables.

The storage system spans across 18 containers hosting the electrochemical cells, the inverters and transformers, and is operated by an Energy Management System (EMS) controlled by ENERCAL. The system is built on a plot of about 1 ha located above the Jacques Lékawé power plant. It is therefore naturally located at a key node of the Grande Terre transmission grid, halfway between the north and the south parts of the island. The BESS plant will support the progressive phase-out of the Jacques Lékawé de Népoui power plant.

It should be noted that the Grande Terre transmission network is branched due to the shape of the island and cannot be looped. For this reason, if part of the transmission infrastructure becomes unavailable, the electrical system operates in separate networks. In such situations, it has been found that the responsiveness of the BESS is likely to cause the thermal machines connected to the same network to lose synchronism. The flexibility of BESS technology has made it possible to add a second operating mode that is used in a separate network. In this mode, the power response to the network frequency is adjusted so as not to disrupt the rotating machines on the network.



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IMPACT

Grande Terre's electricity grid faces critical challenges related to frequency and voltage stability due to the small inertia of the system, the limited generation flexibility and the increasing share of renewables, typical of island grids.

The Népoui BESS system was built to increase reliability via additional system flexibility, and has already had significant positive impacts. With its fast response, the system has enabled a reduction in under and over frequency events, supported voltage profiles stability and improved overall grid stability. This results in a more reliable service, as well as in lower operational costs thanks to lower number of transient operations required to fossil fuel power plants.

Systems such as the Népoui storage facility are fundamental in island grids to:

- Provide ancillary services, essential for a reliable functioning of the grid, which cannot or can only be partially provided by solar and wind generation systems.
- Ensure that an increase in RES production also leads to the shutdown of fossil fuel power plants, reducing the number of conventional power stations which are kept on to provide the required operating reserve.



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LESSONS LEARNT

- ✓ Although the hybridisation of solar and wind power systems on islands remains essential to ensure peak shaving and energy arbitrage services, medium- and large-scale storage facilities to be operated and controlled by TSOs and DSOs are needed to ensure a reliable power supply.
- ✓ With the latest technologies available, large storage facilities can be deployed on relatively limited areas. The use of modular containers suitable for outdoor installation allows for efficient transport and quick installation.
- ✓ To the extent possible, storage facilities providing grid services such as frequency and voltage regulation should be ideally placed near existing fossil fuel power stations. This enables a reduction of the interconnection costs and favours the switching off (or even phase out) of the conventional power plants.



Picture of Lifou, New Caledonia by Raelle Cameron via Unsplash

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BATTERY STORAGE & GRID STABILITY

**BESS and synchronous condensers to
support large wind power integration**

FAROE ISLANDS

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island(s)	Faroe Islands
Country / Territory	Faroe Islands
Area	1 393 km ²
Population (2024)	55 000
Annual electricity production (2023)	480 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Thermal: <ul style="list-style-type: none"> » Fuel oil: 91.1 MW » Diesel: 23.7 MW • Wind: 68.0 MW • Hydro: 39.7 MW • Biogas: 1.5 MW • Solar: 0.3 MW • Tidal: 1.2 MW (pilot project)
Energy storage	<p>Main Grid:</p> <ul style="list-style-type: none"> • BESS 2.3 MW / 0.7 MWh • BESS 12 MW / 12.5 MWh <p>Hybrid power system of Suðuroy:</p> <ul style="list-style-type: none"> • BESS 6.25 MW / 7.45 MWh (Wind Farm: 6.3 MW)
RES penetration (2024)	56.6%



The Faroe Islands are an archipelago in the North Atlantic Ocean and an autonomous territory of the Kingdom of Denmark. The islands have a population of approx. 54 900 inhabitants and an area of 1 393 km². The annual electricity production amounts to 480.4 GWh/ year (2024).

The Faroe Islands' ambition to reach 100% RES penetration by 2030 is reflected in their current electricity mix and recent, ongoing and planned projects. As of 2024, renewables covered 56.6% of Faroe's electricity demand, especially thanks to hydro and wind power.

The archipelago consists of 7 electrically isolated power systems. The main grid covers numerous major islands and is responsible for 90% of the overall electricity production. Sev is the vertically integrated public company operating the grids and generating most of the electricity. There are in the archipelago also some IPPs who generate electricity through wind power plants.



Image courtesy of Sev

Thermal generation is provided by multiple power plants supplied with fuel oil or diesel and operated by Sev. The most significant power plants are the Sund Power Station (102 MW installed capacity) which predominantly burns fuel oil in the main grid and the Vágur Diesel Power Plant (13.4 MW installed capacity) in the smaller Suðuroy grid.

Hydroelectric power in the Faroe Islands has been exploited since 1921, and since then it has grown to the current total installed capacity of 43 MW. The largest installation, Eiði Hydroelectric, has an installed capacity of 21.7 MW, while the remaining ones, spread across the whole archipelago, have capacities between 3 and 6 MW. The annual hydro production is strictly related to the amount of precipitation. None of the plants currently is equipped with pumped storage, but Sev is working to upgrade some of the existing hydro plants.

Wind power represents a crucial and fast-growing source of generation for the Faroe Islands. Thanks to the Gellingarklettur wind farm (25.2 MW), Flatnahagi windfarm (18MW) and the Húsahagi wind farm (11.7 MW) and other smaller scale installations (about 6 MW each), in 2024 the islands reached 68 MW of installed capacity.

Finally, the Faroe utility Sev, in collaboration with the Swedish marine energy company Minesto, has deployed a tidal pilot project (1.2 MW) to investigate the exploitation of tidal energy and scale up the technology. On top of this, ongoing studies are also exploring the possibility of building a pumped-hydro storage installation.

Both on the main grid and on Suðuroy grid, hydro plants – although not reversible – are largely used to stabilise the grid by managing fluctuations in frequency and voltage. Nevertheless, because of the fast-growing wind installations, Sev has been significantly investing in BESS and synchronous condensers to ensure the grid stability also with high non-dispatchable renewable energy penetration.

CASE STUDY

Main Contributors	Sev, Enercon, Hitachi Energy, ABB
Type of installation	Standalone BESS, Hybrid BESS-wind plants, Synchronous condensers
Installed capacity	<p>Battery Energy Storage Systems:</p> <ul style="list-style-type: none"> • Installation at Sund Diesel Power Station (main grid) - BESS: 12 MW / 12.5 MWh. • Installation at Húsahagi 12 MW wind farm (main grid) - BESS: 2.3 MW / 0.7 MWh. • Installation at 6.3 MW Porkeri Wind Farm (Suðuroy grid) - BESS: 6.25 MW/ 7.5 MWh. <p>Synchronous condensers:</p> <ul style="list-style-type: none"> • Installation at Sund Diesel Power Station - Reactive power: 15 MVA • Installation on Borðoy (main grid) - Reactive power: 8MVA • Installation at 6.3 MW Porkeri Wind Farm (Suðuroy grid) - Reactive power: 8 MVA
Commissioning date	2016 to 2024

In order to host an increasingly large wind capacity and fully exploit the wind potential of the islands by limiting curtailment, while still maintaining the stability of the grid, Sev has in parallel deployed several BESS and synchronous condensers to match the wind generation.

Synchronous condensers are electrical machines able to provide some key services which are generally provided by conventional power plants, and which can't generally be provided by renewable energy plants. More specifically, they are rotating electrical machines that provide essential services to the power system, such as inertia, fault current level and reactive power for voltage regulation. They help to keep the grid stable as both loads and renewable energy production change. Synchronous condensers, which mostly mimic the behaviour of conventional plants with rotating masses, are a cost-effective and reliable way to maintain power quality.

Such systems were strategically placed at some of the most important generation facilities on the islands (two wind farms and the main thermal plant) to support ramps and enable an efficient operation of the thermal plants, as well as at key nodes of the islands power systems. This strategy has so far proved very effective in securing green electricity to the islands' grids, improving power quality and overall system reliability and resilience, with a consequent reduction in supply disruptions.

The full list of plants is as follows:

- **BESS + synchronous condenser at Sund Diesel Power Station (main grid):**
 - » BESS: 12 MW / 12.5 MWh.
 - » Synchronous condenser: 15 MVA.

The technology includes an inverter-based Li ion battery integrated with a synchronous condenser to provide grid-forming capability and inertia support.

- **BESS + synchronous condenser at 6.3 MW Porkeri Wind Farm (Suðuroy grid):**
 - » BESS: 6.25 MW/ 7.5 MWh.
 - » Synchronous condenser: 8 MVA.

The power capacity of the battery system is comparable to the power potential of the entire Porkeri wind farm itself, making it essentially a back-up system capable of supplying electricity should the wind suddenly fade away or become inaccessible.

- **BESS at 12 MW Húsahagi wind farm (main grid) - BESS: 2.3 MW / 0.7 MWh.** This was the first system of its kind commissioned in the archipelago already back in 2016. The technology includes a Saft Intensium Max Li-ion battery integrated with a power conversion and power control system.
- **Synchronous condenser on Borðoy (main grid) - Reactive power: 8MVA.** This is the most recent plant, installed in 2024.

IMPACT

BESS with grid-forming inverters and synchronous condensers have proved extremely effective and beneficial in limiting wind curtailment in the Faroe Islands and providing ancillary services to the grid. In particular:

- On the island of Suðuroy, the interventions boosted wind utilization and reduced wind curtailment from 30–40% to under 10%. In 2024, the grid of Suðuroy achieved 110 days of 100% renewable electricity, over half the time supplied solely by hydro and wind supported by the BESS and a synchronous condenser.
- The synchronous condensers installed within the systems have enhanced grid stability by providing ancillary services, such as voltage and frequency control, smoothed rapid wind fluctuations and reduced the use of diesel generators by providing black-start services.
- The BESS and synchronous condensers have enabled Sev to start the decommissioning of some of the diesel and fuel oil generation units, thus decreasing the costs related to their maintenance and readiness to enter into operation.



Image courtesy of Sev

LESSONS LEARNT

- ✓ Synchronous condensers and BESS, equipped with grid-forming inverters that provide virtual inertia, black start, and frequency support, are essential to maintain the stability of islands' grids with high penetration of renewables.
- ✓ BESS with grid-forming inverters have the capability of providing all the necessary services to power grids, including black-start capabilities. Nevertheless, for larger installations and complex power systems, synchronous condensers represent a cost-effective solution to be integrated with BESS. Synchronous condensers represent an alternative source of spinning inertia, supplying and absorbing reactive power, delivering voltage support, and dynamic voltage regulation.



Picture of Gjógv, Faroe Islands by Annie Spratt via Unsplash

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BATTERY STORAGE & GRID STABILITY

Grid stability and load shifting through BESS

TONGA

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island(s)	Tonga Archipelago
Country / Territory	Kingdom of Tonga
Area	748 km ²
Population (2024)	104 175
Annual electricity consumption (2022-23)	70 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Diesel power plants: 18 MW • Utility-scale solar PV plants: 13.2 MW • Distributed solar PV plants: 2 MW • Wind: 1.3 MW
Energy storage	Two BESS installations: <ul style="list-style-type: none"> • 9.3 MW / 5.3 MWh • 7.2 MW / 23.9 MWh
RES penetration in the electricity mix (2024)	19%



The Kingdom of Tonga is an island country in Polynesia. The archipelago counts 45 inhabited islands with 104 175 inhabitants and has a total area of 748 km².

In order to achieve the government's objective of 70% electrical self-sufficiency through renewables by 2030, Tonga has implemented some key projects to increase the country's reliance on renewable energy (especially solar) supported by battery energy storage systems to increase the reliability of the electricity supply.

In the period July 2022 – July 2023, renewables were able to cover about 19% of the country's electricity demand, whereas the bulk of the production was still relying on fossil fuels.

Most generation facilities on Tonga are owned and operated by the public utility Tonga Power Limited (TPL). The main diesel power plant is located in Tongatapu (14 MW).

Tonga's first ever large-scale wind farm (Il 'O Manumataongo wind farm) was completed in 2019, with a capacity of 1.3 MW. TPL also operates 5 solar PV plants with capacities between 200 kW and 1.5 MW.

Importantly, TPL purchases electricity from two solar plants owned and operated by IPPs: Singyes Solar IPP, operational since 2011 with an installed capacity of 2 MW, and Sunergise Solar IPP, with 6.9 MW of installed capacity, commissioned in 2022.

The electricity system of Tonga is in quick evolution. The most significant projects under development are:

- A new 2.2 MW wind farm.
- A new hybrid solar PV-BESS power plant, with 20 MW installed PV capacity and 50 MWh storage capacity, to be constructed and operated by an IPP.

CASE STUDY

Main Contributors	Akuo, Tonga Power Limited
Type of installation	Standalone BESS
Installed capacity	<ul style="list-style-type: none">• Tonga 1: 9.3 MW / 5.3 MWh• Tonga 2: 7.2 MW / 23.9 MWh
Commissioning date	2022

The Tonga 1 and Tonga 2 BESS stations were deployed under the Tonga Renewable Energy Project (TREP), funded by the Green Climate Fund (56%), the Asian Development Bank (23%), the Government of Tonga (10%), Tonga Power Limited (6%) and the Government of Australia (5%).

The project represented, at the time of their commissioning, the largest BESS installation in the South Pacific with a total installed capacity of 16.5 MW / 29.2 MWh. The project was developed with the objective of improving and enhancing grid operation and stability to allow the system to withstand the growing number of RES installations to be deployed, in view of the 70% RES penetration by 2030 goal set by the government.

The Tonga 1 BESS is located in Popua Power Station (Tongatapu) and was conceived as a grid stabilization battery. With an installed capacity of 9.3 MW / 5.3 MWh, the battery's primary purpose is to maintain grid frequency and voltage, and smooth rapid load and renewable generation fluctuations. Additionally, the battery acts as spinning reserve and helps offset intermittency from solar and wind.

The Tonga 2 BESS, on the other hand, is located in Matatoa (Tongatapu) and is designed as a load-shifting battery: it helps the grid to supply electricity at peak times, notably in the evening. With an installed capacity of 7.2 MW / 23.9 MWh (approx. 3.3 hours full discharge), the battery's primary purpose is to store excess solar generation during the day and discharge energy during evening peak demand, enabling higher solar throughput and reducing diesel reliance.

The two battery storage plants are composed of Storage GEM, a modular storage container technology by the Akuo Group. Overall 8 containers have been deployed in Tongatapu: 3 Storage GEM for Tonga 1, and 5 for Tonga 2. The plants are controlled through an Energy Management System developed by Akuo.



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IMPACT

The two BESS facilities deployed by Akuo and TPL were commissioned in 2022. Interestingly, the two facilities contributed in avoiding an outage of the entire power grid during the volcanic eruption of January 2022, which resulted in a tsunami that devastated the archipelago's coastline. The systems also support limiting the blackouts during the planned and unplanned maintenance activities on the islands' power plants.

Since the beginning of their operation, they have already enabled a doubling in the capacity of renewable energy installed in Tongatapu, with the connection of the 6 MW solar plant developed by Sunergise Solar IPP.

The success of the two BESS installations has pushed TPL developing additional projects in this regard. The most important upcoming storage installation will be within the new IPP-operated hybrid PV-BESS plant, which is expected to count on 50 MWh storage for energy time-shifting.



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LESSONS LEARNT

- ✓ Island grids aiming for more than 20-30% non-dispatchable renewable power generation are often required to install battery storage to ensure an efficient and reliable operation of the system.
- ✓ Tonga has installed a grid-stabilisation battery and a load-shifting battery. The complementary design of the two installations has been key to meet the needs of the grid. Complementary BESS can also be installed at different locations, with grid-stabilisation batteries typically being installed beside the conventional power plants.
- ✓ Battery energy storage has also proven to be a resilient backbone, enhancing reliability of the electricity supply during natural disasters in remote island settings.
- ✓ It is possible to develop hybrid PV-BESS power plants operated by IPPs and remunerated through PPAs with the main utility companies.



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HYBRID POWER PLANTS

Hybrid Hub

BONAIRE

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM & CASE STUDY

Island	Bonaire
Country / Territory	Bonaire
Area	288 km ²
Population (2025)	~27 000
Annual electricity production (2023)	156.2 GWh/year
Generation plants	<ul style="list-style-type: none"> • Hybrid Hub: <ul style="list-style-type: none"> » Diesel generators: 23.75 MW » Wind farm: 11.0 MW » Solar PV: 6.0 MW • Wind turbine at Sorobon: 330 kW • Distributed Solar PV: approximately 2 MW
Energy storage	<ul style="list-style-type: none"> • Hybrid Hub: <ul style="list-style-type: none"> » 14 MW / 14 MWh
RES penetration in the electricity mix (2023)	26%



Bonaire is a special municipality of the Netherlands. It has an area of 288 km² and a population of about 27 000 inhabitants. Bonaire had an annual electricity consumption of 156.2 GWh/year in 2023. WEB Bonaire is the public company acting as a Distribution System Operator, whereas the electricity is produced by the Hybrid Hub constructed and operated by ContourGlobal, an Independent Power Producer (IPP).

Overall, including the 2024 solar park, the electricity mix of Bonaire can count on 26% of generation coming from renewables:

- Almost 71% of the renewable generation is produced by wind turbines, most of them being part of the Hybrid Hub described as follows.
- About 22% of the renewable electricity is generated by the solar farm part of the Hybrid Hub (and the pilot project on Barcadera).
- Another 7% is generated by distributed solar PV panels on the roofs of houses and businesses.

The installed capacity on Bonaire is as follows:

- Diesel engines: 23.75 MW from one cluster of 5 MAN diesel generators of 2.85 MW rated capacity each, and a cluster of 5 MAN of 1.8 MW. The engines are dual fuel, designed for potential future conversion to biofuels.
- Wind turbines: 12 Enercon E-44 wind turbines of 900 kW rated capacity each , and 1 Enercon E33 with a rated capacity of 0.33 MW.
- A solar farm of 6.0 MW.
- BESS: 14 MW / 14 MWh of Lithium-ion batteries.

The diesel engines, solar farm and BESS are located in Karpata, on the coast south of the town of Rincón. The wind farm is instead located on the coast north of Rincón and is directly connected with the rest of the Hybrid Hub, while the 0.33 MW wind turbine is located at the Sorobon. Overall, the Hybrid Hub supplies to WEB Bonaire the electricity consumed on the island, as well as the electricity balance and all the ancillary services.

The Hybrid Hub operates under a smart hybrid control system that integrates diesel engines, wind turbines, solar PV, and battery systems in real time and is capable of automatic load-following, quick response and energy mix optimisation. The service of frequency control and regulation, as well as smoothing of load fluctuations, spinning reserve and additional power, are supplied by the diesel engines and storage system.

The development of the project was initiated in 2006 in a Special Purpose Venture (SPV) called “EcoPower” on behalf of ContourGlobal (a private operator) in partnership with WEB Bonaire. The total investment cost amounted to 62 million USD. The economic basis for the investment was a 15-year Power Purchase Agreement. In 2013 the facilities of EcoPower were acquired by ContourGlobal. The PPA was renewed before expiry. Over the years, several expansions have taken place, including the expansion of the solar park in 2024 and the investments in batteries. In addition, a major expansion of the firm capacity (diesel) took place in 2019.

WEB and ContourGlobal are currently working for the further expansion of the renewable power generation in Bonaire, in order to reach an 80% renewable power supply. The required interventions will especially include the undergoing expansion of the solar park, as well as a significant repowering of the wind farm.

Since March 2015, WEB Bonaire has also installed 792 solar panels in Barcadera as part of a pilot project. The households are grid connected and can therefore fall back on the grid when their own solar generation is not enough to cover their needs or inject excess production.

IMPACT

The Hybrid Hub was a key milestone in Bonaire's ongoing process of transition away from fossil fuels. The PPA scheme agreed by WEB Bonaire and ContourGlobal is particularly interesting, since it enabled the attraction of private capital for a public service, under the conditions of stable and secure revenues. The successful scheme is being further used for the expansion of Bonaire's renewable generation capacity.

Overall, the hybrid power plant generates more than 90% of the electricity on Bonaire and supplies all the ancillary services to the grid managed by WEB Bonaire. The wind farm generates about 15% of the annual demands. The excess production of the wind farm and solar park is stored in the BESS and contributes to balancing sudden demand surges or drops.



Image by Rick Farwell via Flickr

LESSONS LEARNT

- ✓ The stepwise approach to the energy transition addressed by Bonaire was successful. The combination of diesel generators and wind turbines has proven to be a safe and productive first step for the integration of renewables in the system. This has opened the ground to additional renewable generation, namely PV and wind.
- ✓ The PPA scheme can be valuable not only for power plants based on a single resource, but also for hybrid power plants supplying electricity and ancillary services at the same time. In Bonaire, the PPA scheme resulted as a win-win situation for both the IPP, that can count on stable revenues thanks to a long-term contract, and the public utility, which secured affordable electricity with limited public capital expenses.



Picture of Bonaire by Israel Gil via Unsplash

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HYBRID POWER PLANTS

Hybrid PV-BESS power plant

SINT EUSTATIUS

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island	Sint Eustatius
Country / Territory	Sint Eustatius
Area	21 km ²
Population (2025)	3 270
Annual electricity production (2023)	17.3 GWh/year
Generation plants	Hybrid Power Plant: <ul style="list-style-type: none"> • Solar: 6.87MW • Diesel: 6 MW
Energy storage	<ul style="list-style-type: none"> • Hybrid Power Plant: <ul style="list-style-type: none"> » BESS: 7.5 MW / 15 MWh
RES penetration in the electricity mix (2023)	55% (100% instantaneous)



45% — Solar PV



55% — Diesel power plant

Sint Eustatius, also known as Statia, is a special municipality of the Netherlands. It has an area of 21 km² and a population of 3 270 inhabitants.

The electricity system of Sint Eustatius is vertically operated by Statia Utility Company N.V. (STUCO), which is fully owned by the Government of St. Eustatius

The electricity mix of Sint Eustatius was exclusively dominated by fossil fuels until 2016, when the first section of the hybrid PV-diesel-BESS power plant went into operation. Since then, and thanks to the expansion of the solar + diesel + BESS installation, Sint Eustatius reaches 55% self-sufficiency by renewable energy.



Picture by Robert Kenney via Wikimedia Commons

CASE STUDY

Main Contributors	OLE (property), STUCO, Ministry EA (90% direct financing), SMA Sunbelt Energy, Eco Energy, Elite Energy
Type of installation	Hybrid Power Plant (Solar + BESS)
Installed capacity	<ul style="list-style-type: none"> • Solar: 6.8 MW • BESS: 7.5 MW / 15 MWh • Diesel gensets: 6 MW
Commissioning date	<ul style="list-style-type: none"> • First Phase: March 2016 • Second Phase: November 2017 • Third phase: April 2025
Share of total electricity production	55% from solar PV

Sint Eustatius' hybrid power plant was conceived to reduce fossil fuel usage and establish a grid-stabilizing electricity supply based on solar energy. The plant was realised over three phases:

- **Phase 1 (2016):** 1.9 MW PV and 1 MW / 570 kWh Li-ion battery, with a maximum instantaneous PV penetration of 89%. A PV share of 23% in the electricity mix was achieved thanks to this first installation.
- **Phase 2 (2017):** +2.15 MW PV and + 2.65 MW / 5.35 MWh batteries. This installation achieved 46% PV annual penetration. The batteries were equipped with grid forming inverters, allowing the island to switch off the generators at daytime and run on solar energy exclusively.
- **Phase 3 (2025):** + 2.8 MW PV and + 5 MW / 10 MWh batteries, with grid-forming inverters. The PV plant ensures the generation of 55% of the annual electricity demand, and diesel engines are off at daytime for about 13 hours.

The key component of the system is the battery inverter with grid-forming characteristics which allows the diesel generators to be shut down fully automatically without affecting the stability of the grid and ensuring a high-quality power supply. This has allowed to operate the island grid in Diesel Off-Mode operation with 100% solar power penetration for at least 13 hours every day. Additionally, a controller is responsible for real-time energy and power management, also synchronizing diesel and battery operation. The system is essential to compensate for the PV array's power fluctuations caused by fast-moving clouds, which can cause a strong reduction of the solar power generation in the time of a few minutes. The hybrid plant has withstood hurricanes Irma and Maria (September 2017).

The different phases of the plant realisation were 90% funded by the Dutch Ministry of Economic Affairs and Climate Policy. Further expansions of the plant are planned for the coming years, with the objective to achieve 85-90% self-sufficiency by early 2027.

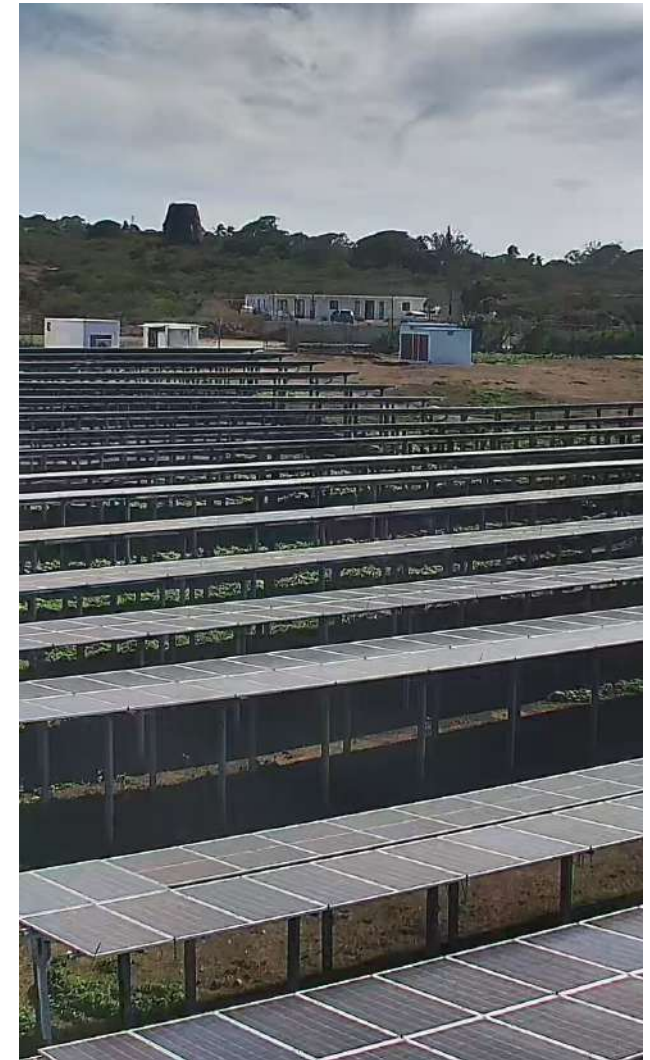


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IMPACT

The hybrid power plant in Sint Eustatius nowadays allows to cover 60% of the island's electricity demand through solar energy and to completely switch off diesel generators and run on a 100% solar power fraction for at least 13 hours a day. During nighttime, the battery system is active and serves to provide ancillary services to the grid, enhancing the overall reliability of the island grid. Furthermore, the hybrid system allows for substantial reduction in operational expenditures, spare parts, and maintenance intervals. The system also features a relevant impact on frequency, grid stability, and harmonics, hence increasing the power quality of the island.

Thanks to this installation more than 1.7 million litres of diesel were saved each year since 2017, with phase 3 savings that will amount to 2.4 million litres.



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LESSONS LEARNT

- ✓ It is possible to run a non-interconnected island grid with power coming from even a single solar PV plant and BESS for more than 12 hours a day. Battery storage systems paired with non-dispatchable renewable generation plants are a reliable way to ensure grid stability and reliability of the electricity supply while achieving high RES penetration.
- ✓ Ambitious targets of self-sufficiency of island grids, above 50% and towards 90%, can be achieved also with a limited diversification of the generating sources. Grid-forming battery inverters play a crucial role in maintaining the frequency of the grid and providing all the necessary ancillary services to completely switch off diesel generators when enough renewable power generation is available.
- ✓ The approach taken by STUCO in developing and designing the project in successive phases has allowed the system operator to learn step by step full functioning of the hybrid plant. The successful work done ultimately led to the achievement of a worldwide unprecedented target.



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HYBRID POWER PLANTS

Hybrid PV-Wind BESS power plant

SABA

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island	Saba
Country / Territory	Saba
Area	13 km ²
Population	2 158
Annual electricity production (2023)	9.8 GWh/year
Generation plants	<ul style="list-style-type: none"> • Diesel: 4.8 MVA • Solar: 2.1 MW • New hybrid plant (solar-BESS)
Energy storage	BESS: 2.2 MW / 2.0 MWh
RES penetration in the electricity mix (2023)	36% (65% by the end of the Renewable Energy Project Phase III)



Saba is a special municipality of the Netherlands. It is a mostly mountainous island in the northern Caribbean, with an area of 13 km² and a population of 2 158 inhabitants.

The electricity system of Saba is fully operated by Saba Electric Company, a fully publicly owned utility. Although still dominated by diesel generation, in 2023 Saba's electricity came for its 36% solely from solar power. The existing renewable installations rely on solar PV in combination with BESS to fulfil the demand during the day. Nighttime and cloudy days, however, still rely on diesel generation.

The island can currently count on a solar PV park of 2.1 MW installed capacity. Due to the lack of available flat areas on the island, the plants were installed on steep slopes. Considering the salty environment and the exposure of the island to hurricanes too, this plant represents a challenging, cutting-edge installation. The PV is coupled with a 2.2 MW / 2.0 MWh BESS, and operated as a unique hybrid plant. The key element of the hybrid plant is in fact the Sunny Central Storage 2200 battery inverter with grid-forming characteristics, which allows the diesel generators in SEC's power plant to be completely shut down in automatic mode, without compromising the stability of the frequency in the grid. Within seconds, the system compensates for the PV array's power fluctuations caused by, for example, fast-moving clouds. In this way, the system can run in diesel-off mode operation for up to 9 hours during sunny days.

The existing PV and BESS facilities were financed by the Dutch Ministry of Economic Affairs and Climate Change Policy and the European Development Fund.

CASE STUDY

Main Contributors	Saba Electric Company (SEC) Public Entity Saba
Type of installation	Hybrid Power Plant (Solar + BESS)
Installed capacity	<ul style="list-style-type: none"> • Solar PV: 2 MW • BESS: 10.4 MWh • + Existing hybrid plant (see electricity system description)
Commissioning date	2027 (expected)
Share of total electricity production	65%

A new hybrid plant, the Saba Renewable Energy Project Phase III, is currently under construction and planned to be commissioned in 2025. The new hybrid plant will include:

- A 2 MW solar PV installation.
- A 10.4 MWh BESS, equipped with grid-forming inverters.



© Public Entity of Saba

Thanks to this new hybrid installation, Saba will reach 65% renewable penetration in its electricity mix, thus achieving a high level of electrical self-sufficiency. The solar PV installation and the BESS are going to be located in the east side of Saba, in Giles Quarter.

Driven by the energy crisis and the unstable price of fossil fuels, the Phase III project was developed since 2022, with the focus on renewable energy from wind. Main concerns for Saba residents were related to the noise, visual and environmental impacts of wind turbines especially. For this reason, several locations for the wind turbines were initially evaluated, and publicly discussed. The project's characteristics, benefits and impacts were discussed in public consultations, including a **Townhall Meeting held in November 2022**. Following more in depth studies including a wind-turbine assessment, it was decided to remove wind from this hybrid system to be built due to construction challenges and legislative guidelines.

The Renewable Energy Project Phase III has been fully subsidized by the Dutch Ministry of Economic Affairs and Climate Change Policy and the EU Multiannual Indicative Program.

The recording of the Townhall Meeting on the Renewable Energy Project Phase III is available at: youtube.com/watch?v=q9tgfnfYTIw



IMPACT

The new hybrid (solar-wind-BESS) power plant in Saba, together with the existing PV and BESS installation, will be able to cover 65% of the island's electricity demand through renewables.

The new hybrid plant will also continue the trend of fuel saving practices and efforts.

Very importantly, the new hybrid plant will not only enhance Saba's energy self-sufficiency, but also further reduce electricity tariffs for final users.



© Public Entity of Saba

LESSONS LEARNT

- ✓ The progressive deployment of renewable installations, and especially the achievement of very high shares of renewable electricity, can substantially reduce the cost of electricity for island energy systems.
- ✓ Hybrid plants do not strictly require that all their components are located next to each other. Different plant components (e.g., solar park and batteries) can also be positioned at more distant locations, as long as interconnected with each other. The hybrid plant concept rather lies in the way the plant is operated, with a centralised control for the optimisation of the system and the provision of all grid services.
- ✓ Grid-forming battery inverters play a crucial role in balancing the grid and providing ancillary services in isolated grids with high shares of RES. They are essential to enable switching off diesel generators.
- ✓ It is possible to build renewable energy infrastructure in corrosive environments, taking the necessary precautions in terms of component suitability and certification.
- ✓ A Service Level Agreement on external expertise is required for trouble shooting and sourcing of parts in highly complex projects, such as Saba's renewable energy project phase 3.



Picture of Saba by Julian Berengar Solter via Unsplash

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HYBRID POWER PLANTS

Wind generation and hydro storage

EL HIERRO

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

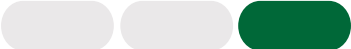
Island	El Hierro
Country / Territory	Canary Islands, Spain
Area	269 km ²
Population (2023)	11 806
Annual electricity consumption (2024)	51.6 GWh/year
Generation plants	<ul style="list-style-type: none"> • Hybrid wind-hydro power plant: <ul style="list-style-type: none"> » Wind turbine: 11.5 MW » Hydro turbines: 11.3 MW • Diesel: 12.7 MW
Energy storage	Pumped hydro: 150 000 m ³ (lower reservoir)
RES penetration in the electricity mix (2024)	45%



45% — Wind turbines



55% — Diesel power plant



El Hierro is an island part of the archipelago of the Canary Islands, which is an autonomous community of Spain. It has a very mountainous territory, with an area of 269 km² and a population of about 11 800 inhabitants (2024).

El Hierro has an annual electricity demand of approx. 51.6 GWh/year (2024) and its electricity system is operated by the private company Endesa. The island's electricity mix has quickly evolved from being fully dominated by fossil fuels (mainly diesel) to mostly renewables, thanks to the construction of a hybrid wind-hydro power plant.

Overall, the island counts on the following key power generation facilities:

- Diesel power plant: the thermal station Llanos Blancos has 9 diesel generators of varying capacities, for a total of 12.7 MW. The plant is operated by the private company Endesa.
- Hybrid wind-hydro power plant: the hybrid plant Gorona del Viento comprises a 11.5 MW wind farm and a pumping hydro station with 11.3 MW turbines. The plant is operated by Gorona del Viento El Hierro S.A. Further details on the plant and its owner are provided in the next pages.

Until 2015, when the hybrid wind-hydro power plant started its standard operation, El Hierro power demand was almost entirely covered by thermal generation. In 2024, about 45% of the electricity consumed on the island came from the hybrid plant.

A new hybrid solar PV-BESS power plant is foreseen for the coming years. This will consist of:

- PV: 5 MW in Phase I, 7 MW in Phase II.
- BESS: 5 MW in Phase I, 5 MW in Phase II.

During Phase I, El Hierro is expected to achieve 80% RES penetration. With the Phase II installations, the island aims at achieving a fully green electricity mix.

CASE STUDY

Main Contributors	Gorona del Viento El Hierro S.A., El Hierro Island Council, Endesa, Instituto Tecnológico de Canarias, Government of the Canary Islands
Type of installation	Hybrid wind-hydro power plant
Installed capacity	<ul style="list-style-type: none">• Wind farm: 11.5 MW (5x 2.3 MW Enercon E-70 turbines)• Pumped hydro power plant:<ul style="list-style-type: none">» Turbines: 11.3 MW.» Pumping station: 6.4 MW» Upper reservoir: 380 000 m³» Lower reservoir: 150 000 m³
Commissioning date	2014
Share of total electricity production	50%

The Gorona del Viento hybrid power plant in El Hierro is a pioneering project of its kind on an island isolated grid. It was initiated by the common vision of different stakeholders of the Canary Islands political, administrative and technical landscape. The Gorona del Viento, S.A., is the company in charge of managing, exploiting and maintaining the hybrid power station and is jointly owned by the Municipality of El Hierro (65,82%), the private utility company Endesa (23,21%), the Instituto Tecnológico de Canarias (7,74 %) and the Government of the Canary Islands (3,23%). The project was conceived in 2007 when the IDAE (Spanish national energy agency) signed an agreement with Gorona del Viento for technical and funding support, launching formal development for the hybrid energy project. After seven years of construction, the plant was eventually commissioned in 2014.

The innovative installation includes wind turbines and a reversible hydro power station, more specifically:

- Wind turbines: 5x 2.3 MW Enercon E70 turbines, for a total wind capacity of 11.5 MW.
- Hydropower: 4x 2.8 MW Pelton turbines, for a combined capacity of 11.3 MW.
- Pumped hydro storage: i) Lower reservoir (artificial basin): 150,000 m³, located at 50 m elevation; ii) Upper reservoir: 380,000 m³ at 700 m altitude, using a natural volcanic crater; iii) Pumping station: 6.4 MW capacity (6x 540 kW fixed pumping units and 2x 1600 kW variable pumping units).

The pumped hydro storage plant operates in a hybrid closed loop design, with wind power act as main power source. Fresh water (obtained on the island from desalination) is used in the closed loop. When wind generation exceeds the island load, surplus electricity powers the pumps to lift water to the upper reservoir; during low-wind periods, stored water flows downhill to drive the turbines and generate electricity. The Pelton turbines were designed as rotating phase shifters, thus being able to provide short-circuit power and reactive power, enabling full disconnection of the diesel generators at certain times.

During its construction and more than 10 years of operation, and as an innovative plant, the El Hierro hybrid wind-hydro power plant has faced relevant technical challenges. Some of them are presented as follows:

- The upper reservoir was constructed taking advantage of an old, inactive volcanic crater. The basin can host 380 000 m³ and, to avoid potentially disastrous leakage, it was covered with waterproof PVC foil. The lower reservoir is instead an artificial basin, that – to limit land use – was design for 150 000 m³. Notwithstanding some water evaporation in both reservoirs, the storage effectively exploitable by the turbines is 150 000 m³, corresponding to around 270 MWh net electricity output (i.e., the electricity demand of a few days).
- When, during a pumping operation, wind power ramps occur due to variations in wind speed and direction, the primary power-frequency control of hydro turbine units and the pump frequency converters help to maintain the generation-consumption balance. If these actions are not sufficient, one or multiple pumps are shedded. Until 2017, a large number of shedding event was registered (about 700 per year). With the aim of increasing the plant efficiency and the overall power system stability, a revision of the speed governor logic of the hydro turbines was carried out in late 2017, designing and implementing a damper to enhance the response from turbines. This led to a significant reduction of the pumps shedding events, ultimately enhancing grid stability.

IMPACT

The Gorona del Viento hybrid power plant was a pioneering project on an island isolated grid and proofed the feasibility and convenience of hydro pumped storage. Such project paved the road to the 100% renewables objective.

Some key achievements:

- Tons of CO₂ avoided per year: 17 945 t in 2022, 13 708 t in 2023, 18 073 t in 2024.
- Hours in which the island load was covered 100% by renewable energy: 1 008 in 2022, 413 in 2023, 859 in 2024.
- Tons of avoided diesel for power generation: 5 981 in 2021, 4 509 in 2023, 6 024 in 2024.

Additionally, the island experienced a record 24 consecutive days (596 hours) fully powered by renewables from the hybrid plant, from 13 July 2019 to 7 August.



Picture by Carlos Teixidor Cadenas via Wikimedia Commons

LESSONS LEARNT

- ✓ The collaboration of different actors from the political, administrative and technical spheres with aligned visions and objectives proved to be crucial in El Hierro for the realization of a first-of-its kind and ambitious project.
- ✓ Public-Private Partnerships should be considered for the implementation of larger generation and storage plants on islands. In the case of El Hierro, local public ownership and buy-in have ensured continuity and trust in the further developments of the project.
- ✓ Hybrid systems including storage technologies, such as pumped hydro storage, prove to be crucial for island grids' decarbonisation.
- ✓ Key technologies for the energy transition, although well consolidated in the continental markets, may need additional effort for finetuning and adaptation to the specificities of non-interconnected island grids.
- ✓ In the case of El Hierro, the combination wind-hydro was particularly successful and led to a significant reduction of fossil fuel-based generation. However, in the absence of natural reservoirs both upstream and downstream, the land required to build artificial reservoirs can be very extensive, affecting the technical and economic feasibility of hydro plants.



Picture of El Hierro by Martin Godetz via Unsplash

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ELECTRICITY SYSTEM REGULATION

The grid code

THE AUTONOMOUS REGION OF MADEIRA

RENEWABLE POWER GENERATION

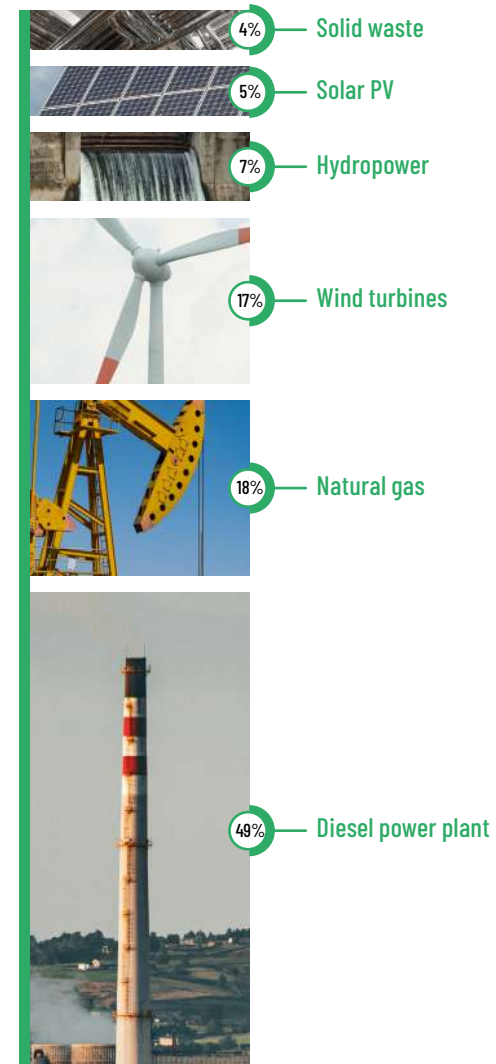
BATTERY STORAGE & GRID STABILITY

HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island	Madeira
Country / Territory	Autonomous Region of Madeira, Portugal
Area	740.7 km ²
Population (2023)	251 060 inhabitants
Annual electricity supplied to the grid (2024)	917.65 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Diesel power plants: 150 MW • Natural gas power plants: 56 MW • Hydro power plants: 83 MW • Wind power plants: 64 MW • Solar PV plants: 15 MW (utility-scale) + 13 MW (distributed) (+9.8 MW distributed installations without a surplus energy sale contract) • Solid waste plant: 8.8 MW
Energy storage (2024)	<ul style="list-style-type: none"> • Reversible hydro pumping stations: 27.8 MW (pumping), 54 MW (turbines), approx. 160 MWh storage capacity. • BESS (DC BoL): 23.7 MVA / 16.4 MW / 16.4 MWh + 27 MVA / 20.5 MW / 20.5 MWh
RES penetration in the electricity mix (2024)	34%



Island	Porto Santo
Country / Territory	Autonomous Region of Madeira, Portugal
Area	42.5 km ²
Population (2023)	5 562 inhabitants
Annual electricity production (2024)	35.76 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Diesel power plant: 17.3 MW • Wind power plants: 0.7 MW • Solar PV plants: 2.0 MW (utility-scale) +0.7 MW (distributed) (+0.4 MW distributed installations without a surplus energy sale contract)
Energy storage	<ul style="list-style-type: none"> • BESS (DC BoL): 12 MVA / 9.3 MW / 18.6 MWh + 5.4 MVA / 4.3 MW / 3.3 MWh
RES penetration in the electricity mix (2024)	12%



Madeira and Porto Santo are the two inhabited islands of the Autonomous Region of Madeira, in Portugal. Madeira is 740.7 km² and a population around 251 060 inhabitants, whereas Porto Santo is 41.5 km² and a population of 5 562 inhabitants.

The electricity systems of Madeira and Porto Santo are non-interconnected with the mainland, nor with each other. The systems are operated by the Empresa de Electricidade da Madeira (EEM), which is a vertically integrated company responsible for the electricity generation, transmission (only TSO), distribution (only DSO) and retail. EEM is 100% owned by the regional government, and its activities are regulated by the Portuguese Energy Services Regulatory Authority (ERSE). Power generation is also open to private producers, and several Renewable Energy Communities (RECs) have already been established on Madeira island.



Picture by European Wind Energy Association via Flickr

Madeira island

Madeira island can count on a diversified energy mix thanks to the following generation facilities (partly owned and operated by EEM, and partly by IPPs):

- 2 thermal power plants (1 on diesel, 1 on diesel and natural gas), for a total of 206 MW installed capacity.
- 11 hydro plants for a total of 82 MW installed capacity.
- 11 wind power plants of overall 64 MW installed capacity.
- 3 utility-scale solar PV plants for a total of 15 MW and multiple small-scale distributed PV plants of overall 13 MW installed capacity.
- 1 solid waste power plant (8.8 MW).

Out of the numerous hydro plants, two of them are reversible and provide a total storage capacity of approx. 160 MWh:

- The Socorridos Reversible Hydroelectric Power Plant, with a generation power of 24.0 MW and a pumping power of 11.3 MW.
- The Calheta III Reversible Hydroelectric Power Plant, with a generation power of 30.0 MW and a pumping power of 16.5 MW.

Both these plants are also able to act as synchronous condensers, providing voltage regulation, inertia and essential short-circuit power. Madeira also has two BESS (lithium-ion) facilities which can operate in grid-following or grid-forming mode, providing both frequency and voltage regulation, among other features:

- The Vitória BESS plant, commissioned in 2022, with a nominal power of 23.7 MVA / 16.4 MW and a storage (DC BoL) capacity of 16.4 MWh.
- The Caniçal BESS plant, commissioned in 2025, with a nominal power of 27 MVA / 20.5 MW and a storage capacity of 20.5 MWh.

The BESS plants contribute to improving renewable energy integration, improve the efficiency of the thermal power plants, provide voltage and frequency control (ancillary services), ultimately reducing the operational costs of the system. The RES penetration on Madeira amounted to about 34% in 2024.

Porto Santo island

The generation capacity of Porto Santo is as follows:

- 1 diesel power plant of 17.3 MW installed capacity.
- 1 wind power plant of 0.7 MW installed capacity.
- 2 utility-scale solar PV plants of overall 2.0 MW and some distributed PV plants of overall 0.1 MW installed capacity.

Porto Santo also has two BESS (lithium-ion) facilities which can operate in grid-following or grid-forming mode, providing both frequency and voltage regulation:

- The Porto Santo I BESS plant, commissioned in 2020, with a nominal power of 5.4 MVA / 4.3 MW and a storage capacity of 3.3 MWh.
- The Porto Santo II BESS plant, commissioned in 2024, with a nominal power of 12.0 MVA / 9.3 MW and a storage capacity of 18.6 MWh.

The RES penetration on Porto Santo amounted to about 12% in 2024.

CASE STUDY

Main Contributors	Autonomous Region of Madeira, Empresa de Electricidade da Madeira (EEM), Energy Services Regulatory Authority (ERSE)
Type of regulation	Development of a grid code specifying the technical requirements for private generation plants connecting to the grid

As non-interconnected islands networks, Madeira and Porto Santo power grids are particularly susceptible to electrical fluctuations and anomalies. Before 2019, the grid code applicable to mainland Portugal was also applied to Madeira archipelago. In the effort of promoting the production of electricity from distributed RES while ensuring a reliable and high-quality power supply, the Regional Government of Madeira has adopted in 2019 a new grid code stating the technical connection requirements for all generation units. This was the result of a common work that was technically led by the regional electrical utility company, EEM, and the Portuguese Regulatory Authority, ERSE.

The rationale behind developing a dedicated grid code for an island power system lies in the fact that large shares of renewable generation can pose significant challenges in terms of system security for isolated power systems. Frequency stability issues may indeed arise since non-dispatchable renewable generation leads to the reduction of dispatchable, fuel-based thermal generation. This ultimately leads to a reduction of the capability of the system to quickly react to frequencies variations. More specifically, reducing fuel-based thermal generation reduces the conventional source of fast frequency control capabilities, thus also reducing the available synchronous inertia. System operators are therefore required to provide alternatives, with many of them installing BESS with fast-responding power-frequency control capable of contrasting grid disturbances. Beside this, on islands where multiple distributed generation systems are connected or are expected to be connected, specific technical requirements also need to be established for all generation units to contribute to grid stability.

Since in the Autonomous Region of Madeira electricity is produced by multiple utility-scale plants and smaller distributed generation systems, the definition of a grid code became essential to ensure the stability of the power grid while reducing fossil fuel generation. The grid code requirements include operating ranges under normal and abnormal grid conditions, dynamic behaviour profiles, and other technical functionalities.

Some of the key parameters which are set for generation units in Madeira grid code are listed as follows:

- Ranges of injections of reactive power in steady state mode.
- Local dynamic modulation of active and reactive power as a function of voltage.
- Under and over voltage fault ride through.
- Sensitivity to under and over frequencies.
- Voltage-sensitive current control during faults (both reactive and active current injection).
- Recovery of active power after faults.
- Dynamic control of active and reactive current during faults.

It is especially noteworthy that different criteria were established for generation units of different nominal powers, in view of a balance between technical necessity and economic viability. The following table summarizes which requirements are established for different generation unit types in the grid code of Madeira.

		Installation type				
	Class	A special	A	B	C	D
	Nominal power	< 2.5 kW	< 100 kW	< 1 MW	< 5 MW	> 5 MW
Steady-state requirements						
Requirements	1. Acceptable frequency range	X	X	X	X	X
	2. Acceptable voltage range	X	X	X	X	X
	3. Range of injection and reactive power consumption			X	X	X
	4. Local voltage control		X	X	X	X
	5. Remote control of the operating point			X	X	X
Dynamic regime operation requirements						
	6. Survival of frequency gradients	X	X	X	X	X
	7. Frequency variation sensitivity mode - overfrequency (LFSM-0)		X	X	X	X
	8. Frequency variation sensitivity mode (LFSM)				X	X
	9. Low voltage ride through capability			X	X	X
	10. High voltage ride through capability				X	X
	11. Active power recovery after voltage dips			X	X	X
	12. Capacity for dynamic control of reactive current during overvoltages				X	X
	13. Capacity for dynamic control of active and reactive current during voltage dips				X	X

IMPACT

The development of a specific grid code for the Autonomous Region of Madeira has given the system operator confidence that the assets connected to the system will not endanger the security of the electricity supply. At the same time, it gave clarity to the private developers on what the specific requirements for their installations should be.

Thanks to the grid code, the system operator of Madeira (EEM) was able to safely connect to its grid hundreds of distributed generation units, with electricity coming from multiple utility-scale plants operated by IPPs and overall 13.4 MW of small distributed generation units.

Ultimately, the grid code provisions have ensured high levels of reliability of the power supply, with all consumers benefiting from very limited disruptions on Madeira electricity system.



Picture of Madeira by Lina Bob via Unsplash

LESSONS LEARNT

- ✓ A grid code setting technical connection requirements is a fundamental document to promote power generation from multiple power plants, including both utility-scale plants operated by IPPs and small generation units of prosumers. A grid code can ensure smooth system functioning and building trust between the power system stakeholders.
- ✓ Specific grid codes are needed on non-interconnected island grids, that are characterised by specific parameters and are more vulnerable than highly interconnected grids.
- ✓ Technical requirements need to be adapted to what is both technically necessary and economically viable. Different sets of requirements depending on the voltage level of the connection and/or the maximum power capacity of the facility.



Picture of Porto Santo by Reinaldo Photography via Unsplash

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ELECTRICITY SYSTEM REGULATION

Feed-in tariffs and Power Purchase Agreements

BERMUDA

RENEWABLE POWER GENERATION

BATTERY STORAGE & GRID STABILITY

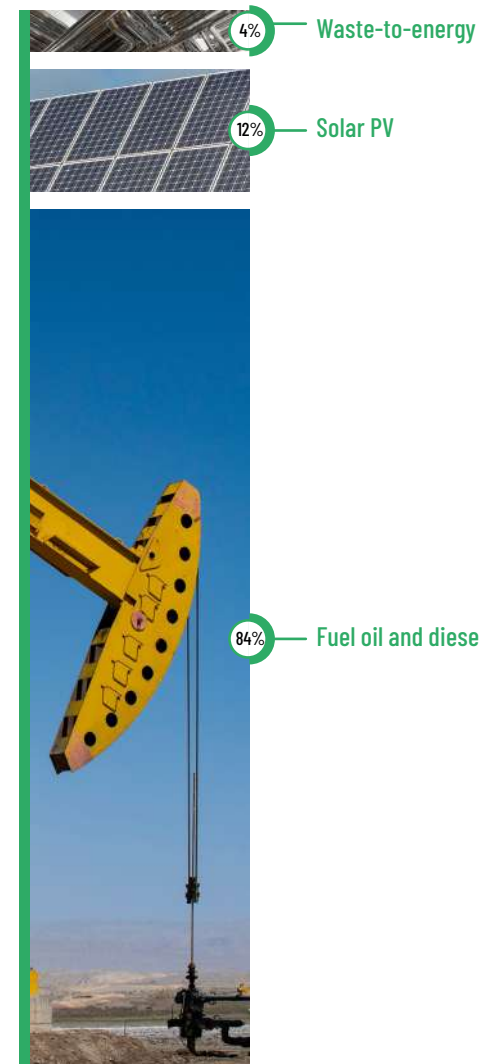
HYBRID POWER PLANTS

ELECTRICITY SYSTEM REGULATION

ELECTRICITY SYSTEM

Island	Bermuda
Country / Territory	Bermuda
Area	53.2 km ²
Population (2024)	64 636
Annual electricity consumption (2024)	590 GWh/year
Generation plants (2024)	<ul style="list-style-type: none"> • Fuel oil and diesel power plants (8 diesel / 4 gas turbines) with maximum capacity 142 MW • Solar PV: <ul style="list-style-type: none"> » Utility-scale: 6 MW » Distributed PV: 14 MW • Waste-to-energy: 7.4 MW
Energy storage (2019)	10 MW / 5.5 MWh BESS
RES penetration in the electricity mix (2024)	16%

Whereas electricity production from fuel oil and diesel power plants, the Airport Solar Project and the Tynes Bay Waste to Energy facility were obtained from data communicated by the Government of Bermuda and are referred to the year 2024, the generation from distributed PV plants was assumed in consideration of an average capacity factor for rooftop installations of 17.2%.



Bermuda is a British Overseas Territory in the North Atlantic Ocean. It is an archipelago consisting of several islands, with the largest of them connected via bridges. Bermuda is 53 km², and has a population of approx. 64 636 inhabitants.

Bermuda has an electricity demand of about 590 GWh/year and 36 214 electricity customers. The electricity sector is regulated by the Regulatory Authority of Bermuda. The utility in charge of power transmission and distribution (Transmission, Distribution & Retail license), as well as of the operation of the main power stations (Bulk Generation licence), is the Bermuda Electric Light Company Limited (BELCO), a private company. Whereas the Transmission, Distribution & Retail services are operated under a regulated monopoly, the Bulk Generation license is open to competition.

Electricity in Bermuda is mostly produced by fossil fuels, namely fuel oil and diesel. BELCO operates the two-fuel oil and diesel thermal power stations (8 diesel / 4 gas turbines): the Serpentine Road power station North Power Station, for a total installed capacity of 142 MW.

Bermuda can also count on an increasing number of renewable energy generation plants, namely:

- A 7.4 MW waste-to-energy plant, the Tynes Bay Waste to Energy Facility.
- A 6 MW solar PV plant installed at the Finger, near the F Wade International Airport. The plant is operated by Saturn Solar, an Independent Power Producer (IPP).
- A total of 14 MW of distributed solar PV plants installed on rooftops of privates and businesses.

As of 1 May 2025, the number of distributed PV installations and their capacity is as in the following table:

Customer type	Number	Installed capacity [MW]
Residential	1 184	8.403
Commercial	72	2.535
Demand	25	2.985
Total	1 281	13.923

Overall, it is estimated that renewable energy penetration in the electricity mix is around 16%.

In 2019, BELCO has installed a power-intensive battery storage system of 10 MW / 5.5 MWh with the aim of increasing the overall reliability of the power supply. The storage plant is used to respond to sudden changes on the network, providing fast frequency response to support power quality, maintain grid stability and avoid load shedding / blackouts. Also, the BESS provides spinning reserves, reducing the required amount of running diesel generators and improving the operational efficiency of the fossil fuel power plants.

Because of its geographically isolated position and current power mix, Bermuda has very high electricity tariffs. The Government of Bermuda and the Regulatory Authority of Bermuda are working to increase the electrical self-sufficiency of the archipelago. Significant efforts have been put in place in order to liberalise power generation and allow Bermudians to generate electricity independently, in particular through rooftop solar PV.

The available space for additional large ground-mounted PV installations is very limited due to the lack of available land. In May 2025 the Regulatory Authority launched a public tender for the development of an offshore wind farm of 60 MW (expandable to 120 MW in future), which is expected to provide 15% of the electricity demand of Bermuda (30% upon expansion).

The future capacity planning is set in the Integrated Resource Plan, which is the tool approved by the Regulatory Authority of Bermuda and updated through an iterative process at least every five years. BELCO and any potential alternative energy providers are asked to submit a plan for Bermuda's energy future, under conditions and criteria set by the Regulatory Authority. The draft Plan undergoes a public consultative process, where stakeholders can provide comments and feedback, and may also submit requests for alternative proposals.



Image courtesy of the Government of Bermuda

CASE STUDY

Main Contributors	Government of Bermuda, Regulatory Authority of Bermuda
Type of regulation	Enabling of distributed power generation for both self-consumption and injection into grid, with remuneration through a feed-in tariff

In 2011 the Government of Bermuda established the creation of the Regulatory Authority of Bermuda, with the power to supervise, monitor and regulate any regulated industry sector. The regulated industry sectors were set to be the electronic communications (other than broadcasting), electricity, and international submarine communications cables sectors.

In 2015, the Government has published the National Electricity Sector Policy, articulating Bermuda's electricity system objectives and presenting a vision of what the sector will look like. The Policy especially includes the identification of the enabling framework for the achievement of the targets, and the desired market structures.

In 2016, with the Electricity Act 2016, the Government of Bermuda defined the different licenses required for the electricity-related services:

- A Transmission, Distribution & Retail (TD&R) License, to be assigned to a single utility company, ensuring that all Bermuda residents are provided with access to a supply of electricity.
- A Bulk Generation Licence, authorising the holders to engage in bulk generation of electricity, i.e. in electricity production through plants above a certain installed capacity threshold (Licence Threshold).
- A Large-Scale Self-Supply Licence, authorising the holders to engage in self-production through generating systems not connected to the transmission and distribution network, and with installed capacity under a certain threshold (Licence Threshold).
- A Bulk Generation Sole Use Installation License which authorizes the Licence holder to generate electricity above the licence threshold from a renewable energy system, provided that the Licence holder uses or stores the electricity generated at its principal location. The license holder can also sell surplus electricity up to 30% of electricity it generates each month.

In 2018, with the Electricity (Licence Threshold) Regulations 2018, the Government of Bermuda established that the threshold under which distributed generation plants do not require a Bulk Generation Licence is 500 kW.

As of May 2024, the generation plants are remunerated as follows:

- Distributed generation plants under Licence Threshold: producers can self-consume their self-produced electricity, inject into grid the excess electricity, and purchase electricity from the grid when self-production is not sufficient (net billing arrangement). Prosumers / producers should sign a Standard Contract which remunerates them with a feed-in tariff established by the Regulatory Authority, based on the following principles:
 - » The rate shall seek to allow compensation for, at most:
 - . The actual cost of generation that the TD&R Licensee avoids by purchasing power from distributed generation; and
 - . An estimate of any economic benefits from distributed generation.
 - » The term of validity of the tariff shall be at least equal to the expected useful lifetime of the system used and maintained efficiently.
- Generation plants above the Licence Threshold: a Bulk Generation Licence is assigned to qualified producers which are affiliated with the TD&R Licensee or that have signed a Power Purchase Agreement with the TD&R Licensee.
- Under the Bulk Generation Sole Use Installation License, the license holder can sell surplus electricity up to 30% of the electricity it generates each month back to the incumbent utility under a PPA.

IMPACT

The provisions set by the Government of Bermuda and implemented by the Regulatory Authority of Bermuda have enabled a significant increase of solar PV power generation:

- A large number of distributed PV plants under the 500 License Threshold installed capacity, where developed on Bermuda, for a total of 14 MW installed capacity (as of May 2025).
- A large PV plant of 6 MW installed capacity, the so-called Airport Finger Solar Farm, was deployed by Saturn Power and commissioned in 2021.

Although Bermuda still has a long way to go to strongly reduce its dependence on fossil fuels, the regulatory work done so far has enabled multiple prosumers to self-produce their own electricity, thus reducing their bills and contributing to the reduction of retail tariffs for all customers.

The same approach that was used for the development of the Airport Solar Farm is being considered for the possible development of a 60 MW wind farm with an IPP agreeing a PPA with the TD&R Licensee. This process is being managed by the Regulatory Authority under the Integrated Resource Planning Process.



Image courtesy of the Government of Bermuda

LESSONS LEARNT

- ✓ A well-developed and tailored legislative and regulatory framework is fundamental for the efficient operation of island grids. The establishment of an electricity sector regulatory authority is a key element to ensure fair treatment of consumers and attention to the public interests, especially for those OCTs/OTs where the main utility company is not publicly controlled.
- ✓ A feed-in-tariff scheme is a good approach for the promotion of distributed generation through small- and medium- sized power plants. The consideration of the avoided costs of fuel in the definition of the tariff can represent an important push for prosumers to invest in generation plants covering part of their demand and even selling electricity to the main utility company.
- ✓ For larger renewable installations, PPA schemes between IPPs and main utility companies should be promoted. PPAs have the potential to attract capitals from qualified developers for the specific technologies and ensure stable electricity prices on the long-term.



Picture of Bermuda island by Sebastian Enrique via Unsplash

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