Technology Collaboration Programme
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International Energy Agency
Photovoltaic Power Systems Programme

Task 14 Solar PV in the 100% RES Power System

PVPS

Best practices for high penetration PV in insular power systems

2021

Report IEA-PVPS T14-13:2021

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The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000? experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Cop- per Alliance are also members.

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What is IEA PVPS Task 14?

The objective of Task 14 of the IEA Photovoltaic Power Systems Programme is to promote the use of grid-connected PV as an important source in electric power systems at the higher penetration levels that may require additional efforts to integrate dispersed generators. The aim of these efforts is to reduce the technical barriers to achieving high penetration levels of distributed renewable systems.

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COVER PICTURE
Landscape in Tenerife (Canary Islands), Emilio Gutiérrez Delgado

ISBN 978-3-907281-20-8

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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ACKNOWLEDGEMENTS

This IEA-PVPS report received valuable contributions from several IEA-PVPS Task 14 members and other international experts. Many thanks to all of them. Special thanks are expressed to all guest contributors outside Task 14 members.

LIST OF ABBREVIATIONS

DER	Distributed Energy Resources
DMS	Distribution Management System
DPV	Distributed Photovoltaics
DSO	Distribution System Operator
HV	High Voltage
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LV	Low Voltage
MV	Middle Voltage
PV	Photovoltaics
RES	Renewable Energy Sources
TSO	Transmission System Operator
UFLS	Under Frequency Load Shedding

EXECUTIVE SUMMARY

Insular territories are uniquely positioned as global laboratories for transforming our energy future as many of them are the first to encounter the emerging perturbations in the earths' systems response to climate change. While each insular territory is unique in its own right, they share several attributes (e.g., isolation, lack of interconnections, limited land availability, seasonal population variations, etc.) and a common goal to reduce electricity costs, limit carbon emissions and ensure a stable electricity grid for sustained economic development. This unique combination of increasing vulnerability and decreasing reliability is driving many insular territories to accelerate the deployment of renewable energy systems for their future while experimenting with innovative solutions and best practices that are applicable to many other areas across the globe. This report summarizes the general attributes of insular power systems that support these territories emphasizing best practices and key insights that have accelerated their transformation, have impeded their progress and/or are relevant to more traditional power systems globally.

As the share of traditional photovoltaic and wind energy generation sources increase in insular power systems, system stability (e.g. expressed by parameters such as frequency deviations, voltage transients) also tends to decrease. Insular systems experience more frequent instabilities in part because of the basic attributes that drive electricity demand (e.g., seasonal tourism), capacity (grid size, increasing renewable penetration, disruptions of generation, etc.) and a lack of interconnections to other power systems. To mitigate these detrimental impacts, system operators regularly focus on several actions including ongoing power system modifications, counterbalancing renewable energy fluctuations with flexible generation, curtailment of renewable systems, or load shedding. Insular power systems are also among the first to deploy advanced technologies that leverage the capabilities of fast-responding power electronics to enhance grid stability.

Solar PV is being deployed at an accelerating rate in insular power systems for a number of reasons including reduced cost, improved versatility in deployment scale, and ease of maintenance and operations. The cost of solar PV system components continues to decrease and overall system costs are only moderately impacted by system scale. Many insular territories are located in areas with high solar irradiance, high population densities and significant rooftop space which helps preserve limited available land for other purposes. Distributed photovoltaics in particular are growing at an accelerated rate, and distributed PV systems increasingly include energy storage due to the increasing availability and the decreasing cost of battery storage. This distributed storage capability can be used to support the grid, or simply to maximize the benefits for the owner (i.e., to maximize the distributed use of generated power).

Storage is the principal option for integrating large shares of non-dispatchable energy in insular power systems. Storage systems today primarily include batteries and pumped hydropower. Storage is critical to balance large amounts of wind and solar PV power under secondary and/or tertiary regulation and to manage seasonal variations in demand and generation capacity throughout the year. As renewable generation sources increase on the grid, the inherent characteristics of synchronous generators that typically contribute significantly to grid stability diminish. In insular power systems relying on RES based generation fast response capabilities from static power-electronic based generation are increasing. Indeed, these new capabilities are starting replacing the legacy of synchronous generators and the reliance on inertia and mechanical frequency response approaches to maintain system reliability.

Insular power systems serve as an excellent test bed and learning center for assessing best practices that have significant relevance to improving the resilience of power systems in all locations around the globe. The challenges associated with assuring a resilient insular power system, defined by our ability to anticipate and adapt to changing conditions that influence the power system or to respond to, withstand or recover rapidly from disruptions, are substantial and require a disciplined and systematic planning and implementation process to mitigate those factors most likely to impact system resilience.

Based mostly on the evolution of the PV technology, case studies reported and lessons learned in this Report, the most important recommendations for insular power systems are the following:

- Insular power systems serve as a global learning collaboratory for transforming the global energy system and accelerating the deployment of traditional and non-traditional renewable energy capabilities that integrate technology, policy, economics and regulation.
- When deploying renewable technologies, performance specifications should take into account the likely future state of the insular power system, which may include greatly reduced conventional generation. It is typically costly and logistically difficult to retrofit advanced features after installation.
- All new renewable generation should be required to be capable of continuing to operate during (riding through) large voltage and frequency transient events, including fast rates of change of frequency. A retrofit of existing renewable generation shall also be considered, maybe based on a cost-benefit analysis.
- Small-scale distributed generation that is not under direct utility control can be more beneficial if equipped with the ability to autonomously respond to voltage and frequency events in a way that helps stabilize the system.
- It is important to apply specific settings (e.g., inverter functions and protections) in insular systems, and not to use only “default” settings designed for the large mainland power grids. Frequency and voltage variations might be larger and faster in insular systems, which could lead to an unwanted tripping and loss of RES generation.
- Large-scale renewable generation should be capable of providing grid stabilizing services such as voltage regulation and fast frequency response in coordination with the local TSO. In systems where non-synchronous generation

may in the future exceed 80% of instantaneous load at times, grid-forming capability should be considered for system relevant new generation.

- Maintaining an emphasis on grid resilience during all phases of planning, design, deployment and operation of large-scale renewable systems is critical to assure cost effective, reliable and efficient customer service and system response.

1. INTRODUCTION

1.1. Motivation

Insular territories[1] are highly motivated to play a significant and critical role in transforming our global energy future because they are most vulnerable if this transformation does not occur. Insular territories are uniquely positioned on the critical path to address the challenges associated with climate change and must adapt and lead the way to survive. Insular territories often have isolated electrical grid systems, with limited or no interconnections, and today are generally migrating from a past reliance on expensive, imported fossil fuel for electricity generation to a future that embraces low carbon generation sources. While interconnections are important for many insular systems to maintain reasonable standards for grid reliability, many are completely isolated; hence they must be early adopters and innovators because they have no choice. This unique combination of vulnerability to ongoing changes induced by climate change, high cost of electricity, limited interconnections and low reliability of the isolated electric grid is driving many insular territories to accelerate the deployment of renewable energy systems (RES) for their future while experimenting with innovative solutions and best practices that are applicable in many other areas across the globe, including, and well-beyond, insular territories.

The cost of electricity generated in insular power systems is often significantly higher than in large interconnected systems because of economies of scale, transportation costs, and energy markets that are largely controlled by a monopoly with few or no options for consumers. The lack of interconnections also limits the development of 100% RES insular power systems unless they are supported by alternative renewable resources including hydro, geothermal or biomass systems that are capable of providing quasi-base load supplies, and/or, as a second emerging alternative, by storage and power electronics capable of providing full renewable electricity and fast frequency response (FFR). However, planning based on the first alternative is often contested locally because of concerns over emissions and increased potential for earthquakes with geothermal, flooding of land with hydro, and air quality from combustion of biomass near populated areas. Wind is another expected contributor to large RES deployments and can be used to support pumped hydro-storage. However, wind turbines is constrained in many islands because of the environmental impact mostly on fauna, doubts about resilience against hurricanes and logistical difficulties in small islands.

Solar PV is being used at an accelerating rate in RES insular power system deployments for a number of reasons that include cost, versatility in deployment scale, and ease of maintenance and operations, among others. The cost of solar PV system components continues to decrease, overall system costs are only moderately impacted

[1] *Insular territories include both independent nation states (e.g. Tonga and Aruba) islands and other territories (e.g., Canary Islands) that are tied administratively to another nation.*

by system scale, and they can be monitored remotely from any location in the world. Many insular territories are located in areas with high solar irradiance, high population densities and significant rooftop space which helps preserve limited available land for other purposes. Distributed photovoltaics in particular are growing at an accelerated rate on insular territories propelled by high electricity costs, favourable policies and the availability and decreasing cost of battery storage. Grid codes should be adopted or modified as PV penetration increases to minimize, detect, ride through, and/or favourably respond to frequency and voltage instabilities often encountered in highly non-dispatchable RES scenarios. While several challenges remain relative to fully controlled integration of DPV into the grid that assures effective frequency response services [1], solar PV will be instrumental in enabling the transformation to 100% RES deployments in many insular locations around the world.

Interconnections play a prominent role in transforming the power systems of insular territories where they are available or feasible. Interconnections can readily allow to increase the share of renewable energy in an insular power system and reduce electricity costs, mostly when the interconnection is economically viable, and the island is part of an archipelago or it is close to a large power system. However, interconnections are expensive, specifically when the seabed is deep and the capacity required is large, and can also fail unexpectedly (e.g. Mallorca-Menorca interconnection), emphasizing the need for, at a minimum, a backup power capacity placed in the insular power system or ready for shipments under emergency circumstances. Investment trade-offs will likely occur between the availability of storage systems, or other alternatives, and access to interconnections as the cost of battery storage, in particular, continues to decrease.

This report is intended to provide the general characteristics, specific conditions and best practices of insular power systems from selected locations around the globe with a desire to highlight specific innovative technology, policy, and regulatory practices for a 100% RES system, based largely on PV.

1.2. Definition of Insular Power System

An insular power system was initially defined as an electric power grid structure in a physically isolated, geographical area, that is typically an island [2-3]. This definition has been refined and expanded to recognize the country's inability due to geographic size and/or remoteness, to connect with other electricity generators and consumers outside its borders [4] with access to large, and usually more efficient power markets because of economies of scale. The expanded definition of insular power systems is similar to the definition of emerging power systems, where geographic size and/or remoteness are also main attributes. However, general attributes of insular territories that must be considered when developing a power system also include a limited range of available natural resources, a limited ability to achieve economies of scale, seasonal variations in population, high infrastructure costs, climatic conditions and microclimates, offshore territories for interconnections, limited waste management, fisheries, and agriculture dependency. Combining these thoughts, an **alternative definition of insular power systems is a territory that is geographically defined**

by conditions that makes interconnections with large power systems unattractive economically compared to alternatives based on the combination of endogenous energy, storage systems, and power electronics.

It is also necessary to add other conventional restrictions to limit the scope of study for insular power systems. These systems can be classified into four groups: **(i) very small (< 1 MW and < 2 GWh/yr.); (ii) small (1 – 5 MW and 2 – 15 GWh/yr.); medium (5 – 35 MW and 15 – 100 GWh/yr.); and large (> 35 MW and > 100 GWh/yr.)** [2]. The limitation is in terms of peak power demand and annual power demand instead of other indicators (e.g., population or area) because many islands experience large seasonal variability in electricity consumption, mostly due to tourism. In general, we **limit our study to medium and large insular power systems** because these are the most complex, challenging and costly for a 100% renewable energy solution to be implemented. Our study is also limited to **insular power systems in IEA countries** in general, except to highlight very specific best practices that may accelerate the transition to 100% RES production on other islands.

1.3. Key parameters for Insular Power Systems

The first parameter defining the peculiarities of an insular power system is the high cost of the electricity supplied to customers. The average price of electricity for different countries can be extracted from the World Bank database (Table I).

Table I: 2020 average price of electricity included in the World Bank Doing Business Report for selected IEA countries (blue) [5], and for insular territories (grey).

country	USD/kWh[1]	country	USD/kWh[1]	country	USD/kWh[1]
Antigua and Barbuda	0,449	Grenada	0,309	Philippines	0,181
Australia	0,204	Haiti	0,211	Portugal	0,222
Bahamas, The	0,285	Iceland	0,122	Samoa	0,385
Barbados	0,266	Italy	0,168	São Tomé and Principe	0,183
Cabo Verde	0,263	Jamaica	0,264	Seychelles	0,321
China	0,146	Japan	0,212	Solomon Islands	0,716
Cyprus	0,191	Kiribati	0,413	Spain	0,260

country	USD/kWh[1]	country	USD/kWh[1]	country	USD/kWh[1]
Comoros	0,281	Korea, Rep.	0,114	Sri Lanka	0,173
Denmark	0,242	Madagascar	0,113	St. Kitts and Nevis	0,306
Dominica	0,368	Maldives	0,394	St. Lucia	0,321
Dominican Republic	0,201	Malta	0,190	St. Vincent and the Grenadines	0,346
Fiji	0,218	Marshall Islands	0,406	Tonga	0,362
France	0,136	Mauritius	0,205	Trinidad and Tobago	0,660
Germany	0,256	Micronesia, Fed. Sts.	0,414	United States	0,181
Greece	0,204	Palau	0,321	Vanuatu	0,382

[1]For states the price of electricity is measured in U.S. cents per kWh. A monthly electricity consumption is assumed, for which a bill is then computed for a warehouse based in the largest business city of the economy for the month of March. The bill is then expressed back as a unit of kWh. The index is computed based on the methodology in the DB16-20 studies.

It should be noted that the price of electricity reported by the World Bank in Table I includes subsidies and also the values for countries where the cost of electricity is dramatically affected by extreme economic chaos (e.g., Venezuela showing the highest price of electricity worldwide). Further, these values do not consider the price or cost of electricity in insular territories belonging to these countries. However, it is obvious that the price of electricity in insular countries is higher than in continental ones (Fig. 1).

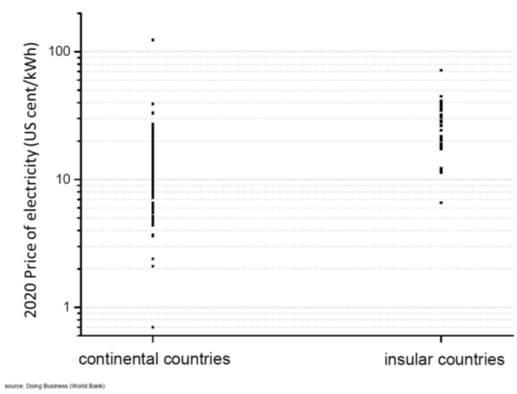

Figure 1: 2020 price of electricity for continental and insular countries considered in the Doing Business Report of the World Bank [5].

In the case of insular systems belonging to continental countries, (e.g., Hawaii) sometimes there are substantial differences between the price of electricity in continental and insular territories. In other cases, countries (i.e., Spain and France) have approved regulations to assure consistent electricity prices for all the territories under their jurisdiction. Indeed, in France, the electricity market has been open to competition since 2007. However, the price of electricity in the islands of Corsica, Réunion and Guadeloupe is set to mitigate the high generation production costs in these islands [6]. The inhabitants of these islands are charged a tariff similar to rates in continental France, and Electricité of France (EDF) is in charge of producing, distributing and commercializing the electricity. Thus, these islands are subject to a specific energy policy which requires achieving energy autonomy by 2030. Specific information about the cost of electricity for the insular power systems studied in this report is summarized in Table II. In this case, it is important also to refer the data to a specific year because this cost is greatly affected by the highly variable price of fossil fuels.

Table II: Generation cost of electricity in 2019 for selected locations and power mixes discussed in this report. Source: Endesa, KIUC, HECO

Insular System	USD/kWh-EUR/kWh
El Hierro	0,2862 EUR/kWh
Kauai	0,3430 USD/kWh
Maniisoq	0,3500 EUR/kWh
Tenerife	0,1742 EUR/kWh

The collection of data for Table II has been difficult because insular systems use to have the information not so publicly available that in continental power grids. This is usually due to the lack of wholesale markets defining the price of electricity under a fair composition between buyers and sellers. However, some insights can be obtained from these data, as the strong sensitivity between the size and isolation of the insular power system and the cost of the electricity, and also the difficulties to obtain a comparable data, as many time variations are dependent on the taxes system applied to the insular territory.

2. FUNDAMENTALS OF INSULAR POWER SYSTEMS

2.1. Grids in insular power systems

To guarantee supply security and reliability in any power system, the frequency of the grid must lie within a predefined range. If this predefined range is not maintained, automatic and manual grid protection controls begin to activate to protect equipment from long term frequency deviations and to assure the power system remains operational. These out of range frequency excursions are a significant challenge relative to assuring grid stability in insular power systems trying to reach 100% renewable energy from variable wind and solar PV resources. Other important concerns include fault protection, voltage control, and voltage stability (i.e., grid strength). The unique attributes of insular power systems (e.g., small grids, limited generation capacity, large seasonal demands, etc.) dictate that innovative and more resilient strategies must be implemented to assure grid stability.

Currently, kinetic energy from synchronously connected rotating generators (e.g., gas or steam turbines) and motor loads contribute to maintain operational frequency in the designated range, providing inertia. The inertia from energy stored in rotating parts of a turbine-generator can supply a load equal to the rated apparent electric power of the turbine-generator over a very short, yet defined time period. The inertia is linearly dependent on the inertial momentum and the square of the mechanical angular velocity of the rotor and is additive in a power system depending on the number of rotating units connected to the grid. This contribution is usually expressed in MW·s for large grid systems.

PV and wind power plants interface to the power grid through power electronic converters without electromechanical linkage to the system frequency; hence, without additional control features, they add no inertia to the power system. The same concern emerges from rotating motor loads connected to the grid through power electronics. For insular power systems where solar PV, wind and other sources are expanding, inertia is reduced. This can be mitigated through emerging power electronic synthetic or virtual inertia which can be introduced in the power system grid codes or as market services.

Conventional synchronous machines (i.e., rotating electromagnetic devices) contribute to what is commonly referred to as "strength" of a grid, meaning the ability of the grid to withstand current disturbances. Thus, **strong grids** are conventionally classified as those with many synchronous machines [7], where each synchronous machine acts as an "anchor" to fix the energy voltage and frequency at selected values and oppose sudden changes in these parameters in the proximity of the synchronous machine. The synchronous machines (e.g., turbo-generator drivetrains, hydroelectric plants, synchronous condensers, or synchronous motor loads) have a magnetic flux in the core that is resistant to sudden changes, helping to maintain a stable terminal voltage. Conversely, **weak grids** are conventionally classified as those that contain relatively few synchronous machines online. Typically, weak grid regions are those locations where large-scale renewable generation is sited far from load or other conventional generators. Insular power systems can experience sudden weak grid conditions across the entire grid if large amounts of wind and solar generation are added quickly to the grid and rapidly displace conventional generation. As solar PV increases significantly relative to synchronous sources during the day and on weekends when demand is lower, grid strength decreases. This reduction in grid strength can impact: (i) the severity of **voltage excursions and distortion**; (ii) **protective relaying** accuracy, (iii) **system frequency** event severity; and (iv) overall **system stability**.

As power electronic generation sources (e.g., wind, solar PV, and battery energy storage) increase on the grid, the inherent characteristics of synchronous generators that contribute significantly to grid stability diminish, even though the actual power (MW) produced remains very similar. Further, most power electronic devices depend on the AC power grid to define wave shapes and internal control functions. A routine grid event (e.g., switching shunt capacitors and energizing transformers) will produce greater voltage excursions and distortion on a weaker grid. Protective relays continuously monitor transmission and distribution lines for faults and disconnect these lines quickly when a fault is detected. They are designed to operate over a specified range of grid strength. If the grid strength falls outside of a predefined range, the protection scheme and relay settings need to be re-evaluated.

The **short-circuit ratio (SCR)** is one approach that can be used to quantify grid strength. The SCR can be defined at a particular bus in the grid as the ratio of the short-circuit current at that bus (in MVA) from only the synchronous machines in the grid to the MW rating of the power electronic equipment connected locally at the bus [7]. Values are obtained using complex models and electromagnetic transient programs. For locations with multiple power electronic plants connected close together, the Electric Reliability Council of Texas (ERCOT) has defined a simplified approach named **weighted short-circuit ratio** (WSCR) assuming that all power electronic equipment is closely connected. This approach can be adapted for insular power systems and, consequently, a single WSCR value can be calculated for an entire island for a given dispatch condition [7]. The validity of calculating a single WSCR for an entire island decreases as the size of the island increases; it may not be valid for large islands. Detailed electromagnetic transient studies are typically needed to truly determine stability of weak grids. However, there is a risk that **weak grid pockets** (e.g., where a large amount of power electronic devices are clustered together and connected to the grid by long transmission lines that separate these pockets from most of the large synchronous machines on the grid) will arise on the insular system and could become unstable. The WSCR simplified approach can be difficult to implement in an insular power system for multiple reasons: (i) the individual power-electronic devices deployed originate from a diverse number of vendors; (ii) there is no defined geographical differentiation between the placement of power electronic equipment, synchronous machines and loads; and (iii) the power electronics associated with generation are connected to the distribution grid, where the topology of the system is much more complicated. For these reasons, both SCR and WSCR are best used as guidelines to help identify cases in need of further study (e.g. through electromagnetic transient simulations), rather than to impose hard limits.

2.2. Grid codes in insular power systems

As the share of renewable energy generation sources increases in insular power systems, frequency deviations, voltage transients and harmonics are also likely to increase. To mitigate these detrimental impacts, operators must focus on several actions including: (1) the **proper design** or modification of the power system, (2) **counterbalancing** renewable energy fluctuations with flexible generation and demand, (3) **curtailment** of renewable systems, (4) **load shedding**, and (5) **advanced controls** of renewable energy sources.

A **grid code** is a technical condition or requirement for connecting and operating a power generator to the grid to assure continued power system stability when it is connected or disconnected. The requirements can be static (frequency, voltage, power factor, active power, etc.) or dynamic (fault ride through and fault recovery capability, etc.). Grid codes typically evolve depending on the share of renewable generation in the system:

1. **No renewable generation, or generation very low:** *No specific grid codes*
2. **Renewable generation is low:** *Grid codes ordering disconnection of renewable generation under disturbances in the power grid. (This type of grid code was common historically but is strongly recommended against going forward as it can result in serious grid stability problems as renewable generation becomes more common; retrofitting legacy generation can be very costly and logistically challenging).*
3. **Renewable generation is significant:** *Grid codes ordering renewable generation to remain connected to the power grid under specific disturbances (e.g., increasing fault tolerance and frequency ride-through capability). The capability to ride through voltage and frequency transients including high rates of change of frequency is strongly recommended for all modern grid codes.*
4. **Renewable generation is large:** *Grid codes adding communication protocols for receiving commands from the system operator for curtailment, ramping, or dispatch of grid services*
5. **Renewable generation is very large:** *Grid codes adding requirements for renewable generation to actively assure the power system stability (e.g., supply or absorption of reactive power, frequency response, grid forming capability, etc.)*

Rather than follow this evolution, which reflects the rough historical order in which grid codes have been updated, it is recommended for power systems now to consider implementing the requirements listed in items 3 through 5 as soon as it seems plausible that distributed generation levels may one day become high. This is recommended because, with the exception of communication networks, it costs very little to implement the above grid support functions when commissioning a system, but it is often very challenging for logistical, contractual, and economic reasons to add such grid support functionality after a distributed generation system is commissioned. Ride-through capability, reactive power control, and frequency response are all autonomous functionalities that a distributed generation inverter can perform without any need for communications, and at little to no cost, and hence are beneficial to improve grid operations with all levels of distributed generation. In contrast, communication-based functionalities, while potentially beneficial, require deployment and maintenance of a communication network, so benefits should be weighed against non-negligible costs.

DPV inverter manufacturers should fulfill additional requirements on their devices for actively assuring the stability of the power grid during the integration of high shares of intermittent renewable generation. Specifically, manufacturers should conduct tests to evaluate the performance of their devices under the weak grid conditions that are particular to insular power systems. These tests should lead to specific grid codes and inverter interconnection requirements for insular systems, that will also be useful for weak grid pockets in large power grids. An example of this could be to change under-frequency trip setting for solar inverters down to 56,5 Hz (in US) to remain connected during abnormal conditions to avoid exacerbating under frequency events. When the distributed generation penetration is of the order of magnitude of the large generation units, losing the DG due to a frequency deviation can cause an even wider frequency deviation.

2.3. Frequency Response

A common characteristic of all power grids is the requirement that system generation (supply) and system load (demand) must be balanced at all times. This balance is measured by the stability of system frequency (nominally 50/60 Hz) that is standardized for each grid across the globe. If generation is higher than load, frequency rises above the nominal level; if generation is lower than load, frequency declines below the nominal standard level. Given that the load on the system is constantly changing throughout the day, generation resources must constantly adjust their output to regulate grid frequency back to the standard level. Solar PV under conventional control constantly changes its supply output as a function of irradiance from the sun, typically relying on other generators with dispatchable supply to regulate frequency.

While minor fluctuations in grid frequency are normal and expected, large deviations are a risk to grid stability. Loads and/or generators may trip offline and grid collapse (black-out) becomes a possibility. While large generator trips are not common, they do occur in most island grids at least annually, so the grid operator must manage the grid to prepare for such events. Generally speaking, when this occurs the remaining online generating units quickly increase output to restore balance. These actions traditionally consist of quickly increasing generation from conventional generators (spinning reserves) controlled by the generator’s governors, which quickly detect any grid disturbance and balance the system usually in the range of seconds. For this purpose, it is typical to define the **net load** as the load after the subtraction of non-dispatchable generation from the overall generating power. Hence, as PV or other non-dispatchable sources increase, the net load decreases.

As example, Figure 2 shows a stable power system at a nominal frequency of 50 Hz and a generator trip event at 10 secs. The **frequency nadir** is defined as the lowest frequency point following a contingency event (point C in Figure 1), and the **frequency response** is defined as the change in power output from controlled power units (mostly generators). It should be noted that another option for the adjustment of generation and demand is load shedding, where the system load is reduced at the expense of disconnecting some customers from the power grid, but usually after a trip event, the generation is increased. Load shedding is more common is insular power grids than in large interconnections, but it is still generally used only as a last resort. In contrast, advanced demand response systems or fast-responding batteries may be able to achieve the same effect without blacking out customers. Over the course of some seconds, the power system will stabilize at a frequency that may be lower than the initial condition (e.g., 50 Hz) because the final restoration to the nominal frequency (50 Hz) requires a longer period through the re-dispatch of generation units, referred to as secondary frequency control.

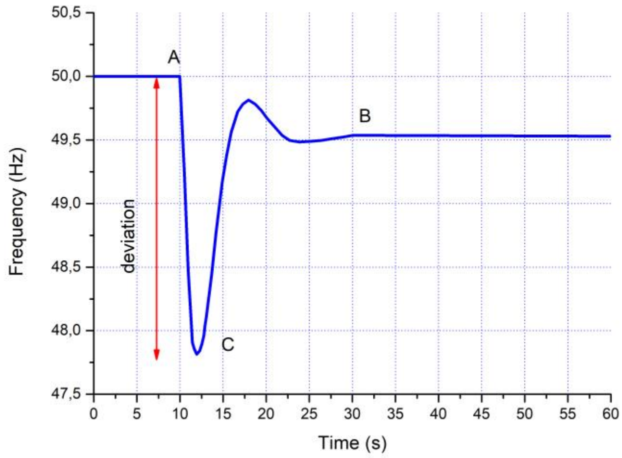

Fig. 2.- Illustrative example of the frequency response in a power system after a generation trip [1].

Insular power systems experience more frequent instabilities in part because of the basic attributes that drive electricity demand (e.g., seasonal tourism in islands with relatively small reserve capacity from conventional sources) and capacity (grid size, increasing renewables, disruptions of generation, etc.). Specific examples of contributors to insular system include:

- A single interruption of a large power unit in the system
- A low number of synchronous generators (i.e., low inertia)
- Synchronous generators that do not have governors
- The lack of interconnections to neighboring systems
- High level of PV and/or wind penetration

To counter imbalances when several causes are contributing, an **under-frequency load shedding** (UFLS) scheme can be added in addition to the generator governor response. As DPV increases on load feeders, the net load available to avoid imbalances is reduced and is less predictable. The UFLS protocol has several set points to shed load from different customers (e.g., alternating load shedding areas or subscribing interruptibility agreements). UFLS acts as an effective tool for maintaining grid stability, but it is used as a last resource because it interrupts customers' electric service without notice.

Emerging technologies can be used to improve system frequency response. For example, large-scale PV plants have been demonstrated to provide frequency response (similar to governor droop response), automatic generation control (secondary frequency control), and voltage control on the island of Puerto Rico and in other locations [8]. As the cost of battery energy storage drops, many PV plants are now coupled with storage to provide dispatchable renewable energy, capable of providing fast frequency response, load following, and many other services. Hawaiian Electric plans to stop relying on UFLS during typical loss-of-generation contingencies, instead using a battery system to provide fast frequency response [9]. It is technically feasible for a fleet of aggregated distributed PV and/or storage systems to provide similar services, though this technology has not been widely demonstrated.

Lowering the minimum operating power of thermal units would be also a mandatory option for the near future. This modification enables the thermal steam units to reduce their output to lower levels when renewable energy is available. This helps in increasing the "available room" on the grid to accommodate available renewable energy by increasing the ability to manage frequency with adequate downward regulating reserve.

For a deeper understanding of how an insular power system can increase the penetration of renewable technologies, the following studies can be performed [1,7,10]:

- Dynamic analyses considering inverter-based resources that are conducted by the utility, system operator, regulator or other stakeholders.
- Studies of load contingency events or short circuit ratios.
- Studies of different values of non-dispatchable renewable energy commissioned in the insular power system, as grid stability is not linear to the amount of renewable energy installed.
- Studies at the bulk-transmission grid level, and also at the individual distribution feeders.
- Studies about the circuit loading issues that arise from the increase in the share of renewable non-dispatchable energy from high levels of DPV.

2.4. Interconnections

The insular power systems defined in this report are those geographically defined by conditions that make interconnections with large power systems economically unattractive compared to alternatives, based on the combination of endogenous energy resources and storage systems. Given the advantages of interconnections for grid stability it is important to evaluate and understand the technical and economic conditions related to interconnections.

The most obvious costs related to interconnections are those associated with the power line joining the two power networks and include: electrical conductors and insulators, purchasing and erecting transmission towers, clearing the area where the power lines are placed, substations, control hardware and software. For calculating the cost of interconnections, we distinguish between submarine and aerial power cables and recognize that power losses vary substantially depending on current type and if the interconnection configuration is aerial or submarine. Generally, high voltage direct current (HVDC**)** is substantially more attractive for submarine and aerial connections than high voltage alternating current (HVAC**)** in terms of efficiency (Table III [11]), though economic considerations may make HVAC more attractive over shorter distances, especially for aerial lines.

Table III. General loss characteristics of HVAC and HVDC interconnections [11].

Operation	Losses	HVAC	HVAC	HVDC	HVDC
Voltage	kV	760	1,160	600	800
Aerial line	%/1,000 km	8	6	3	2.5
Submarine line	%/1,000 km	60	50	0.33	0.25
Terminal	%/terminal	0.2	0.2	0.7	0.6

For determining the **unit cost** of electrical connections there are databases connected to proprietary information and presumably accurate system data [12]. However, many times these data are limited to specific regions and time periods, and do not include the cost associated with submarine power cables. Early cost projections are often many times less than the final cost because specific project details are not fully known. Statistical learning methods (i.e., linear regressions, artificial neural networks or classification trees) are often introduced to assess cost estimates [13]. The primary cost elements for interconnections include at a minimum: (i) the cost of copper or aluminum used in the conductor; (ii) the number of conductor cores in each cable; (iii) the cross-section of the conductor; (iv) AC or DC; (v) the number of cables; (vi) the length of the submarine route; (vii) voltage and power; (viii) the cost of power conversion stations at each end of the cable; and (ix) operation and maintenance costs.

A database containing design features and commissioning data for 313 submarine power cables worldwide has been developed [13-14], where maximum submarine cable routes (425 km), depth (1,620 m), voltage (600 kV) and project length (up to 6 years) are provided as reference.

A bathymetric data map [15] provides important information about the seabed depth between the islands that must be traversed which contributes significantly to the cost of submarine interconnections and may actually make the interconnection unfeasible from the technical and/or cost perspective. Tools are available to establish a first approximation of the average costs for HVAC and HVDC interconnections (Table IV [11]). A reasonably accurate multivariate adaptive regression splines (MARS) model, trained and tested elsewhere with data input usually publicly available [13], is also available if a more precise cost determination is required.

Table IV. Average costs for HVAC and HVDC interconnections [11].

Operation	Cost	HVAC	HVAC	HVDC	HVDC
Voltage	V	760 kV	1,160 kV	600 kV	800 kV
Aerial line	MEUR/km	0.45 – 0.84	1.12	0.45 – 0.50	0.28 – 0.34
Submarine line	MEUR/km	3.58	6.60	2.80	2.00
Terminal	MEUR/terminal	89	89	280 - 391	280 – 391

Finally, it is important to recognize that the interconnection option for insular power systems should not be intended as an alternative for the total replacement of the generating units of any insular power system, but serves as a complement to assure appropriate security levels of energy supply in the insular system. Indeed, grid planning standards typically consider the n-1 rule and limit the capacity of the interconnection to the largest power unit in the insular system that can supply electricity to the grid. There can be attempts to supply the insular power system with two independent interconnections and, thus, to fulfil the n-1 rule. However, other limitations may be introduced specifically for interconnections. Indeed, EirGrid, the system operator of Ireland, has introduced limitations on “simultaneous non-synchronous penetration”, including HVDC imports from interconnections, to 70% due to stability concerns, with curtailment required afterwards [1].

2.5. Storage

Energy storage is a principal option for integrating large shares of variable energy in insular power systems. Storage systems can act as loads when charged and as generators when discharged. As many power purchase agreements (PPAs) associated with the production of electricity from wind and solar PV resources are “take-or-pay”, there is an incentive for the operator to store the curtailed energy for later use. Storage systems for islands include primarily batteries and pumped hydropower but in the future may also include thermal storage, thermochemical storage, and power-to-fuel-to-power systems, among others. Storage addresses three main concerns in insular power systems:

(i) **Balancing** large amounts of wind and solar PV power under primary, secondary and/or tertiary regulation requires more storage than in large power grids because there are no exchanges or balances between different renewable resources.

(ii) Insular power systems are more likely to have **low inertia** and low grid strength than large interconnected systems; fast-responding battery energy storage systems (BESS) can be designed to address these concerns by providing advanced controls such as primary frequency response, FFR, fast voltage regulation, and grid-forming controls.

(iii) **Seasonal storage** is also an important concern, mainly in seasonal-touristic islands and in those islands where the wind and solar resources vary greatly over the year.

There is no specific storage configuration that fits all grid and use cases. There are different configurations, where power (MW), energy ratings (MWh) and cell chemistry will offer different services to the grid. A storage system can provide different services to power plants and power grids at the generation, transmission, distribution and customer side:

- system ramp management
- fast frequency response (FFR)
- primary frequency response
- frequency regulation/secondary reserves
- spinning and non-spinning reserves
- replacement/tertiary reserves
- capacity resource
- energy arbitrage
- curtailment avoidance
- wind/solar firming/smoothing
- replacement of UFLS
- voltage regulation
- grid-forming controls
- black start
- congestion reduction
- reliability improvement deferral upgrade
- reduction of outage rates
- DER integration
- power supply uninterruptibility
- demand charge management
- offer and demand aggregation
- seasonal storage
- energy bill management

Many of these services can be offered while the storage system is charging or discharging and can be simplified into energy shifting, system ramp management, and regulation and contingency reserves. Power and energy ratings should be defined based on the specific service the storage system will provide. An overall storage round trip efficiency value can be considered for each technology to evaluate the best options depending on the intrinsic characteristics of the insular power system under consideration.

Energy storage systems are co-located and/or co-operated with renewable energy systems with increasing frequency. For example, it is becoming common in Hawaii for both distributed and utility-scale PV systems to be coupled with BESS [9,17]. The electric coupling between the PV and the BESS can occur either before the DC energy is converted to AC (known as DC coupling), or after the energy is converted to AC (known as AC coupling). Historically DC coupling was common only for small distribution-connected systems, but DC coupling is now becoming common for utility-scale systems as well, allowing excess PV energy to be very efficiently stored in the battery for later use. The optimal choice between AC coupling and DC coupling depends on the expected pattern of use of battery energy and co-located renewable energy. The more renewable energy stored for later use, the more DC coupling makes economic sense.

Battery energy storage systems are interconnected to the power system through inverters, very similar to PV inverters and Type IV wind converters. Thus they share many of the characteristics specific to power-electronic coupled generation, including the ability to respond very quickly when needed, and the ability to independently control power and reactive power.

Battery energy storage systems can be an enabling technology for grid-forming inverter controls, which help stabilize power systems with extremely high instantaneous levels of inverter-based generation. It is technically feasible for renewable resources without storage to provide grid-forming controls, but it is technically more challenging and requires at least some level of curtailment at all times.

Planning a 100% insular power system based largely on solar PV requires that the storage system: (i) is charged utilizing what is normally curtailed solar energy, (ii) increases the system's load during hours or days of surplus solar energy; (iii) increases the system generation during hours or days of solar energy deficit; (iv) frees up reserve generators operating at their minimum power; (v) allows lower cost generating units to operate more efficiently and ramp less; and (vi) covers seasonal variability of renewable resources and power demand.

2.6. Power Electronics

Power electronics holds great promise in replacing the legacy of synchronous generators and significant reliance on inertia and mechanical frequency response, with inverter-based resources, including wind, solar PV, and certain types of energy storage, while maintaining system reliability. Current primary frequency response (PFR) practices, based mainly on fuel valves in synchronous power generators, rely on relatively slow-responding mechanical systems. The response range from actual synchronous generators is not linear, and a typical range of response rates is about 0.3%/sec for slower responding units to 2%/sec for fast units, including certain gas turbines. It takes about 0.5 sec for the synchronous generator output to begin to increase. In contrast, some power electronic resources can respond within as little as a few AC line cycles (50-100 ms) if desired.

As more renewable, non-dispatchable power is injected into the grid, the amount of inertia available from synchronous generators and other sources is decreased while the demand for more inertia to maintain grid reliability continues to increase. Inverter-based resources (IBRs) such as PV, wind, and BESS with advanced controls for fast frequency response (FFR) can reduce the need for conventional inertia and synchronous generator response. Inverter-based resource controls can respond much faster than conventional resources, potentially reducing the amount of inertia actually needed, which mitigates the significance of reducing the amount of inertia available. Current research activities point to the possibility of maintaining grid frequency in systems with very low or no inertia, by the development of grid forming inverters [18]. Grid-forming inverters are already used in many zero-inertia microgrid systems (typically less than 10 MW), with others acting in grid-following mode (the conventional control mode of most inverters today). Stabilization of future insular power systems that operate at times with 100% inverter-based resources may be accomplished through a combination of grid-forming inverters, grid-following inverters, and synchronous condensers. The specific amounts of each type of resource needed for a given scenario is an area of active research, and may be system-specific.

Power electronic resources have the capability to control their active and reactive power output largely independently, subject to device current limits. This allows inverters interconnecting PV, wind, and storage to provide frequency-related services such as FFR simultaneously with voltage regulation controls leveraging reactive power. When current limits are reached, system designers should consider whether inverters should prioritize reactive or active current; it is often best to prioritize reactive current in order to support voltage. Standards can provide guidance on these topics [18].

Power electronic resources have strict output current limits that are needed to avoid damage to their internal components. Among other things, this means that protection systems may need to consider adjustments as PV, wind, and storage become the dominant resources. Inverters can also be programmed to adjust the phase angle and sequential components of their fault current in ways that assist with fault detection. Alternatively, (or in addition), synchronous condensers can be used to provide fault current in inverter-dominated systems.

To obtain full dispatchability of inverter-based resources, they must be held at less than full output capacity, providing headroom (i.e., the difference between full output and the inverter-controlled holding value) to increase output as needed, similar to conventional generators. When this active power dispatchability is used to provide a grid stabilizing response on inertial time-scales (sub-second response times), it is referred to as fast frequency response (FFR). Some results show that wind IBRs can increase output by as much as 25%, and solar PV IBRs can increase output over its full range in much less than a second [19].

As mentioned previously, energy storage is another IBR capable of providing FFR and other services. Indeed, some batteries can increase output over their full range in less than a second and provide additional flexibility by quickly switching between charging and discharging states. In addition, solar PV and wind IBRs can operate over a larger range of power plant output levels than thermal generators, which are restricted by minimum generation levels. Moreover, the periods when inertia is at the lowest level because of high penetration of solar PV and wind, corresponds to the times where large amounts of headroom from IBRs is likely to be available due to IBRs operating in a curtailed state. Then, growth in wind, solar PV and storage can be considered not a challenge but an opportunity to reach 100% renewable energy in insular power systems. In combination, the transition to inverter-based resources represents a paradigm shift in how we think about providing frequency response today [19].

A market is being built in many power systems for electricity consumers to offer ultrafast flexibility in power demand to the power grid, and also for DPV producers to offer ultrafast flexibility in power injected to the power grid, based on premiums for the providers of such flexibility. Aggregators are the new actors that can provide access to the market for these small distributed IBR players. Examples of flexibility options managed by the aggregator could include provision of demand response, PFR, FFR, or load-shifting.

Finally, blockchain technology can provide secure record-keeping for highly distributed inverter-based resources, allowing those resources to be economically compensated for grid services, for example seamlessly and autonomously restoring the system after a blackout. While blockchain itself is not a power electronics technology, it may enable greater grid use services in the future from highly distributed power electronics-based generation.

3. RESILIENCE CONSIDERATIONS FOR INSULAR POWER SYSTEMS

3.1. Introduction

Insular power systems serve as an excellent test bed and learning center for assessing best practices that have significant relevance to improving the resilience of power systems in all locations around the globe. The challenges associated with assuring a resilient insular power system, defined by our ability to anticipate and adapt to changing conditions that influence the power system or to respond, withstand or recover rapidly from disruptions, are substantial and require a disciplined and systematic planning and implementation process to mitigate those factors most likely to impact system resilience [20]. Insular power systems are routinely impacted by a number of factors including a limited range and type of generation and distribution resources, aging infrastructure, interconnections to other systems, cyberattacks, constrained economies of scale, highly variable seasonal demand (e.g., tourism), vulnerability to extreme weather events, climatic conditions and impacts from climate change, and natural disasters associated with hurricanes/typhoons, volcanoes and earthquakes, among others. The impact of these factors and others are inextricably linked to the health and well-being of the local economy, to the availability of financial investment resources and to the responsiveness of critical community services such as the availability of water, medical care and communication for citizens.

As natural, technological, and human-caused threats grow increasingly more complex and sophisticated for all power systems, many are exacerbated for insular power systems. In particular, climate-related threats (e.g., frequency and intensity of typhoons, magnitude of sea-level rise, etc.) and natural disasters (e.g., earthquakes, volcanoes, etc.) often disrupt the entire power system for months and even years in insular systems, having an associated impact on all segments of the economy. Infrastructure reliability and scale are greatly impacted in smaller generation systems because generation disruption has a disproportionate effect for smaller grids. Greater penetrations of distributed power capacity from renewables will influence overall resilience depending on their scale, distribution and connectivity across the island. Developing an in-depth understanding of the local threats and impacts is critical to assess the unique vulnerabilities of the power system, to delineate the most important risks and to develop solutions that mitigate these risks. This risk mitigation strategy will vary depending on the type of renewable resource (e.g., hydro, geothermal, wind and solar PV) which could respond differently to external events (e.g., floods, hurricanes, volcanoes, etc.), the connectivity of renewables within the power system and the connectivity to other dispatchable generation and storage sources.

3.2. Lessons Learned on insular power systems resiliency

Many insights and lessons learned have been gathered from insular power systems throughout the Caribbean as a result of the 2017 hurricane season and the widespread destruction from Hurricanes Harvey, Irma and Maria. In many cases, the most extensive damage was experienced by the transmission and distribution system and the overall electrical grid [21]. Investments in grid improvements should be based on detailed modelling, such as load flow and contingency analyses, to identify optimal resiliency and hardening benefits for the transmission system. To reduce this damage in the future a number of grid hardening activities should be considered including burying power lines on primary and secondary systems underground. Placing utility lines underground eliminates the distribution system's susceptibility to wind damage, lightning, and vegetation contact. However, underground utility lines present significant challenges, including additional repair time and much higher installation and repair costs. Perhaps more importantly, for insular power systems underground wires are more vulnerable to damage from storm surge flooding than overhead wires [22].

Upgrading damaged poles and structures can protect against high winds (up to 250 km/hr.). For distribution systems this usually involves upgrading wooden poles to concrete, steel, or a composite material, and installing support wires and other structural supports. For transmission systems, this usually involves upgrading aluminum structures to galvanized steel monopoles or concrete, ensuring industry-best practices for vegetation control to protect grid asset integrity, and elevating critical structures (e.g., substations, control rooms and pump stations) or relocating mission critical facilities to prevent damage from flooding. Results presented in the Puerto Rico "Build Back Better " Report [23] suggests that steel monopole towers may be more resilient under high wind conditions than steel lattice structures because the wind cross section is smaller. Smart sensors and control technology can also help mitigate impacts to power flow and to identify system problems in near real-time. The broad scale adoption of micro-grid systems, guided by detailed analysis to determine the potential applicability and location, can also minimize power system impacts locally and facilitate system repair and restoration efforts. Hardening of interconnections, which includes the coupling between the underground cables and substations, is essential to mitigate storm surge impacts and minimize subsequent recovery time. Resiliency entails a certain amount of redundant capabilities in the power generation, transmission, and distribution functions. Electric utilities generally try to manage the potential costs of actions to promote system reliability by considering the risks of various extreme weather events. Deciding just how much redundancy is considered necessary will likely go beyond the usual cost-benefit analyses to address perceived risk.

Experience from 2017 shows that electric system resiliency can enhance utility preparedness through programs and investments which improve general readiness (e.g., conducting hurricane preparedness planning and training, complying with inspection protocols, participating in mutual assistance groups, improving employee communications and tracking, purchasing or leasing mobile transformers and substations, and procuring spare equipment). Storm-specific readiness can also be improved by activities such as maintaining minimum fuel tank volumes, facilitating employee evacuation and re-entry to storm areas, securing fuel contracts for emergency vehicles, expanding deployment staging areas, and supplying logistics to recovery staging areas [24].

3.3. Resilience of Renewable Generation Assets

The resilience of renewable generation assets is now becoming more important as more insular power systems move to transform their generation capacity from fossil fuels (mainly diesel, fuel oil and natural gas) to the alternative low carbon systems of tomorrow (solar PV, wind, geothermal, small-scale hydro and others). Currently solar PV distributed across islands in the Caribbean is the fastest growing power generation source for most islands. Experience from 2017 with solar PV in the Caribbean show that the impact of hurricanes on these systems was site or location-specific, with some island power systems (e.g., Puerto Rico, US Virgin Islands and Barbados) suffering major damage or complete failure, and others (British Virgin Islands, Turks, and Caicos) that continued to produce power the next day with limited impact. Lessons learned and insights from this experience are instrumental in deploying systems for the future and provide a basis for best practices to improve insular system resilience [22]. Post-storm assessments of several PV solar systems revealed many similarities in failure mechanisms including module clamp systems, undersized racks, under-sized bolts or under-torqued bolts, a lack of bolt locking solutions and a lack of lateral racking support. Conversely, the PV solar systems that prevailed after these storms often had through-bolted modules (i.e., no clamps), bolts with locking solutions and lateral racking supports. Further assessments of the key observations by the Rocky Mountain Institute (RMI) conducted in a systematic assessment identified a number of key recommendations that were categorized as either system specification findings or collaboration findings [21]. These findings include:

System Specifications Findings:

- Specify high-load (up to 5,400 Pa uplift) PV modules, based on structural calculations; these are currently available from a number of Tier-1 module manufacturers.
- Require structural engineering in accordance with ASCE 7 and site conditions, with sealed calculations for wind forces, reactions, and attachment design (ground-mount foundation).
- Confirm with the racking manufacturer that actual site conditions comply with their base condition assumptions from wind-tunnel testing.
- Specify bolt QA/QC process: there were several instances of inadequate torqueing of bolts in the investigation—a workmanship and oversight issue.

- Specify bolt hardware locking solution.
- Specify through bolting of modules as opposed to top-down or T clamps. If top clamping is required, use clamps that hold modules individually or independently.
- Require structural engineer review of lateral loads due to racking and electrical hardware—often lateral loads are missed and recent failures have proven them to be a critical source of weakness (e.g., combiner boxes attached to end solar array posts caused increased loading and led to failure).
- Do not recommend trackers for projects in Category 4 (210 - 250 km/h) or higher wind zones
- Specify all hardware be sized based on 25 years (or project life) of corrosion.
- Do not recommend any self-tapping screws.
- Specify dual post fixed tilt ground mounts, which significantly reduce foundation failure risk.

Collaboration recommendations identify opportunities for increased resiliency, which require multi-party consideration and action but do not represent current industry standard actions.

- Collaborate with module suppliers for implementation of static and dynamic load tests representative of Category 5 hurricane winds.
- Collaborate with racking suppliers for full scale and connection test representative of Category 5 winds.
- Collaborate with equipment suppliers to document material origin and certificate of grade and coating consistent with assumptions used in engineering calculations.
- Perhaps the most opportune recommendation is for a regional and even international community of solar PV power plant stakeholders who have extreme wind exposure to regularly share lessons learned from new designs and extreme wind events.

Calculating the additional cost to implement the recommendations for enhanced resilience depends on the specific projects and sites. In the Eastern Caribbean, RMI estimates that a 1 MW ground mount project on suitable soil and flat terrain would incur an increase of approximately 5 percent (~ $ 90,000) in engineering, procurement, and construction (EPC) costs when these best practices are implemented versus the standard category IV rated installation. These additional costs come in the form of labor for the extra time needed to through-bolt the modules and install more foundation and racking supports. There are also additional costs in material (racking supports, dual post piers, and fasteners) as well as minor costs for additional engineering and construction oversight.

Wind turbines are also subject to significant damage from hurricane force winds whether they are land-based or offshore [25], and are designed with built-in mechanisms to lock and feather the blades (reducing the surface area pointing into the wind) when wind speeds exceed 90 km per hour (for reference, a Category 1 hurricane has sustained winds of ~120km/hr.). Basically, the wind turbine is placed in "survival mode," waiting for the storm to subside, so it can safely go back to producing energy.

Offshore wind turbines are also subjected to large powerful waves that interact with the tower structure and underlying foundation. Our understanding of this dynamic process continues to evolve to include extreme loading conditions, coupling of hydro-aerodynamic forces and other impacts that will become more obvious as our understanding of the anatomy of a hurricane continues to improve [25-26].

Researchers predict new offshore wind turbines could face hurricane wind gusts of more than 350 km per hour in the future. Design criteria for offshore wind turbines today are largely based on extensive offshore European experience. The vast majority of this experience is in regions where hurricane conditions do not exist. In many cases, wind turbine design criteria will not include wind gusts that exceed 250 km per hour. Failure modes can include loss of blades, buckling of the supporting tower and damage to the nacelle. Turbine blades are relatively easy to replace although their loss can cause other structural damage that is costlier. Modelling predictions on hurricane damage to the turbine structure often incorporate assumptions for maximum sustained wind speeds and for yaw conditions that range from no yawing to the condition where the nacelle can yaw at a rate to track variations in the wind direction of the hurricane. The non-yawing case is a very conservative but realistic assumption because often during a hurricane the wind turbines lose all backup power required for the yaw motors, potentially leading to extensive damage resulting in widespread power failures. [26]. Wind turbine design standards require that turbines withstand a yaw misalignment of up to ± 180° if no yaw backup power is available. In addition, the wind direction in a hurricane may change faster than a wind turbine can yaw resulting in severe structural damage. Future design advancements are taking both of these elements into consideration as part of the design process [26].

Forensic analysis completed on a large number of wind turbine failures (715 sources) between 1999 and 2009 [16] shows each type of accident and the distribution of wind turbine accidents that occurred after a case-by-case analysis of descriptive statistics. The majority of accidents were associated with wind turbine structural failure and blade failure accidents (~ 35%) with a lesser but significant number of accidents involving tower collapse (62 of the 715 cases, 8.7%). Of the 44 identified turbine failure cases, storms (34.1%) and strong winds (18.1%) were the primary external forces causing turbine collapse worldwide and serve as the main factors that must be considered when evaluating risk for the wind turbine lifecycle including planning, design, construction, and operation. Other factors included fire, material fatigue, and braking system failure.

In 2003 Typhoon Maemi struck Miyakojima Island (Japan) with a central pressure of 912 kPa [16]. An average wind speed of ~ 140 km per hour and a maximum gust of ~ 275 km per hour were recorded at the Miyakojima' meteorological station. The observed wind direction showed a sudden change in wind direction of 120°. All the wind turbines on the island were extensively damaged. Three of six turbines collapsed and the other three suffered destructive damage including broken blades or the nacelle cover drooped (REF). The maximum bending moment of the foundation of Nanamata wind turbine No.1 was larger than the ultimate bending moment, resulting in complete failure of the foundation. Turbines 3 and 5 buckled and collapsed as a result of the maximum bending moment exceeding the ultimate bending moment.

Based on these collective observations, the integration of wind turbines into insular power systems must accommodate a number of possible conditions that further complicate the resilience assessment of these systems under adverse conditions. Backup power to manage turbine yaw throughout a storm event becomes critical. Foundation designs must accommodate substantial bending moments as storms intensify and the nacelle structural integrity must be preserved throughout a storm event. It is necessary to evaluate the ultimate strength of the turbine in the design process and it is important that the manufacturers provide data needed to perform structural analysis and wind resistant design [9]. As a result of these studies and observations and others, it is recognized that as storms intensify in response to climate change, the designs of wind turbines must be continually reassessed or the impacts on insular power systems can be catastrophic.

4. OVERVIEW OF BEST PRACTICES IN INSULAR POWER SYSTEMS

Today, more than 100,000 islands of variable size and population are scattered across the world with nearly 500 million inhabitants. These islands have become laboratories for transforming the global energy system and for leading the way to a more sustainable energy future in large part because their survival depends on it. While each island is unique in its own right, they share several attributes (e.g., isolation, lack of interconnections, limited land availability, seasonal population variations, etc.) and a common goal to reduce electricity costs while ensuring a stable electrical grid that supports sustained economic development. Many islands are on the cusp of this energy transformation, have experienced some great successes and have provided tremendous opportunities for others to learn and innovate to meet their specific needs. This Section attempts to characterize the general attributes of many of these islands (Figure 3) and to capture some of the key insights and best practices that have accelerated their transformation or have impeded their progress:

- Coober Pedy (Australia)
- Easter Island (Chile)
- El Hierro (Spain)
- Galápagos (Ecuador)
- Kauai (US)
- King Island (Australia)
- Maniitsoq City (Greenland – Denmark)
- Maui (US)
- Nii Jima and Shikin Jima (Japan)
- Tenerife (Spain)

Fig. 3.- Location of the Insular power systems under study in this report.

4.1. Coober Pedy (Australia)

Iain McGill and Dale Philip

Coober Pedy is a town in south-central Australia built solely for the local opal mining industry, located 846km north of the state capital of Adelaide. The mining town has no connection to the east Australian electricity grid, with electricity being supplied by a 4.24MW diesel station. In 2017, the Coober Pedy Renewable Hybrid Project was implemented with $18.4M of the $38.86M cost being supplied from the Australian Government's Renewable Energy Agency as part of wider funding to explore taking remote Australian communities off-grid. The design of the system was based on the successful King Island insular system, designed by Hydro Tasmania.

The upgraded power system includes 4 MW of wind, 1MW solar PV; with a hybrid renewable system that supports the variable renewable energy involving two 850kVA diesel uninterruptable power supply (DUPS) with flywheels maintaining system stability during high renewable output, a 1.5MW/0.49MWh battery and 3MW dynamic resistor system for load control. The new Coober Pedy Renewable Hybrid project has led to 70.7% of energy supply coming from renewable sources in 2018 and 75.6% in 2019. The original diesel systems are maintained in case of system failure, but the project was run on a "zero-diesel" basis for 52% of 2019; saving more than 2.1 million liters of diesel per year. The system has seen success in continuous operation, setting a record 71.5 hours continuous in 2018 then building on this with 97 hours in 2019.

Contingency events such as a load feeder trip, diesel generator trip or wind or solar feeder trip are extreme variability events. The system has proved very resilient to such events which continued to occur in FY19 with only 2 unplanned outages of average duration 0.52 hours. The DUPs with flywheels are particularly important to this resilience. The frequency of engagement is highly variable and dependent on RE variability, but on average the DUPS engage around 1.5 times per day. The 1MW solar array sees response times in the order of seconds, therefore are curtailed before the wind as system stability measure.

With the successful implementation and operation of the Coober Pedy insular system, EDL was engaged to design and operate a similar system for the Agnew Gold Mine in Australia. The Agnew microgrid project is dramatically larger than the Coober Pedy mine with 22MW (4Mw Solar & 18MW wind) renewables supplemented by 19MW (16MW gas & 3MW diesel) hydrocarbons. With successful operation, Agnew will provide more evidence that insular systems can be operated with high renewables in many applications, regardless of size.

Table V.- Coober Pedy power system master table.

Insular Power Systems	Coober Pedy, Australia
2019 Attributes	

Population	
• Inhabitants	1762
• Floating	No Data Available (NDA)
Surface (% protected)	NDA
GDPpc (Coober Pedy, 2019)	57000 AUD [44225 USD] (District Council of Coober Pedy, 2020)
Solar radiation (non protected areas)	1925 kWh/kWp (SolarGis, 2021)
Total Energy Demand	11,6 GWh
Electricity price	
• Residential	338,7AUD/MWh (SA Government, 2021)
• Industry	360,8 AUD/MWh (SA Government, 2021)
% renewable electricity	~75%
Record % instantaneous renewable	100% [97 hours continuous December 2019]
Curtailment of renewables	42% [Curtailment and “spill” through dynamic resistor]
Total Generation Capacity (MW)	5.94MW Conventional + 5MW RE Gen + 1MW/0.5MWh storage
• Heavy Oil steam turbines	-
• Diesel engines	Eight 530kW Diesel fired Gen units. Two 850kVA Diesel UPS, Hitzinger/Cummins KTA38
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	Two 2.05MW Senvion MM92 wind turbines
• Solar PV	1MW Solar Array + 0,83MW Domestic (Clean Energy Regulator, 2021)
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro (pumping)	-
Power peak	NDA
Conventional minimum/full load ratio	30%
• Battery	1MW/0.5MWh
• Pumped Hydro	-
• Thermal	-
Programmed shedding	3897MWh Spilled into dynamic resistors over 2018/19FY
Water Treatment	4.12% Electricity consumption of town [based on 40,240kWh per month energy consumption] (A. De Munari, 2009)

SAIDI & SAIFI

	Year	Unplanned Outages (occurrences)	Duration (hours)
Pre-hybridisation	FY15	4	3.5
	FY16	5	1.1
	FY17	4	4.2
	Average	**4.3**	**2.9**
Post-hybridisation	FY18	4	0.47
	FY19	2	0.52

A. De Munari, D. C. B. R. A. S., 2009. Application of solar-powered desalination in a remote town in South Australia. Desalination, 248(1), pp. 72-82. Clean Energy Regulator, 2021. Postcode data for small-scale installations - All Data. [Online] Available at: http://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/Postcode-data-for-small-scale-installations.aspx [Accessed 10 03 2021].
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SolarGis, 2021. Global Solar Atlas. [Online] Available at: https://globalsolaratlas.info/map?c=-29.013368,134.753616,11&s=-29.013368,134.753616&m=site [Accessed 05 03 2021].

4.2. Easter Island (Chile)

Lionel Perret

Easter Island is one of the most remote inhabited islands in the world, located at more than 3,500 km from the nearest continental point. The triangle-shaped island extends over 164 km^2, with a local population of 7,700 inhabitants (2017). During the tourist season, the population grows significantly with around 100,000 visitors. The climate of Easter Island is maritime subtropical; the temperatures typically vary between 16 and 25°C with average wind speeds between 20 and 30 km/h. The island benefits from an annual horizontal irradiation of 1,544 kWh/m^2. Currently, electricity is supplied by six diesel-based generators, for an overall annual electricity consumption of 13.2 GWh, with a minimal permanent power of approximately 1 MW in 2017. In 2018, the first PV generation plant composed of 400 solar panels providing a total power of 100 kWp was inaugurated.

A recent study [27] analysed the financial and performance advantages and disadvantages of different electricity production mixes. These mixes include various novel and classical production and storage units as shown in Figure 4. The objective was to identify the economic potential for renewable energies on remote islands such as Easter Island. The interest is all the greater as these areas are heavily dependent on fossil fuels imported by cargo boats. This leads to higher prices as compared to the mainland and induce energy supply uncertainty.

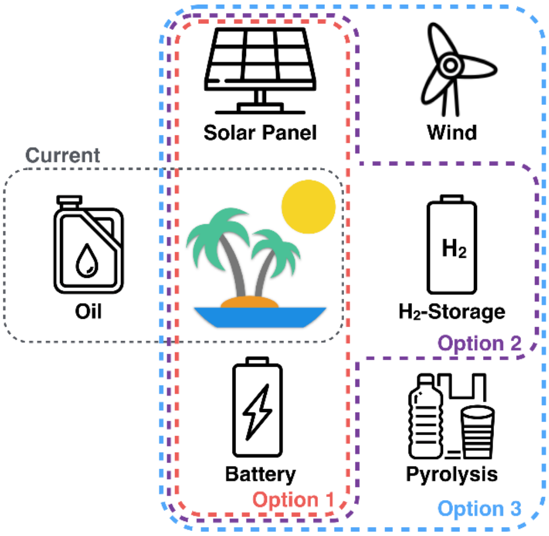


Figure 4: Illustration of the electricity production mixes explored.

The results of this study show that more diversified production and storage resources come with both decreased energy losses and overall cost, as illustrated in Figure 5 and 6, respectively. A first conclusion that can be drawn from these results is that an exclusively PV production leads to an oversize of the whole system with a significant impact on the investment costs. In contrast, including other energy resources as presented in Option 3 decreases both installation costs and energy losses. Indeed, that option exploits the complementary nature of production sources: PV and wind sources present complementary production profiles, and pyrolysis ensures a baseline production at all times. The implementation of a pyrolysis plant would also take advantage of plastic waste, a major problem on the Island. The initial investment costs for each option is represented in Figure 5a. Finally, Figure 5b shows that the electricity cost in the case of such an energy system would be close to the current one, which is currently heavily subsidized by the Chilean state.

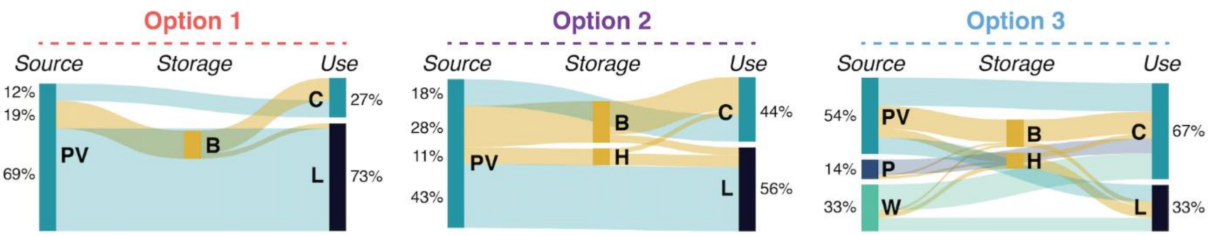


Figure 5: Summary of the annual energy fluxes between energy sources, storage systems and uses. Energy sources include photovoltaic (PV), wind turbines (W) and pyrolysis (P); storage systems include lithium-ion batteries (B) and hydrogen-based storage (H); and uses include consumption (C) and losses (L).

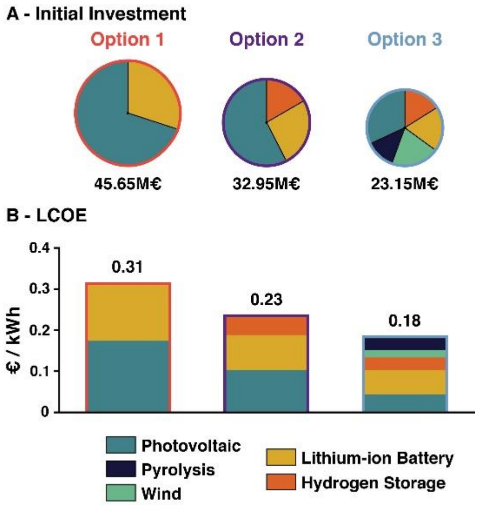


Figure 6: (A) Initial investment costs for each option in millions of € and (B) the levelized cost of energy (LCOE) based on the energy consumed over the first year. A discount rate of 3% was considered to compute the LCOE.

In spite of favorable weather conditions and a significant economic potential for renewable energies, the energy transition on the island raises different concerns. The production is currently centralized in the south-west end of the island, but the deployment of a distributed energy production requires to dispatch production sites across the island, which is likely to come with additional grid costs and constraints coming from the limited unprotected sites available. Likewise, the scenery impact of wind turbines has raised controversy on Easter Island. Alternatives exist, such as kite power, but these constraints result in the need for a tailor-made solution and delay the implementation of a rapid energy transition.

Table VI.- Easter Island power system master table.

Insular Power Systems	Easter Island, Chile
2019 Attributes	
Population	
● Inhabitants	7,700 (2017)
● Floating	+/- 100,000 annual visitors
Surface	164 km^2
Solar radiation	1,544 kWh/m2
Temperature	16° C to 25° C
Total Energy Demand	13.2 GWh
Electricity price	
● Residential	Between 0.08 (very low consumers) and 0.32 EUR/kWh (subsidized)
● Industry	0,32 EUR/kWh (subsidized)
% renewable electricity	1%
Record % instantaneous renewable	8%

Curtailment of renewables	None (yet)
Total Generation Capacity (MW)	8,05 MW
• Heavy Oil steam turbines	-
• Diesel engines	8.05 MW
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	-
• Solar PV	126 kWp
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro	-
Power peak	2,2 MW
Conventional minimum/full load ratio	2
Storage	None
• Battery	NA
• Pumped Hydro	NA
• Thermal	NA
% synchronous generation	99 %
Frequency	
• Δf > |150 mHz|; < 5 min	Hours
• Δf > |250 mHz|	Hours
New Projects Planned/Coming Online	2 to 5 MWp PV plant in planning Related energy storage in planning

4.3. El Hierro (Spain)

Ricardo Guerrero-Lemus, Les E. Shephard

El Hierro is an island of 268,7 km^2 and 10.986 inhabitants (2018). It is the least populated island of the Canaries, an archipelago situated at the northwest of Africa, Spanish territory from the XV century and integrated in the European Union. This island has an isolated power grid, and it is not expected in the future to be connected to any other power system. El Hierro generated 42,87 GWh in 2019 (Table VII), and most of this energy is produced in a wind park (11.8 MW) belonging to a hydro-wind power station (Gorona del Viento SA) composed of 6 Pelton hydro turbines (11,32 MW) and 8 pumping systems (6 MW). The storage capacity of the upper water reservoir is equivalent to about 2 days of electricity supply to El Hierro. There is also a thermal power plant for backup services composed of 11 diesel engines (14,9 MW) [28].

The solar resource in El Hierro is quite high, reaching values about 1900 kWh/kWp·yr. in favorable locations, mostly in areas oriented to the southeast, but PV capacity installed is minimal (0,03 MW) due to an historical political consensus to reserve the potential renewable capacity to the wind farm belonging to Gorona del Viento. The wind resource is also high, but irregularly distributed throughout the year. Indeed, higher wind speeds are regularly concentrated in July and August (Figure 7) so that electricity in July is mostly supplied by the hydro-wind power plant whereas in most other months electricity is mostly supplied by diesel engines. Also, the power system is showing that the maximum annual share of renewable energy reachable is about 55%, but irregular (56% renewable penetration in 2018, 54.5% in 2019, and 41,8% in 2020).

It is important to mention that the severe wind gusts produce an average curtailment of about 25% of the wind resource potentially available at the 11.8 MW wind farm to avoid frequency and voltage excursions out of the defined limits, despite the Spanish grid codes have been adapted to the insular power systems to make these more flexible. Indeed, voltage and frequency limits for the insular systems are the following:

Table VII.- The ranges within which grid operators must maintain the Canary Islands power systems (P.O. 12.2).

voltage dip	90 - 1%, 10 ms - 1 min
voltage stability	0,85 pu - 0,90 pu: 1h 0,90 pu - 1,118 pu: unlimited 1,118 pu - 1,15 pu: 1 h
frequency	47,0 - 47,5 Hz: 3 sec 47,5 - 48,0 Hz: 1 h 48,0 - 51,0 Hz: unlimited 51,0 - 52,0 Hz: 1 h

Indeed, with these more flexible parameters still there are detected substantial frequency excursions (Table VIII).

All this accumulated experience in recent years is very useful for concluding that the production of electricity from wind has reached a limit, and additional increases in wind capacity would not significantly increase the share of renewable energies in El Hierro. Then, the insular government has understood that to increase the share of renewable energies in El Hierro the introduction of PV-battery systems, including grid forming inverters, is needed. A first step will be to connect a 1 MW PV system with batteries that could add power fast frequency response services to the grid. It is also crucial to optimize introduction of PV-battery systems and the role of the hydro-wind power station in the power system.

Table VIII.- El Hierro power system master table.

Insular Power Systems	El Hierro, Canary Islands, Spain
2019 Attributes	
Population	
• Inhabitants	10.968
• Floating	About 300
Surface (% protected)	269 km^2 (61.34%)

GDPpc (Canary Islands, 2018)	20.892 EUR
Solar radiation (non-protected areas)	~ 1900 kWh/kW$_p$ in most favorable areas
Total Energy Demand	42,87 GWh
Electricity price (IEA Key World Energy Statistics 2019, subsidised)	
• Residential	311,5 USD/MWh
• Industry	127,5 USD/MWh
% renewable electricity	54,4 (- 3.7% compared to 2018)
Record % instantaneous renewable	160,8% (100% supplied to El Hierro and 60.8% for pumping) (24 continuous days in July 2019)
Curtailment of renewables	About 25% of wind energy
Total Generation Capacity (MW)	14,9 MW conventional + 22,85 MW renewable
• Heavy Oil steam turbines	-
• Diesel engines	14,9
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	11,8 (98% connected to control centers)
• Solar PV	0,03 (0% connected to control centers)
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro (pumping)	11,32 (6 MW pumping capacity)
Power peak	8,1 MW (20/08/2019, 21:20)
Conventional minimum/full load ratio	50% diesel engines
Ramping up from technical minima	+24%/10min diesel engines
Storage	
• Battery	1 MW / 3 MWh
• Pumped Hydro	210 MWh
• Thermal	-
% synchronous generation	
Costs	
• Fossil fuels	548,31 EUR/t for diesel oil
• Variable generation costs	96,95 EUR/MWh
• Fixed generation costs	18,93 EUR/MWh (0,559 MEUR/MW·yr)
Frequency	
• $\Delta f > \|150 \text{ mHz}\|$; > 5 min	6,37 hours
• $\Delta f > \|250 \text{ mHz}\|$	29,73 hours
Programmed shedings	0
Unprogrammed shedings	0
Water Treatment	33% of the electricity consumed in the island
• Desalination	About 1,3 Hm^3/yr.
New Projects Planned/Coming Online	1 – 2 MW large PV plant under study

SAIDI (min)	Documental force majeure	0,0
	Other causes	55,2
	Planned with notice	26,4
	Planned without notice	25,0
	Third parties	44,6
SAIFI (min)	Documental force majeure	0,00
	Other causes	2,97
	Planned with notice	0,12
	Planned without notice	0,10
	Third parties	0,73

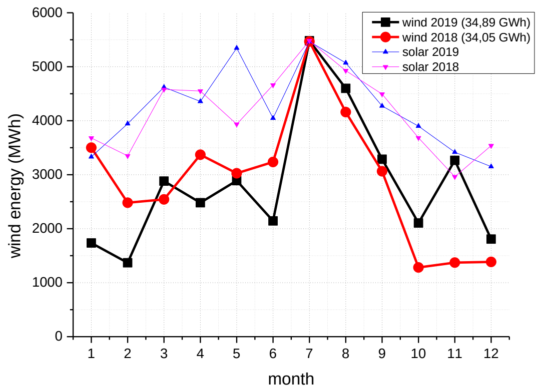


Fig. 7.- Monthly wind energy production in El Hierro in 2018 and 2019, and expected monthly shape of the PV production considering PV production in Tenerife the same years.

4.4. Galápagos (Ecuador)

Gunter Arnold

The archipelago of Galapagos consists of more than 100 small and 13 medium sized islands (≥ 10km²) with an accumulated land area of approx. 7,880km². The archipelago of Galapagos belongs to Ecuador and is situated in the eastern, equatorial Pacific Ocean, around 1000km distant to the mainland of Ecuador.

Only five of the Galapagos islands are populated (Santa Cruz, San Cristóbal, Isabela, Floreana and Baltra) with a total number of 30,000 residents and around 270,000 visitors per year (2018). Due to its unique wildlife (fauna and flora) most of the land

(97%) and of the surrounding oceanic area (99%) belongs to the protected UNESCO world heritage sites since 1978/2001.

The annual electric energy demand in the five inhabited islands of the Galapagos archipelago amounted to 49.091GWh (2017/2018). Up to now, thermoelectric power stations with diesel-gensets are the main source of electricity generation with an aggregated rated capacity of 27.6MW (85% of energy demand). Distributed renewable energy power plants (Solar PV systems and wind turbine generators) with a rated capacity of 8.9MW are producing approximately 15% of the annual energy demand.

Due to its geographic location close to the equator in the eastern Pacific Ocean the solar and wind conditions are very good in many sites of the Galapagos archipelago. In 2007 the Ecuadorian government launched a policy “Cero combustibles fósiles en las Islas Galápagos al 2020”- No fossil fuel on the Galapagos Island up to 2020. In the context of this policy several RES projects have been realized in the last years:

- Hybrid System on Isabela: 0.952MWp PV + 660 kW / 330 kWh Battery
- Hybrid System on Baltra: 0.067MWp PV + 4MWh (Lead-Acid) + 268 kWh (Li-ion) Batteries
- Hybrid System on San Christobal: 1.0MWp PV + 2200kWh Battery
- PV System Puerto Ayora on Santa Cruz: 1.5 MWp
- Windfarm on San Christobal: 2.4MW (3 x 800kW)
- Windfarm at Baltra on Santa Cruz: 2.25 MW (3 x 750kW)

Further RES installations are planned in the next years up to 2025.

Table IX.- Galápagos power system master table.

Insular Power Systems	Galapagos Islands Archipielago de Colon - an offshore territory of Ecuador
2017/2018 Attributes	
Population	
• Inhabitants	Approx. 30,000 (2018)
• Floating (visitors /a)	About 270,000 (2018)
Surface (% protected UNESCO world heritage site)	7,880 km^2 (97%)
GDPpc (Ecuador, 2019)	11,375 USD
Solar radiation	Up to 1800 kWh/kW$_p$ in most favorable areas
Total Energy Demand	49.091 GWh
Electricity price	
• Residential (LV)	173.9 USD/MWh
• Industry (LV)	123.2 USD/MWh
% renewable electricity	Around 15 %
Total Generation Capacity	27.6 MW conventional + 8.9 MW renewable
• Heavy Oil steam turbines	-
• Diesel engines	Diesel: 27.6 MW

	Vegetable Oil based: Isabela: 5x 0.325 MW Floreana: 2x 0.069 MW
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	San Christobal: 2.4 MW Baltra-Santa Cruz: 2.25 MW
• Solar PV	Santa Cruz: 1.5 MWp San Christobal: 1.0 MWp Isabela: 0.952 MWp Baltra: 0.067 MWp
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro	-
Storage	
• Battery	Isabela: 660 kW / 330 kWh (Li-ion) Baltra: 4MWh (Lead-Acid) + 268 kWh (Li-ion) San Christobal: 2.2MWh

Creative Policies	In 2007 the Ecuadorian government launched a policy “Cero combustibles fósiles en las Islas Galápagos al 2020”- (No fossil fuel on the Galapagos Island after 2020).

4.5. Kauai (US)

Brad W. Rockwell

Kauai is the fourth largest of the Hawaiian Islands (1,456 km^2) and 72,029 inhabitants (2016). Kauai’s climate is tropical, with generally humid and stable conditions all over the year.

Although the data for the number of under frequency load shedding (UFLS) events on Kauai are not readily available (Table X), the activation of UFLS has gone way down as a result of the large amounts of BESS that are now present on the system. Kauai used to shed load any time a generator tripped, and now they can cover even the largest generator with the batteries. Indeed, it must be highlighted the very precise synergy of DC coupled PV and BESS, where the PV fluctuations can be absorbed by the BESS with very little losses, and then converted to AC on demand when the grid needs it. That conversion occurs through shared inverters, so the amount of equipment is reduced.

Also Fast Voltage Response, or Volt/VAr response, has proven very helpful in Kauai high-penetration system and the utility has prioritized that over FFR in batteries, up to a point.

Synchronous condensers have been demonstrated as a very cost-effective way to maintain grid stability as increased renewables displace conventional synchronous generators. By keeping the generator and interconnection to the grid, and using them to provide inertia, voltage support, and fault current, the grid can be kept very stable even while at 100% IBR. Kauai's system has come close to this situation.

Table X.- Kauai power system master table.

Insular Power Systems	Kauai, Hawaii. USA
2019 Attributes	
Population	
• Inhabitants	72.293
• Floating	27.734 (this is average daily tourist count)
Surface (% protected)	
GDPpc (2018)	58.981 USD
Solar radiation (non protected areas)	~ 5.7 kWh/m2/day in most favourable areas
Total Energy Demand	460 GWh
Electricity price (average 2019 KIUC Rate)	
• Residential	327,5 USD/MWh
• Industry	286,3 USD/MWh
% renewable electricity (2019 total)	56,6
Record % instantaneous renewable	100,0+% (first achieved in Nov 2019; have since achieved on 150+ different days, for as long as nine hours at one time) *this does not include additional energy that is being stored in batteries while operating at 100%, but a significant amount of energy is also being stored while operating at 100%, we just haven't tried to measure that yet
Curtailment of renewables	Total of 646 MWh for 2019; total of 1.004 MWh Jan-Jun 2020 (increase due to lower demand caused by COVID and lack of tourism)
Total Generation Capacity (MW)	116 MW conventional + 134 MW renewable
• Steam turbines (ULSD fuel)	9 MW
• Diesel engines (ULSD fuel)	40 MW
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle (ULSD or naphtha fuel)	67 MW
• Wind	-
• Solar PV	110,8 MW
• Concentrating Solar	-

• Geothermal	-
• Biomass	6,7 MW
• Hydro	16,3 MW
Power peak	80 MW
Conventional minimum/full load ratio	~0% (we can run everything at min load)
Ramping up from technical minima	We try to keep ramps at 5 MW / min or less
Storage	
• Battery	53 MW / 230 MWh
• Pumped Hydro	-
• Thermal	-
% synchronous generation	55,6% (139 MW oil + biomass + hydro/ 250 MW total)
Costs	
• Fossil fuels	2019 average: $16,68 USD/MMBtu ULSD and $13,90 USD/MMBtu naphtha
• Variable generation costs	2019 average: $167 USD/MWh
• Fixed generation costs	$176 USD/MWh (0,379 MEUR/MW·yr)
Water Treatment	
• Desalination	-
New Projects Planned/Coming Online	35 MWac Solar PV and Pumped Storage Hydro

4.6. King Island (Australia)

Iain MacGill and Dale Philip

King Island is situated in the Bass Straight channel between mainland Australia and Tasmania, with a population of approximately 1600 people living across the 1100km^2 island. The island is not connected to either the mainland or Tasmania and is owned by the state-owned utility Hydro Tasmania. Electricity on the island was traditionally supplied by a 6 MW diesel power station then converted to a hybrid energy system in stages from 1998-2014. The renewable energy on the island now consists of 2.45MW of wind and 0.47MW Solar PV; with a hybrid system that aids in maintaining system stability and managing surplus renewable generation including a 3MW/1.5MWh Lead Acid battery, two 1 MVA flywheels, 1.5MW dynamic resistor and an aggregated customer demand response system. The hybrid system also included a 200kW/800kWh vanadium-redox battery system, but an overcharging event led to irreparable damage to the system and is no longer in commission and was replaced by lead acid batteries.

The main project aim was to reduce the reliance on the diesel power station on the island and has seen resounding success. King Island now supplies 65% of its annual energy needs using renewable energy, with the island energy system running at 20% of the year with “diesel off” (100% renewable penetration); setting a world record at the time of 33 hours straight at 100% renewable generation in 2015. The success of this project can be attributed to the non-generation aspects of the hybrid system that were installed from 2008 onwards. Two diesel uninterruptable power supplies were installed with 1MVA flywheels, with the diesel gen rarely operating and the flywheels being supplied from excess wind energy. The flywheels enabled the system to be run with the diesel off, filling the "gap" between wind/solar rapid supply drop and the maximum ramping of the diesel generation and ensuring system stability through instantaneous backup and voltage control. Other excess wind/solar is stored in the 3MW/1.5MWh battery which can supply energy to the island for 45 minutes at typical peak demand. Finally, frequency control is ensured through load management, coordinated via the 1.5MW dynamic resistor and an aggregated customer demand response of approximately 200kW (Dusan Nikolic, 2019).

In late 2019, Hydro Tasmania put forward amendments to the Tasmania Energy Code which removed an exemption for generating units less than 5kW from being required to enter into an agreement with Hydro Tasmania that gives them the contractual right to interrupt their generation. This is in response to increasing rooftop solar generation in the community, reducing the controllable generation available to the operator and reducing the ability to maintain system stability.

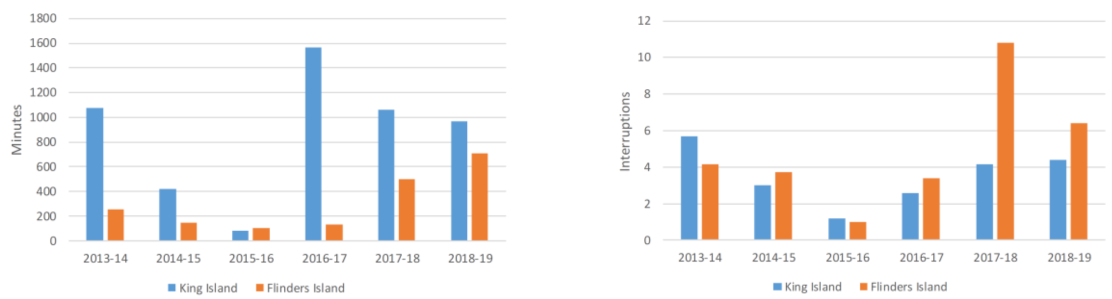
The success of the King Island Renewable Energy Integration Project has resulted in the system design being used in other insular territory energy grids in Australia; including Flinders island (Tas), Rottnest Island (Western Australia) and Coober Pedy (South Australia). Additionally, the island continues to test new renewable energy systems, with a 200kW wave swell energy 12-month trial commencing in February 2021.

Table XI.- King Island power system master table.

Insular Power Systems	King Island, Australia
2019 Attributes	
Population	
● Inhabitants	1585 (Australian Bureau of Statistics, 2016)
● Floating	-
Surface (% protected)	1100 km^2 (61.34%)
GDPpc (State of Tasmania, 2019)	61,249 AUD (Knoema, 2020)
Solar radiation (non protected areas)	~ 1350 kWh/kW$_p$ (SOLARGIS, 2020)
Total Energy Demand	12 GWh
Electricity price (Momentum Energy energy retailer tariffs)	
● Residential	203,18 USD/MWh (Momentum Energy, 2019)
● Industry	203,18 USD/MWh [According to energy retailer, same for all customers]
% renewable electricity	65% per annum
Record % instantaneous renewable	100% over 33 hours in 2015 (average 20% or higher per annum of diesel off operation)

Curtailment of renewables	About 25% of wind energy
Total Generation Capacity (MW)	6 MW conventional + 22,85 MW renewable
• Heavy Oil steam turbines	-
• Diesel engines	6
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	2,45
• Solar PV	0,47
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro (pumping)	-
Power peak	2,5 MW
Ramping up from technical minima	+24%/10min diesel engines
Storage	
• Battery	3 MW / 1.5 MWh
• Pumped Hydro	-
• Thermal	-
% synchronous generation	
Costs	$18M for renewable energy integration
Water Treatment	33% of the electricity consumed in the island
• Desalination	About 1,3 Hm^3/yr.
New Projects Planned/Coming Online	200kW Wave energy generation 12 month trial beginning Feb 2021

Australian Bureau of Statistics, 2016. *2016 Census Quickstats.* [Online] Available at: https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/604031093 [Accessed 20 11 2020].
Dusan Nikolic, M. N., 2019. Smart Grid in Isolated Power Systems - Practical Operational Experiences. *Energy Procedia,* Volume 159, pp. 466-471. Knoema, 2020. *Tasmania - Gross Domestic Product per Capita, Current Prices.* [Online] Available at: https://knoema.com/atlas/Australia/Tasmania/GDP-per-Capita [Accessed 20 11 2020].
Momentum Energy, 2019. *Electricity Tariffs,* Hobart: Momentum Energy. SOLARGIS, 2020. *Global Solar Atlas.* [Online] Available at: https://globalsolaratlas.info/map?c=-39.893934,143.768463,9&s=-39.656456,143.978577&m=site [Accessed 20 11 2020].



(a) (b)

Fig. 8.- (a) System Average Interruption Duration Index (SAIDI) in minutes; and (b) System Average Interruption Frequency Index (SAIFI) in number of interruptions, for the insular power systems of King Island and Flinders Island.

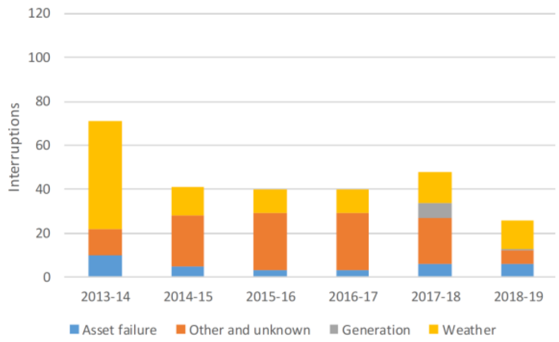


Fig. 9.- Cause of interruptions for the insular power systems of King Island in the period 2013-19.

4.7. Maniitsoq City (Greenland - Denmark)

Kenn H.B. Frederiksen

Maniitsoq City is a remote city on an island located in the southwestern part of Greenland. It is the sixth largest city in Greenland. The city has 2.467. inhabitants (2019) and the main business in the city is the fishing industry. Maniitsoq is a part of the municipality of Qeqqata which covers an area of 115.000 km2. The climate in the region is artic and can get down to (-) 35°C in the winter and up to (+) 20°C in the summer.

The island has an isolated power grid as do most of the cities in Greenland. The generation is 112,48 GWh/year which is primarily produced by the 4,47 MW installed diesel powered gensets. In the last decade PV has become a renewable power source and the installed capacity at the moment is about 0,5 MW.

The vision for the utility Nukissiorfiit is that all their supply of water and energy in 2030 will be without the use of fossil fuel. Currently almost 72% of the consumption is covered by renewable energy.

The energy balance for the whole of Greenland is a bit different with approximately 75% from fossil fuel, approximately 20% from renewable energy and the remaining part from waste heat.

With the future expected increase of solar power in the island, the utility Nukissiorfiit is having a greater focus on the long-term power planning with RE and how this should be implemented.

Table XII.- Maniitsoq City power system master table.

Insular Power Systems	Maniitsoq City, Greenland
2016/2018/2019 Attributes	
Population	
• Inhabitants Greenland	55.992

• Inhabitants Maniitsoq	2.467
• Floating	NA
Surface (% protected) Greenland Maniitsoq	 2.166.000 km^2 (X%) 79.500 km^2
GDPpc (2016)	233.600 DKK (31.314) EUR
Solar radiation	800 kWh/m^2 (Yearly Global Radiation)
Temperature	- 35° C to +20° C
Total Energy Demand Greenland Maniitsoq settlement	235 GWh 12,48 GWh
Electricity price	
• Residential	221,19 EUR/MWh
• Industry	198.68 EUR/MWh
Total Generation Capacity (MW)	9,53 MW conventional + 0,5 – 0,6 MW Solar
• Heavy Oil steam turbines	-
• Diesel engines	Normal operation 1 x 1,275 MW 1 x 1,275 MW 1 x 1,920 MW Backup generator (reserve capacity) 1 x 0,92 MW 1 x 0,92 MW 1 x 0,92 MW 1 x 1,90 MW 1 x 0,40 MW
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	-
• Wind	-
• Solar PV	0,5 – 0,6 MW
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro	-
Power peak	2,2 MW
Conventional minimum/full load ratio	1:2
Costs	
• Sum of generation cost	350 EUR/MWh

4.8. Maui (US)

Julieta Giráldez and Andy Hoke

Maui is the second-largest of the Hawaiian Islands (1,883 km^2) and a population of 145,834 (2015 – 16). Tropical and quite uniform temperatures are observed all over the year, but orography produces a wide range of climatic conditions and weather patterns.

We describe first the transmission-related changes, followed next by the distribution-related changes based on the lessons learned in the Hawaiian Islands.

The first actions to adapt to the rapid increase in rooftop solar PV that were taken by Hawaiian Electric after 2012, when solar capacity penetration surpassed 10% of the peak load, were:

1. **Lowering the minimum operating power of thermal units.** This modification enables the thermal steam units to reduce their output to lower levels when renewable energy is available. This helps in increasing the “available room” on the grid to accommodate available renewable energy by increasing the ability to manage frequency with adequate downward regulating reserve.
2. **Change under-frequency trip setting for solar inverters down to 57 Hz** to remain connected during abnormal conditions to avoid exacerbating under frequency events. In 2014, both under and over frequency-ride-through were required (57-62.5 Hz), **as well as low- and high-voltage ride-through (0.85-1.13 pu)**. When the distributed generation penetration is in the order of magnitude of the large generation units, losing the DG due to a frequency deviation can cause an even wider frequency deviation.

During the past few years, it has become increasingly clear that integrating additional rooftop solar PVs onto the grid will require capabilities of state-of-the-art advanced inverters to participate in maintaining stable and reliable operations. Therefore, the most feasible way for PV inverters to support the grid is by autonomously responding to local conditions (i.e., to the ac voltage waveform the inverter measures at its terminals) in a way that stabilizes voltage and frequency.

The wider frequency settings are recommended to be studied and required from the earlier stages of DG deployment since re-programming inverters that have already been installed is not an easy task, often hard or impossible to do if solar developers don’t have communication capabilities to and from the inverter, and/or if the upgrade affects the certifications or warranty of the equipment. In a collaboration with inverter manufacturer Enphase Energy in 2014, approximately 60% of the legacy DG PV capacity in Hawaii was re-programmed to enable wider Frequency Ride-Through (FRT) settings, which was important in creating a critical mass of inverters that would not trip offline with frequency deviations. This retrofit was partly enabled by Enphase’s large market share in Hawaii markets, and could be harder to implement in a different market environment.

In 2017, the Hawai‘i Public Utilities Commission approved Hawaiian Electric’s interconnection requirement of frequency-watt control for all new solar PV systems.

Today's PV inverters can reduce power in response to over-frequency events. The typical way of doing this is called frequency-watt control, and it follows a frequency-watt curve (Figure 10). If an inverter has additional active power available, it can also increase power in response to under frequency events, which could potentially be an even more helpful modification.

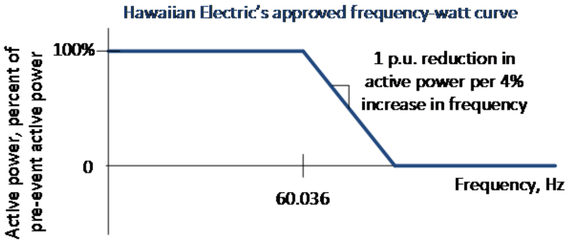


Figure 10. Hawaiian Electric's approved frequency-watt droop curve.

Another important effect of distributed generation is that it can affect the ability to perform under-frequency load-shedding. In island systems, utilities such as Hawaiian Electric, rely on shedding load to arrest under-frequency events to a greater degree than larger interconnections. However, if there are high percentages of distributed generation embedded in the block of load that the utility intended to use for load-shedding, it considerably reduces the amount of load reduction, and as such, its effectiveness in counter-balancing the under-frequency issue. In 2018, Hawaiian Electric performed a system stability study and changed the under-frequency load-shedding schemes to dynamically account for the effect of distributed generation by measuring real-time feeder loads and adjusting load-shedding accordingly. In the future, Hawaiian Electric hopes to avoid load-shedding entirely for most contingencies using fast-responding utility-scale PV-battery systems.

Finally, in 2019, Hawaiian Electric started to upgrade the manual unit-commitment of generation assets to a new software for unit-commitment that is capable of including a forecast of DG that results in more accurate calculations of the required regulation reserves needed based on the DG foreca**st**. By understanding the amount of regulating reserve required to manage the system frequency with renewable energy, unit commitment is currently being adapted to take into consideration renewable energy variability along with customer loading.

In the distribution grid, the impact of having reverse power flow tends to cause steady-state voltages to rise on the distribution system, sometimes to levels that exceed American National Standards Institute (ANSI) C84.1 requirements. Hawaiian Electric has been adapting to the impacts of solar on the distribution grid by:

1. **Updating legacy utility-owned voltage regulation equipment** such as load-tap-changers (LTC) and voltage regulator settings in order to accommodate the voltage rise during the day and bi-directional current flow. Most conventional voltage regulator controllers are not bi-directional, (i.e. the devices cannot detect the direction of the current flow), and when DG production is high and load is low during the day, the voltage regulator or LTC will compensate and step up primary voltage, resulting in unacceptable high voltage levels.

2. **3-Phase rebalancing of load and PV on specific circuits** with voltage issues, also reducing losses and thermal heating on distribution assets.
3. **Deploying grid-edge distribution primary circuit measurement devices** that help planners and operators with increased visibility and improve the ability to diagnose grid problems and validate the models to come up with innovative solutions.
4. **Upgrading secondary circuit infrastructure**, in particular older overhead low-voltage circuits with a large number of customers connected relative to the service transformer size, and where customers are fed by highly resistive secondary and service conductors.
5. **Requiring volt-var control in PV systems** in order to have local reactive power support.

From a distribution planning perspective, Hawaiian Electric first invested in distribution modelling software in 2012 in order to be able to perform power flow studies on their distribution feeder models. In 2013, high-penetration PV studies were performed on a subset of feeders, and later in 2016, a full hosting capacity study was performed on the distribution system and posted publicly on Hawaiian Electric's website for customers and customer developers to consult. The map (Figure 11) indicates the approximate amount of available hosting capacity on the utility' primary distribution network[2], and give an indication of potential grid constraints mapping feeders with up to more than 250% GDML (gross daytime minimum load), i.e., the minimum feeder load the utility would see during daylight hours if PV were not present.

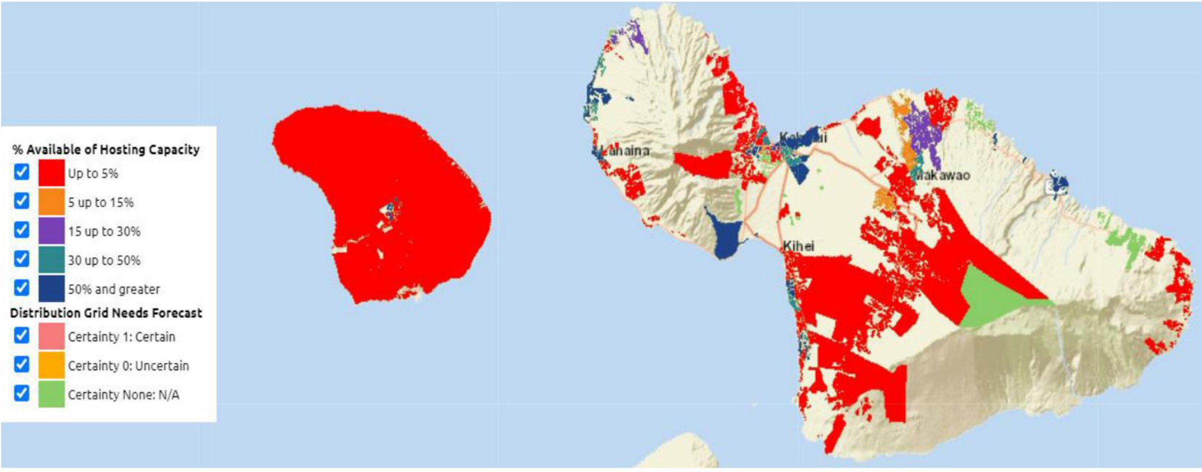


Figure 11. The Locational Value Map / Address Tool on the island of Maui allows customers and solar contractors to see approximately how much space may be available for private rooftop solar installations in their area.

Table XIII.- Maui power system master table.

Insular Power Systems	Maui, Hawaii

[2] https://www.hawaiianelectric.com/clean-energy-hawaii/integration-tools-and-resources/locational-value-maps

2019 Attributes	
Population	
• Inhabitants	167.000
• Floating	About 60.000
Surface (% protected)	1.883 km^2 (10%)
GDPpc (2019)	64.000 USD
Solar radiation (non protected areas)	~ 1800 kWh/kW_p in most favorable areas
Total Energy Demand	1.450 GWh
Electricity price (IEA Key World Energy Statistics 2019, subsidised)	
• Residential	336,5 USD/MWh
• Industry	309,7 USD/MWh
% renewable electricity	40,8%
Record % instantaneous renewable	80% (4/14/2018)
Curtailment of renewables	2,5%
Total Generation Capacity (MW)	231,7 MW conventional + 221,1 MW renewable
• Heavy Oil steam turbines	25
• Diesel engines	95,6
• Coal steam turbines	-
• Open cycle gas turbines	-
• Combined cycle	111,2
• Wind	72
• Solar PV	5,7 (central) 143,4 (distributed)
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro	-
Power peak	200 MW
Conventional minimum/full load ratio	23-48% steam; 28-34% diesel engines
Storage	
• Battery	21 MW
• Pumped Hydro	-
• Thermal	-
% synchronous generation	20% minimum (2018)
Costs	
• Fossil fuels (2016)	• 5,59 USD/MMBtu for medium sulfur fuel oil (<2% S) • 9,87 USD/MMBtu for ultra-low sulfur diesel • 9,52 USD/MMBtu for No. 2 diesel
Frequency (2017)	
• $\Delta f > \|150\ mHz\|$	7,24 hours
• $\Delta f > \|250\ mHz\|$	3,39 hours

Water Treatment	32% of the electricity consumed in the island (including for water heating)
• Desalination	None
New Projects Planned/Coming Online	205 MW additional PV+BESS planned by 2024: https://www.hawaiianelectric.com/clean-energy-hawaii/our-clean-energy-portfolio/renewable-project-status-board

SAIDI (min)	External	200
SAIFI (min)	External	2,1

4.9. Nii Jima and Shikine Jima (Japan)

Yuzuru Ueda, Yuta SATO, Takeshi MAENO and Toshiyuki KUROYAGI

Nii Jima and Shikine Jima are small islands of 27.52 km^2 (Nii Jima 23.64 km^2, Shikine Jima 3.88km^2) and 2,635 inhabitants (2019) located in the Tokyo prefecture in Japan. They are islands that make up the Izu Islands, and are located about 160 km south of Tokyo. Nii Jima and Shikine Jima are interconnected by submarine cable because the distance between the two islands is about 8km. These islands have an isolated power grid.

Nii Jima and Shikine Jima generated 21.6 GWh in 2013 (Table XIV), and energy is produced with diesel generation (7.7 MW), wind power (600kW) and solar power (485kW) supported by battery storage (1084kWh). The wind power, solar power and battery were installed by New Energy and Industrial Technology Development Organization (NEDO) in 2016 for demonstration project. These renewable energies and storages can increase the ratio of renewable energies to the power grid scale of the two islands, thus simulating the situation of Japan's major power grids in the future. These are used to investigate the effects of integrating variable renewable energies and the grid inertia.

Table XIV.- Nii Jima and Shikine Jima power system master table.

Insular Power Systems	Nii Jima and Shikine Jima, Japan
2019 Attributes	
Population	
• Inhabitants	2635
• Floating	-
Surface (% protected)	27.52km2 (Nii Jima 23.64 km2, Shikine Jima 3.88km2)
GDPpc (2019)	
Solar radiation (non protected areas)	~6.85kWh/ m^2 (Daily maximum, typically in July)
Total Energy Demand	21.6GWh (2013)

Electricity price (IEA Key World Energy Statistics 2019, subsidised)	
• Residential	19.52 JPY/kWh
• Industry (example, < 500kW)	17.05 JPY/kWh in summer peak 15.94 JPY/kWh in other seasons Plus 1,269 JPY/kW for kW charge
% renewable electricity	9% (including NEDO project's generators)
Record % instantaneous renewable	
Curtailment of renewables	
Total Generation Capacity (MW)	
• Heavy Oil steam turbines	
• Diesel engines	7.7MW
• Coal steam turbines	
• Open cycle gas turbines	
• Combined cycle	
• Wind	600 kW
• Solar PV	485 KW
• Concentrating Solar	
• Geothermal	
• Biomass	
• Hydro	
Power peak	4.4 MW
Conventional minimum/full load ratio	
Ramping up from technical minima	
Storage	
• Battery	1,084 kWh
• Pumped Hydro	
• Thermal	
% synchronous generation	
Costs	
• Fossil fuels (2016)	
• Variable generation costs	
• Fixed generation costs	
Frequency (2017)	50 Hz
• Δf > |150 mHz|; > 5 min	
• Δf > |250 mHz|	
Programmed load sheddings	
Unprogrammed load sheddings	
Water Treatment	
• Desalination	
New Projects Planned/Coming Online	

4.10. Tenerife (Spain)

Ricardo Guerrero-Lemus and Les E. Shephard

Tenerife is an island of 2.034 km^2 and 933.402 inhabitants (2018). It is the most populated island of the Canaries, an archipelago situated at the northwest of Africa, Spanish territory from the XV century and integrated in the European Union. This island has an isolated power grid, without storage capacity available, and it is only expected in the near future to be connected to La Gomera, the second smallest island in the Canaries Archipelago (369,8 km^2 and 21.794 inhabitants).

Tenerife generated 3.548 GWh in 2019, has wind farms (195,9 MW), PV power plants (107,4 MW), mini-hydro (1,2 MW), biogas from municipal waste (1,6 MW) and 2 large and 4 small thermal power stations (906,04 MW). Technical minimum/full load ratios for conventional power units are about 35% for steam turbines, 15% for gas turbines, and 70% for diesel engines. The record instantaneous share of renewable electricity in Tenerife (63,92%) was obtained on 27 September, 2020, 10:55.

It is important to mention that wind capacity in Tenerife grew from 60 MW on December 31, 2017 to 196 MW on December 31, 2019. In parallel, frequency excursions ($|\Delta f| >$ 150 mHz) grew from 3,38 hours in 2017 (third higher value for the Canaries power systems) to 52,37 hours in 2019 (far higher value than for the second insular system, Gran Canaria: 20,56 hours). At the same time, the TSO started curtailment protocols in 2019 (0,35% energy curtailed from wind and 0,02 from PV). These curtailment programs have been increased in 2020, mostly due to the impact of covid on the electricity demand across the Island.

An important debate is on place about how continuing increasing the share of renewable energy in the island placing the first storage units connected to the power grid. The TSO is more oriented to place a large hydro-pumping system, but its location is still not defined. The utility is more oriented to large stationary batteries and other kind of storage systems, like liquid air storage.

Table XV.- Tenerife power system master table.

Insular Power Systems	Tenerife, Canary Islands, Spain
2019 Attributes	
Population	
• Inhabitants	933.402
• Floating	About 100.000
Surface (% protected)	2.034 km^2 (48,61%)
GDPpc (Canary Islands, 2018)	20.892 EUR
Solar radiation (non protected areas)	~ 1900 kWh/kW$_p$ in most favourable areas
Total Energy Demand	3.548 GWh
Electricity price (IEA Key World Energy Statistics 2019, subsidised)	

• Residential	311,5 USD/MWh
• Industry	127,5 USD/MWh
% renewable electricity	18,3
Record % instantaneous renewable	62,98% (11/08/2019, 15:50)
Record % renewables daily	49,15% (10/11/2019)
Curtailment of renewables	48 limitation orders; 0,35% wind and 0,02% PV
Total Generation Capacity (MW)	906,04 MW conventional + 304,50 MW renewable
• Heavy Oil steam turbines	223,04
• Diesel engines	28,18
• Coal steam turbines	-
• Open cycle gas turbines	222,52
• Combined cycle	432,30
• Wind	195,9 (100% connected to control centers)
• Solar PV	107,4 (97,4% connected to control centers)
• Concentrating Solar	-
• Geothermal	-
• Biomass	-
• Hydro	1,2
Power peak	576 MW (02/10/2019, 20:20)
Conventional minimum/full load ratio	15%-gas turbines; 35%-steam; 70%-diesel engines
Ramping up from technical minima	+27%/10min steam; +28%/10min CC gas; +24%/10min diesel engines; +77%/10min gas
Storage	
• Battery	-
• Pumped Hydro	-
• Thermal	-
% synchronous generation	
Costs	
• Fossil fuels	378,83 EUR/t for heavy oil 1% S, 407,96 EUR/t for heavy oil 0,73% S, and 546,63 EUR/t for diesel oil 0,1% S
• Variable generation costs	145,24 EUR/MWh
• Fixed generation costs	28,96 EUR/MWh (0,379 MEUR/MW·yr)
Frequency	
• $\Delta f > \lvert 150\ mHz \rvert$; > 5 min	52,37 hours
• $\Delta f > \lvert 250\ mHz \rvert$	29,08 hours
Programmed shedings	2
Unprogrammed shedings	1
Water Treatment	7% of the electricity consumed in the island
• Desalination	About 50 Hm^3/yr.
New Projects Planned/Coming Online	About 90 MW large scale PV and 58MW wind farms approved

SAIDI (min)	External	362,5
	Documental force majeure	0,0
	Other causes	38,0
	Planned with notice	3,8
	Planned without notice	35,6
	Third parties	1,3
SAIFI (min)	External	1,22
	Documental force majeure	0,00
	Other causes	0,80
	Planned with notice	0,03
	Planned without notice	0,23
	Third parties	0,02

5. SUMMARY AND OUTLOOK

5.1. Technical Planning and Operation Changes to Accommodate High Distributed Photovoltaics

With higher and higher deployments of distributed PV, many distribution feeders routinely export electricity back into their substations. This "back feed", in and of itself, is not necessarily a problem for insular systems, although it does require some changes to the solar equipment specification requirements from the way the grid is currently operated, and re-examination of utility voltage regulation and protection device settings is advised.

For insular power systems, a rule of thumb commonly heard in grid operation and control rooms, is that distributed generation starts requiring special attention when it reaches aggregated capacity levels of the size of the largest conventional generation unit or when the regulating reserve required to accommodate distributed generation is projected to be difficult to obtain.

The change in flexible operation of the utility-owned assets, as well as the wider frequency settings on the customer-owned inverters, are the critical requirements as perceived by transmission grid planners and operators, toward integrating large penetrations of utility-scale and customer-owned renewable generation.

During the past few years, it has become increasingly clear that integrating additional rooftop solar PV onto the grid will require capabilities of state-of-the-art advanced inverters to participate in maintaining stable and reliable operations. Therefore, the most feasible way for PV inverters for rooftop systems to support the grid is by autonomously responding to local conditions (i.e., to the ac voltage waveform the inverter measures at its terminals) in a way that stabilizes voltage and frequency.

Another important effect of distributed generation is that it can affect the ability to perform under-frequency load-shedding. In island systems, utilities rely on shedding load to arrest under-frequency events to a greater degree than larger interconnections. However, if there are high percentages of distributed generation embedded in the block of load that the utility intended to use for load-shedding, it considerably reduces the amount of load reduction, and as such its effectiveness in counter-balancing the under-frequency issue. In the future, an alternative to avoid load-shedding entirely for most contingencies will be by using fast-responding utility-scale PV-battery systems. Dynamically reconfiguring load-shed schemes can also be implemented for more precise control of UFLS.

It is also important to upgrade the manual unit-commitment of generation assets to a new software for unit-commitment that is capable of including a forecast of DG that results in more accurate calculations of the required regulation reserves needed based on the DG forecast.

In the distribution grid, the impact of having reverse power flow tends to cause steady-state voltages to rise on the distribution system. Strategies for adapting to the impacts of solar on the distribution grid can include updating legacy utility-owned voltage regulation equipment; phase rebalancing of load and PV on specific circuits with voltage issues; deploying grid-edge distribution primary circuit measurement devices; upgrading secondary circuit infrastructure; and requiring volt-var control in PV systems in order to have local reactive power support.

Adopting interconnection process improvements that take advantage of the capabilities of advanced inverters and smart metering information when available can also help validate the local impact of solar and improve the technical interconnection screens. A good amount of time, effort and costs can be saved by allowing customers to interconnect with the activation of volt-var and volt-watt combination. Using pre-installation and post-installation monitoring of smart meter and/or inverter data can help ensure that customers are not unduly burdened by high-voltage conditions that could possibly affect the energy production performance of their DER system.

Finally, from a distribution planning perspective, a full hosting capacity study on the distribution system posted publicly can indicate the approximate amount of DG currently on the utility' primary distribution network, and give an indication of potential grid constraints. The hosting capacity map has the limitation of including only the primary feeder constraints, and does not give further localized information into local clusters of PV in secondaries that could also be limiting the availability to interconnect more PV, but it still provides a good indicator of aggregate levels of PV penetration in distribution circuits.

5.2. Present and future advanced controls for renewable and inverter-coupled generation

As mentioned previously in this report, the manner in which renewable and inverter-coupled power systems are controlled is important to the reliability and stability of the power systems to which they are connected, and this is especially important in insular power systems. Basic functionalities such as voltage and frequency event ride-through are crucial to grid stability and should be required for all generation. This may require utility protection engineers to consider adjusting settings as levels rise. Going beyond that, other functionalities can further improve the ability to maintain reliability and stability even with high levels of non-conventional generation. These more advanced functionalities can be divided into those that apply to small, more distributed generation and those that apply to larger, centralized generation, with some degree of grey area between the two.

In the case of smaller, distributed renewables including but not limited to rooftop PV systems, real-time monitoring and communications may not be economically viable at present (though that may change in the future). Therefore, insular systems have focused on requiring or incentivizing functionalities the inverters can perform themselves based only on local measurements, as previously described. These include responding to high or low voltages by adjusting reactive or active power, and responding to high or low frequencies by adjusting active power (i.e. primary frequency response), as has been done in the Hawaiian Islands. Incentivizing inclusion of energy storage, if coupled with intelligent tariff design, can also help ensure distributed generation is supplied at times of day when it is beneficial to the power system and used to cover local loads when it is not needed by the rest of the system. As technologies improve, distributed generation could also incorporate into microgrids to improve power system resilience.

One piece of advice that experienced insular grid planners and operators have to recommend to other insular systems expecting large deployments of distributed generation, it is that they anticipate the need for grid services to be provided by DER systems and not wait until the transmission and distribution system operating limits are reached to require the use of advanced inverters. Take early advantage of the advanced inverter and storage technologies from the beginning of DG deployment. Requiring the combination of volt-var and volt-watt control, for example, for customers installing rooftop PV does not increase the installation cost, and it will have a minimal impact, if any, on the solar production, and thus minimal or no impact on the rate-of-return of the distributed generation.

Another recommendation from the lessons learned (e.g., in Hawai'i) is the early adoption of standards (e.g., IEEE 1547-2018) as the default minimum requirement for grid services programs. Establishing compliance with the standard as the minimum eligibility threshold for participation in grid services will incentivize customers to invest in the adoption of the best available technology when installing rooftop PV systems. Advanced inverters that exceed the default settings of the IEEE 1547-2018 standard for voltage regulation and frequency response can be viewed as optional grid services for which customers can elect to provide with compensation-based awards. Grid planners can work closely with customers, DER stakeholders and their regulators to define market programs that provide customer incentives to upgrade legacy inverters to install grid-supportive utility-interactive advanced inverters. Sharing a common vision of the future where high penetration of DG PV can maintain stable and reliable operations of the grid will ensure that all customers can benefit from DER.

Larger, more centralized PV, wind, and storage plants typically are monitored by grid operators, and sometimes even controlled by grid operators. This allows them to provide controls and services such as closed loop voltage regulation, frequency response and regulation, and other ancillary services, as demonstrated in Puerto Rico [23] and Kauai. This capability is now well-proven in both pilot projects and in day-to-day operations (for example, the Cerro Dominador 120 MW PV plant currently providing ancillary services in Chile) but often not yet leveraged by grid operators.

Going forward, insular grid operators should continue to consider emerging technologies as they develop. For example, inverters that can operate in grid forming mode in parallel with the rest of the power system are now becoming available, particularly for larger plant applications. This means that the inverters regulate their output voltage waveforms and do not require an external voltage reference to operate, leading to increased grid stability, especially when instantaneous levels of inverter-based generation exceed 80% of system load. Hawaiian Electric required this technology for all Stage II generation (meaning new PV-battery plants currently under study to be installed in 2023 and 2024). Various organizations are conducting studies to ensure this new technology successfully integrates with the rest of the power system (36). Other island grids will soon be able to leverage this capability, benefiting from the lessons learned in Hawaii.

Further ahead, technologies currently in the research stage may provide even better grid stability with very high levels of inverter-based generation. For example, researchers at the U.S. National Renewable Energy Laboratory are currently developing a technique to synchronize inverters using signals from global positioning system (GPS) satellites. If successful, this would be particularly suitable for stabilizing power insular systems with 100% wind, PV, and battery generation.

6. SELECTED KEY FINDINGS AND RECOMMENDATIONS

As we look to the end of this decade, it is clear that solar PV will play a considerable role in assuring an energy future for insular territories that limits carbon emissions, reduces electricity costs and ensures a stable electric grid for sustained economic development. As solar PV deployments continue to accelerate across insular power systems there will be many new insights and experiences that will supplement the findings, observations and recommendations captured throughout this report and summarized below. A central theme that continues to emerge integrates the many challenges associated with a marked increase in the utilization of power electronic inverters leading to a decoupling of sources from loads and the subsequent rapid change of frequency and frequency deviations under power imbalance that substantially affect the frequency stability of the system. Future experience from insular power systems will be essential in addressing this theme worldwide.

This final chapter provides an overview of selected project key findings and recommendations. Recommendations and key findings with high relevance for PV are marked bold.

6.1. Fundamentals of insular power grids

1. **Insular power systems are defined in this report by conditions that make interconnections with large power systems unattractive economically compared to alternatives based on the combination of endogenous energy resources, storage systems and location**. Given the advantages of interconnections for grid stability, it is important to evaluate and understand the technical and economic conditions related to interconnections early in the initial planning stages for large-scale renewable deployments. The most obvious costs related to interconnections are those associated with the power line joining the two power networks which vary significantly based on geographic separation distance and ocean bathymetry.
2. **Frequency excursions beyond specified criteria are a significant challenge relative to assuring grid stability in insular power systems trying to reach 100% renewable energy from variable wind and solar PV resources**. Other important concerns include fault protection, voltage control, and voltage stability (i.e., grid strength). The unique attributes of insular power systems (e.g., small grids, limited generation capacity, large seasonal demands, etc.) dictate that innovative and more resilient strategies must be implemented to assure grid stability.
3. Load shedding is more common in insular power grids than in large interconnections. **Energy storage is a principal option for limiting the needs for load shedding when integrating large shares of variable energy in insular power systems.** Storage systems can act as loads when charged and as generators when discharged. As many power purchase agreements (PPAs) associated with the production of electricity from wind and solar PV resources are “take-or-pay”, there is an incentive for the grid operator to store the curtailed energy for later use. Storage systems for islands include primarily batteries and pumped hydropower but in the future may also include thermal storage, thermochemical storage, and power-to-fuel-to-power systems, among others.

4. **Power electronics hold great promise in replacing the legacy of synchronous generators and significant reliance on inertia and mechanical frequency response, with inverter-based resources, including wind, solar PV, and certain types of energy storage, while maintaining system reliability.** As the share of renewable energy generation sources increases frequency deviations, voltage transients and harmonics will likely also increase. To mitigate these detrimental impacts, operators must focus on several actions including: (1) an early proper design or modification of the power system, (2) counterbalancing renewable energy fluctuations with flexible generation, and (3) advanced controls of renewable energy sources, mainly by grid forming inverters. Then, grid support functionalities must be considered as part of the system commissioning process to mitigate the logistical, contractual and economic impacts incurred after the system is commissioned.

6.2. Resilience considerations

1. **Infrastructure reliability and scale are greatly impacted in smaller generation systems because generation disruption has a disproportionate effect for smaller grids.** Greater penetrations of distributed power capacity from renewables will influence overall resilience depending on their scale, distribution and connectivity across the island. Developing an in-depth understanding of the local threats and impacts are critical to assess the unique vulnerabilities of the power system, to delineate the most important risks and to develop solutions that mitigate these risks.
2. Electric system resiliency can enhance utility preparedness through programs and investments which improve general readiness (e.g., participating in mutual assistance groups, improving employee communications and tracking, and procuring spare equipment). Storm-specific readiness can also be improved by activities such as maintaining minimum fuel tank volumes, facilitating employee evacuation and re-entry to storm areas, securing fuel contracts for emergency vehicles, expanding deployment staging areas, and supplying logistics to recovery staging areas.
3. **Post-storm assessments of several PV solar systems revealed many similarities in failure mechanisms including module clamp systems, undersized racks, under-sized bolts or under-torqued bolts, a lack of bolt locking solutions and a lack of lateral racking support.** Conversely, the PV solar systems that prevailed after these storms often had through-bolted modules (i.e., no clamps), bolts with locking solutions and lateral racking supports.
4. The integration of wind turbines into insular power systems must accommodate a number of possible conditions that further complicate the resilience assessment of these systems under adverse conditions. Backup power to manage turbine yaw throughout a storm event becomes critical. Foundation designs must accommodate substantial bending moments as storms intensify and the nacelle structural integrity must be preserved throughout a storm event.

6.3. Summary of best practice case studies in insular power systems

Coober Pedy (Australia): The design of the Coober Pedy system was based on the successful King Island insular system, designed by Hydro Tasmania. The upgraded power system includes 4 MW of wind, 1MW solar PV; with a hybrid renewable system that supports the variable renewable energy involving two 850kVA diesel uninterruptable power supply (DUPS) with flywheels maintaining system stability during high renewable output, a 1.5MW/0.49MWh battery and 3MW dynamic resistor system for load control.

Easter Island (Chile): As more diversified production and storage resources are deployed, energy losses and overall costs are decreased. Exclusively PV production leads to an oversize of the whole system with a significant impact on the investment costs. In contrast, including other diversified energy resources decreases both installation costs and energy losses. In spite of favorable weather conditions and economic potential, several challenges for the energy transition remain including distribution challenges occurring from limited access to unprotected sites and adverse impacts from wind turbines on the view shed.

El Hierro (Spain): Hydro-wind power plants can supply electricity to insular power systems up to a limiting value if the water reservoirs are not oversized for covering seasonal fluctuations on the wind resource. However, this oversizing brings higher electricity costs, and also can bring environmental concerns, as many insular systems are placed in protected areas. Experience to date indicates that any strategy to reach 100% renewables must include diversified resources (wind and solar) and storage. The production of electricity from wind has reached a limit, and additional increases in wind capacity would not significantly increase the share of renewable energies in El Hierro.

Galapágos (Ecuador): In 2007 the Ecuadorian government launched a policy "Cero combustibles fósiles en las Islas Galápagos al 2020"- No fossil fuel on the Galapágos Island after 2020. Future RES installations are planned through the year 2025 that will include parallel operation of conventional synchronous generators with battery inverters to assure grid stability and reliability and the integration of advanced energy management concepts that invole more directly the consumer.

Kauai (USA): Synchronous condensers have been demonstrated as a very cost-effective way to maintain grid stability as increased renewables displace conventional synchronous generators. The grid can be kept very stable even while at 100% renewable by maintaining a generator and grid interconnection to provide inertia, voltage support, and fault current.

King Island (Australia): Frequency control is ensured through load management, coordinated via dynamic resistors and an aggregated customer demand response. In addition, amendments to the energy codes can provide greater control over available solar generation below 5kW to improve system stability.

Maniitsoq City (Greenland – Denmark): The sixth largest city in Greenland with a population of 3,552 inhabitants. The island has an isolated power grid that operates under extreme weather conditions (- 35º C in winter). Long-term planning for renewable expansion is focused on solar PV as an integral part of the future even under extreme winter conditions.

Maui (USA): During the past few years, it has become increasingly clear that integrating additional rooftop solar PVs onto the grid will require capabilities of state-of-the-art advanced inverters to participate in maintaining stable and reliable operations. Therefore, the most feasible way for small-scale PV inverters to support the grid is by autonomously responding to local conditions (i.e., to the ac voltage waveform the inverter measures at its terminals) in a way that stabilizes voltage and frequency. In contrast, large-scale PV-battery systems can best benefit the system if contracts allow flexible control by the utility. Studies show significant benefits from both synchronous condensers and grid-forming controls of large PV-battery plants.

Nii Jima and Shikine Jima (Japan): These small islands located to the south of Tokyo are being used as test beds to simulate the expansion of renewables and integration of renewables in and around Tokyo in the future.

Tenerife (Spain): When wind and PV capacity in an insular power system grow without adding storage capacity, curtailment levels increase substantially with the greatest increase in wind curtailment and lesser curtailment for solar.

6.4. Outlook

Insular power systems continue to forge the path forward for fully integrating solar PV, wind and storage under real-world conditions that will continue to make substantial contributions to the global energy transition that is currently underway. These systems serve as a collaboratory for learning, testing, integrating and evaluating new technologies combined with novel policy and economic frameworks that must continue to evolve in parallel to assure future success.

It is clear based on the specific case studies provided in this report, and those elsewhere, that location specific solutions are required, but that these solutions can draw upon the broad, diverse and growing amount of experience around the world, particularly in insular territories. It is also clear that while interconnections provide many obvious benefits, power electronics will play a much more substantial role in assuring the stability of the electric grid in the coming decade. Energy storage will complement these efforts going forward and is particularly important in insular power systems where the range of disturbances are often greater in total than those enabled by large interconnections.

Disciplined, strategic planning will be required to assure the success of future renewable deployments leading to 100% renewables with a growing emphasis on solar PV as a significant driver for the future. Based on insular power system experiences globally, the key to meet significant goals for renewable penetration is to learn from others and to adopt innovative and proven technology, policy and regulatory advances early in the planning process. Ultimately, the global energy future will be determined by our experience working on insular power systems worldwide.

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ISBN 978-3-907281-20-8

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