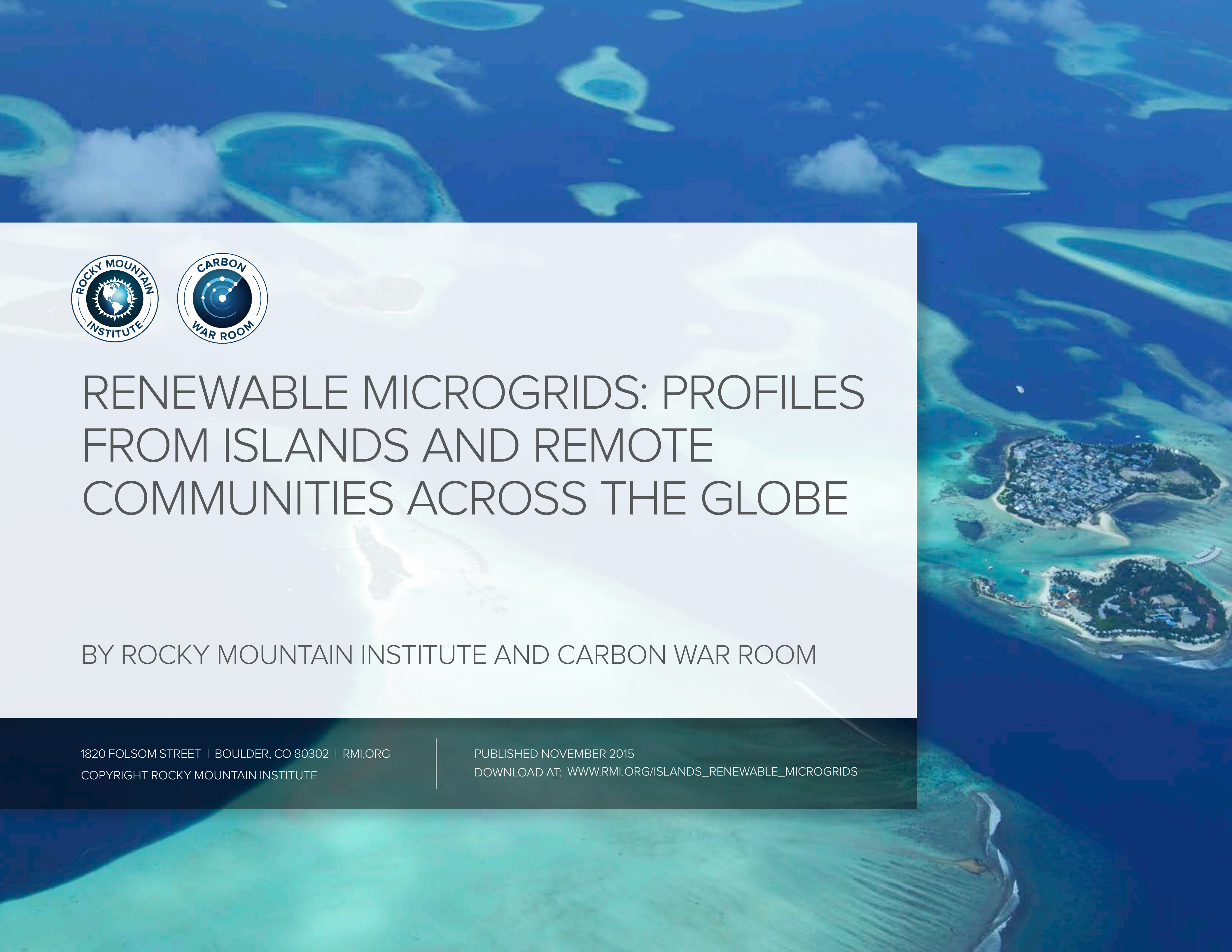

RENEWABLE MICROGRIDS: PROFILES FROM ISLANDS AND REMOTE COMMUNITIES ACROSS THE GLOBE

BY ROCKY MOUNTAIN INSTITUTE AND CARBON WAR ROOM

1820 FOLSOM STREET | BOULDER, CO 80302 | RMI.ORG

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AUTHORS

AUTHORS:

Kaitlyn Bunker, PhD
Stephen Doig, PhD
Kate Hawley
Jesse Morris

*Authors listed alphabetically. All authors from Rocky Mountain Institute unless otherwise noted.

CONTACT:

Stephen Doig, PhD (sdoig@rmi.org)
Kate Hawley (khawley@rmi.org)

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Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. In 2014, RMI merged with **Carbon War Room (CWR)**, whose business-led market interventions advance a low-carbon economy. The combined organization has offices in Snowmass and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

The Clinton Climate Initiative serves as a partner to RMI and CWR to accelerate energy transition in the Caribbean. The Clinton Climate Initiative (CCI) launched in 2006 to implement solutions to the root causes of climate change. CCI works to improve building energy efficiency and advance building retrofits; to increase access to clean-energy technology and deploy it at the government, corporate, and homeowner levels; to help over 20 island nations reduce their reliance on diesel and adopt renewable energy; and to monitor, preserve, and grow forests in line with national governments and communities. CCI's approach addresses the major sources of greenhouse gas (GHG) emissions and the people, policies, and practices that impact them, while also saving money for individuals and governments, creating jobs, and growing economies.

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THE ISLAND AND REMOTE COMMUNITY ENERGY OPPORTUNITY

THE LIVELIHOODS OF INDIVIDUALS and families living on islands and in remote communities across the globe are directly tied to the availability and price of one volatile global commodity: oil. While oil is also used for various purposes in larger communities across the globe, islands and remote communities are disproportionately dependent on oil for their well-being. In these communities, oil powers the way people move. It propels the ships and trucks that bring in goods from the outside. It enables the tourism industry that keeps many of these local economies afloat. It also powers the electricity system in most of these communities. For well over 100 years, oil has enabled remote communities to generate electricity and enjoy the benefits of a consistent electrical supply. However, unlike many larger, non-isolated communities across the globe that are increasingly turning to a diverse supply of resources to generate electricity, most islands and remote communities continue to rely on oil and oil alone for their electricity and other energy needs.

Relying solely on oil for electricity generation has left island and remote communities exposed to several risks and drawbacks. Oil-based electricity generation is often more expensive and subject to price volatility, which can result in the use of risky fuel hedging strategies that can lock in prices for years to come. Importing oil puts these communities at risk of supply interruption, reducing energy security. Furthermore, small-scale electricity systems that aren't connected to a larger electricity grid tend to be more expensive and difficult to maintain: in the U.S. and Europe, regionally interconnected grids can support one another, whereas remote and island community grids have no such luxury.[1] Accordingly, residents of island and remote communities pay some of the highest retail electricity prices in the world. While the average residential rate in most U.S. states is 12.5 cents per kilowatt-hour (USD[i]) for electricity,[2] the average in most Caribbean nations is at least three times higher.[3]

These risks and drawbacks—paired with continuing cost reductions in solar, wind, and energy storage technologies—suggest that an alternative to the fully oil-based electricity systems of the past is now available to islands and remote communities across the globe: **affordable renewable energy.**

Leading islands and remote communities, from the deserts of Australia to the isles of the United Kingdom, have already transitioned from 100 percent oil-based electricity systems to ones with significant renewable penetration. These communities are enjoying the many benefits that come with the transition: operational cost savings, reliable and stable power, long term energy price stability, and reduced dependence on oil. This casebook profiles islands and remote communities actively embracing this transition in order to provide examples for other communities looking to make the switch away from oil to efficiency and renewables.

> Leading islands and remote communities, from the deserts of Australia to the isles of the United Kingdom, have already transitioned from 100 percent oil-based electricity systems to ones with significant renewable penetration.

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[i] *All currency throughout this casebook is noted in U.S. dollars*

RENEWABLE MICROGRIDS

02

THIS CASEBOOK EXPLORES several remote, islanded microgrids from around the globe,[ii] sharing examples of communities transitioning from one resource (oil) to a diverse set of resources including wind, solar, biodiesel, hydro, and energy storage. The examples include small microgrids serving fewer than 100 people, and larger microgrids serving over 10,000, with a peak demand range from 60 kW to 27 MW. Although the communities reviewed in this casebook are all unique due to local grid characteristics, renewable resource availability, production costs, load profiles, community support, and opportunities for external funding, they share many similar drivers of change, challenges, and lessons learned in the transition from fossil fuels to renewable microgrids.[iii]

DRIVERS OF CHANGE

The communities described in the casebook transitioned from oil-based microgrids to diverse, renewable microgrids for different reasons. According to in-depth interviews of individuals involved with the renewable transition for these islanded microgrids, drivers of change centered around three major themes:

1. **COSTS.** Many communities faced high costs of electricity from oil-based microgrids (i.e., they are dependent on expensive fossil-fuel imports such as diesel).

> *“Economics was a primary driver. Cost of power production far exceeds revenues.”*
> - Mr. Juergen Zimmerman, Coral Bay

2. **ENVIRONMENTAL CONSIDERATIONS.** Communities expressed concern over the future impacts of climate change, the corresponding desire to take action and reduce carbon emissions, and their deep cultural connection to land and nature.

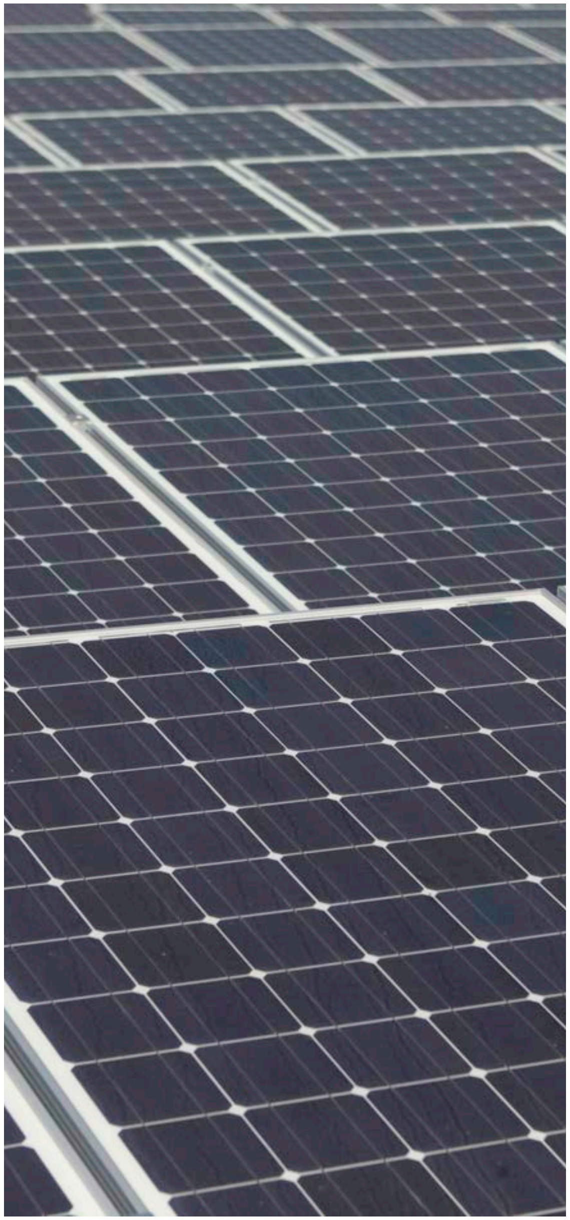
> *“The people here are of a green ilk.”*
> - Mr. John Booth, Isle of Eigg

3. **ABUNDANT LOCAL RESOURCES.** All the communities profiled in this casebook have an abundance of local energy sources available for electricity generation. Wind energy provides the largest addition to the overall energy mix of the cases profiled here (usually greater than 20 percent). By shifting away from imported oil to rely more on local resources, communities can reduce the likelihood of system outage due to resource availability constraints.

> *“All communities are vulnerable to imported fuels; we have a vast [local] wind resource.”*
> - Mr. Glenn Ross, Falkland Islands

[ii] While the term “microgrid” is often used to describe many different things, in this casebook we use it to refer to small electricity grids supplying island and remote communities, with no connection to a larger electricity grid.

[iii] In this casebook, we define a renewable microgrid as any microgrid currently generating 30 percent or more of its annual electricity from renewables.



CHALLENGES

Although some of the renewable systems discussed in this casebook have been in successful operation for many years, communities faced challenges transitioning from an oil-based microgrid. Three of the main challenges to integrating renewables were grid stability, remote location, and administrative and bureaucratic requirements.

1. GRID STABILITY. Maintaining grid stability with renewable integration proved challenging in many cases. Maintaining a reliable electricity system for the community's residents is essential, so system operators must incorporate renewables, especially those that are variable, in a way that preserves the operation of the overall system. Using a phased integration approach, operators were able to see how to initially bring a small amount of renewable technologies online, work with these while balancing the system, and then continue to step up their renewable penetration by integrating more resources alongside energy storage and advanced controls.[iv]

> *"We started adding renewables 18 or 19 years ago, and the challenges have been technical. We had to solve the problems we uncovered as we went."*
> - Mr. Simon Gamble, King Island

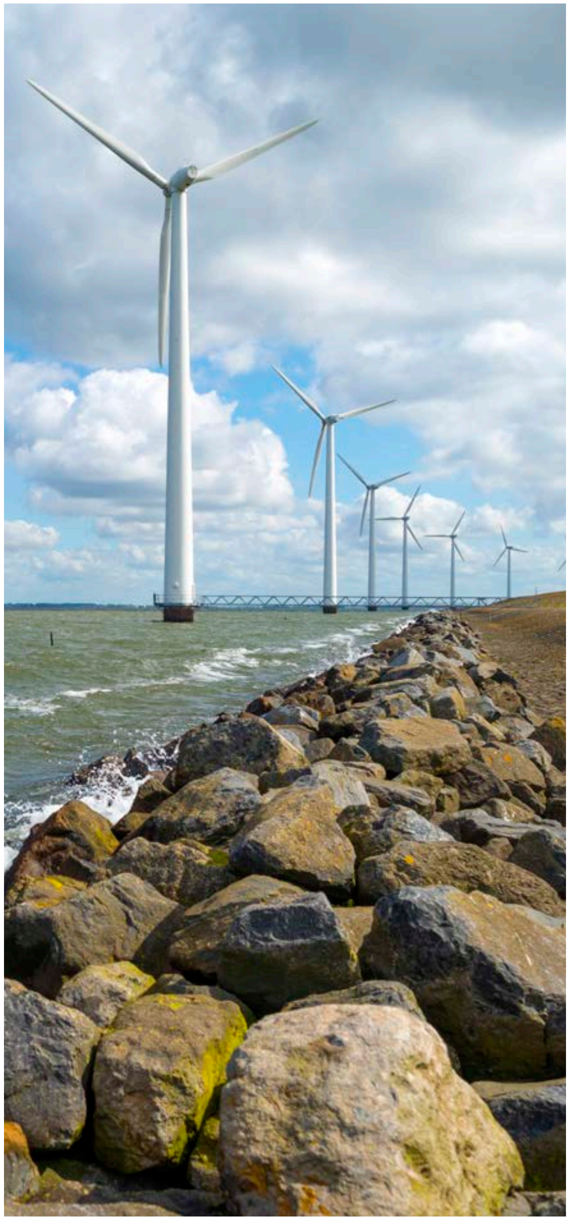
2. REMOTE LOCATION. Procuring and transporting new technologies and equipment as well as getting actual construction crews on-site presents another challenge for remote locations. Often, only one or two operators live nearby, so if major technical issues arise, teams must fly in to address the problems.

> *"The PV system was assembled and tested in Perth, then loaded into a truck and driven (1,500 km) to the site. The concrete feet were also trucked in, after being cast in a location about two and a half hours drive away."*
> - Mr. David Edwards, Marble Bar & Nullagine

3. ADMINISTRATIVE AND BUREAUCRATIC REQUIREMENTS. A combination of government grants and utility equity funded the addition of renewables in most cases profiled for this casebook. In light of this, many communities faced challenges stemming from fund or grant application processes, onerous documentation requirements, and the need to align bureaucratically imposed requirements with the overall energy transition timeline.

> *"It was challenging to align the timelines for the grants with the timelines for the project."*
> - Mr. Darron Scott, Kodiak

[iv] *While there are multiple definitions for renewable penetration, in this casebook we use the term to mean the percentage of annual electricity generation that comes from renewable resources (which is included in a chart for each case). In addition, a chart showing the installed capacity of each type of generation resource is included for each case, which is another way to think about renewable penetration.*



LESSONS LEARNED

The pathways pursued by islands and remote communities to develop renewable microgrids provide examples of how communities might embark on a similar transition. From the cases studied, we have identified several lessons learned in order to help guide decision making within communities currently considering a transition from oil to renewables.

Transitioning to renewable microgrids can reduce costs. Reducing costs is not always a straightforward process. Relying on more diversely and renewably powered microgrids led to reduced diesel usage in every situation reviewed in this casebook. In some cases, reduction in purchased fuel resulted in reduced electricity prices, as well as reduced operating costs. For many others, governments that provide subsidies to ensure equitable access to electricity found that the addition of renewables reduced the amount of subsidy required, freeing up taxpayer dollars for other investments. Creating a project, with the requisite business plan to lower overall costs and attract investment, is a difficult and lengthy task, but one made easier with a deep understanding of the technologies, processes, and pitfalls outlined in this document.

Adding renewables enhances microgrid system resiliency and stability. Microgrids with diverse resource mixes are often less prone to system failure than microgrids that rely on a single resource, since they have multiple resource options for electricity generation. In addition, when renewables are added to the grid, key components like power electronics and control systems are added as well, enabling a more stable grid through better controls. At the same time, relying more on local resources, and less on imported oil, increases overall resiliency for a community.

Energy efficiency is an important component of a renewable microgrid transition. It is well known that energy efficiency measures such as lighting, more efficient appliances, and adding insulation are more cost effective than any generation option. The importance of energy efficiency as a starting point for any transition is particularly acute for islands where space for renewable technologies like wind and solar is typically in short supply. However, most of the profiled cases underutilize energy efficiency, and indicate that energy efficiency should play a more prominent role in any transition plan.

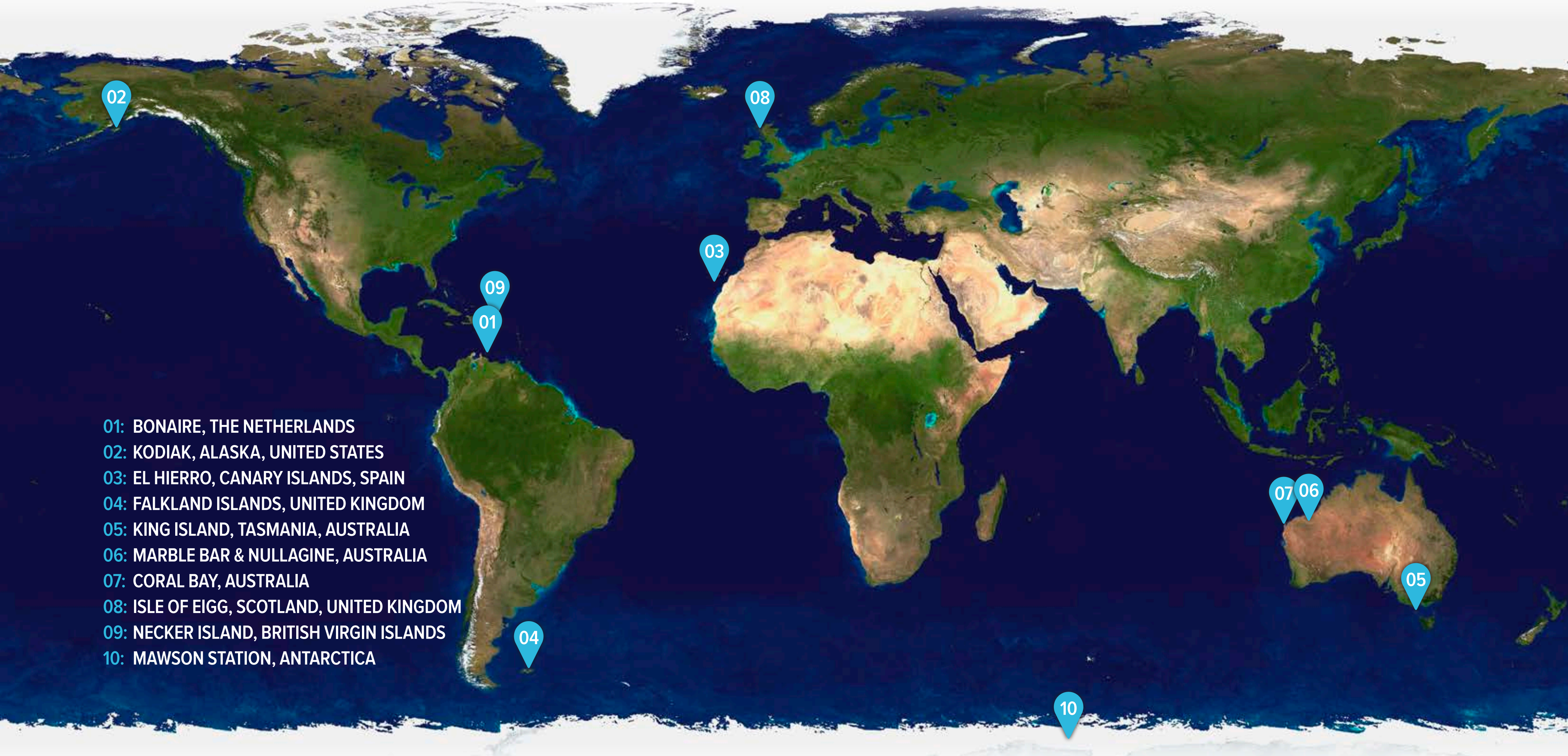
Energy storage is a key component of largely renewable island and remote community microgrids. Every community profiled in this casebook has either already integrated or is currently considering the installation of flywheels, batteries, or pumped hydro energy storage systems. Generally speaking, renewables like solar and wind can be integrated into diesel-based island and remote community microgrids at penetrations around 10 to 15 percent of annual electricity consumption without causing operational challenges.[4] Above 20 percent, it is often necessary to curtail renewable generation, implement demand response or load-shifting programs, or incorporate energy storage. However, as penetration of renewable energy increases, energy storage—alongside smart controls to enable load shifting—becomes an important component of any community's transition.

RENEWABLE MICROGRIDS: 10 CASE STUDIES

03

RENEWABLE MICROGRIDS: 10 CASE STUDIES

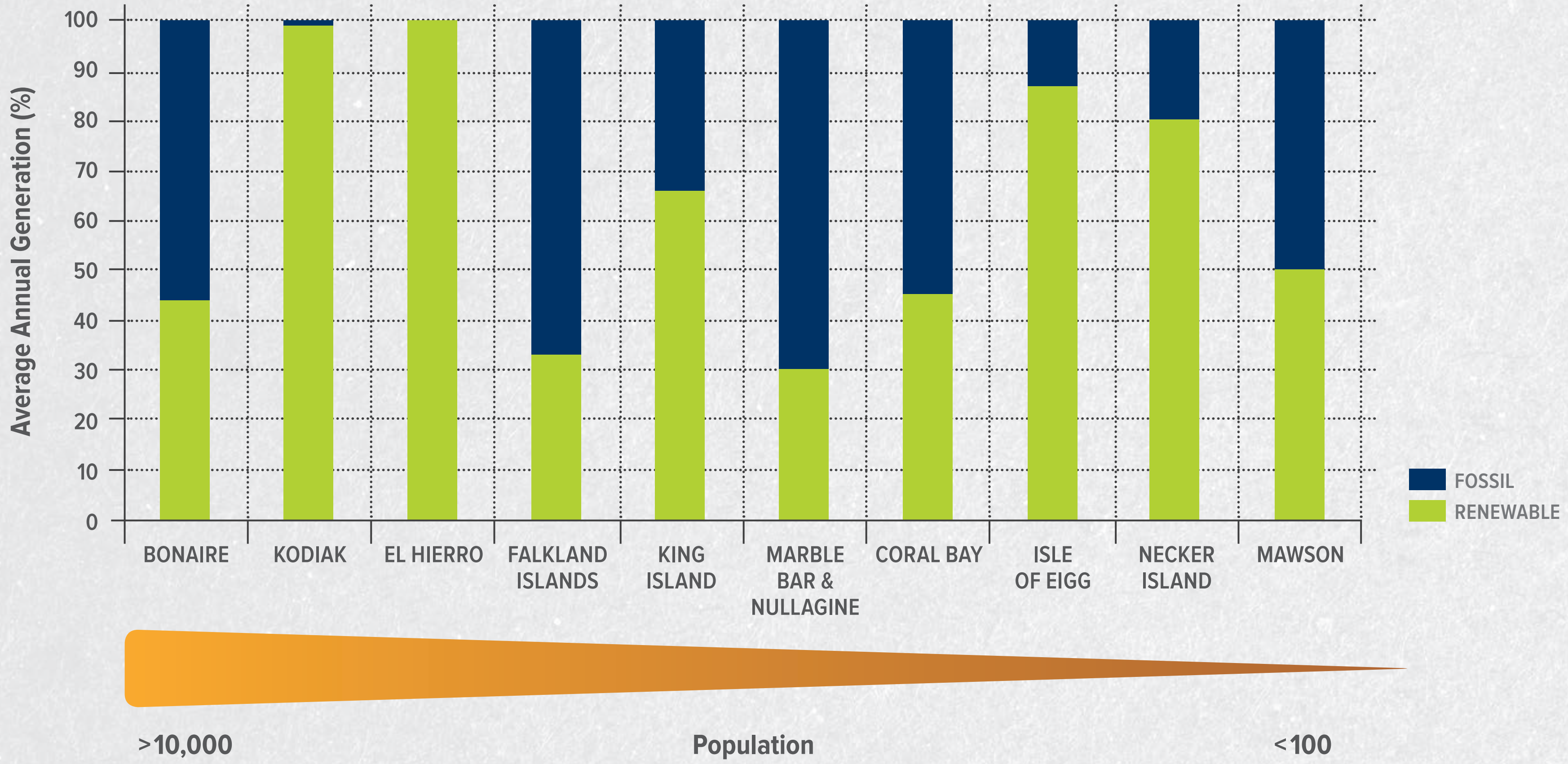
FIGURE 1: THE 10 REVIEWED MICROGRIDS



WE INTERVIEWED UTILITY owners, grid operators, and microgrid engineering experts to develop 10 case studies from around the globe that integrate a mix of energy efficiency and renewable energy. This diverse set of examples demonstrates the potential for energy transitions for similar communities around the world. The microgrids reviewed are illustrated in Figure 1 above. Figure 2 shows what percentage of the average annual electricity generation in each location comes from renewable sources. In addition to the 10 cases outlined in this section in detail, Appendix A includes additional information about 13 other islanded or remote microgrids from across the globe.

RENEWABLE MICROGRIDS: 10 CASE STUDIES

FIGURE 2: AVERAGE ANNUAL ELECTRICITY GENERATION, % RENEWABLE VS. FOSSIL



ICONS KEY

WIND

SOLAR

HYDRO

BATTERY

FLYWHEEL

DIESEL

BONAIRE, THE NETHERLANDS

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
14,500	*25,000 kW*	*11,000 kW*	*44%*	*$0.34/kWh*	*$0.34/kWh*

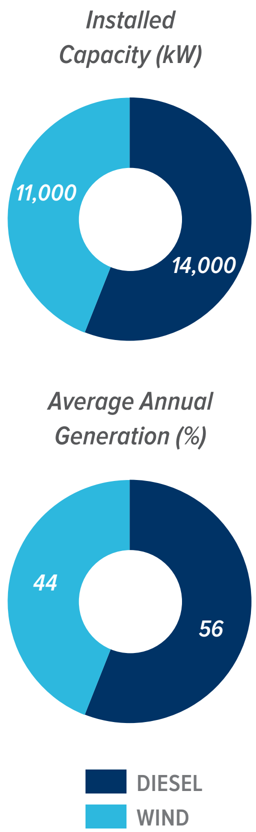
THE CARIBBEAN ISLAND of Bonaire is famous for its beautiful marine reefs visited by 70,000 tourists every year. In 2004, a fire destroyed Bonaire's existing diesel power plant. Although disruptive, the event afforded Bonaire and its residents an opportunity to design a new electricity generation system from scratch. After immediately renting diesel generators, the government and local energy company began jointly creating a plan to generate 100 percent of Bonaire's electricity from renewable sources. The motivation behind the goal of 100 percent renewable electricity was to reduce the rates that residents pay for electricity, create local jobs, and serve as an example for other islands and remote communities. Bonaire was one of the first Caribbean islands to set a goal and develop a plan to move towards a largely renewable future.

Today, almost half of Bonaire's electricity comes from wind power (44 percent). The 12 wind turbines installed can provide up to 90 percent of the island's electricity during times of high wind. A 100 kWh battery is included in the system and allows time for additional diesel generators to be started when there is a sudden drop in wind availability. The electricity rates paid by Bonaire consumers decreased from a peak of $0.50/kWh in 2008, when the island relied on the temporary diesel generators for electricity, to $0.34/kWh today. Many of Bonaire's 70,000 annual tourists explore the island's famous marine reefs and the new renewable microgrid supports branding efforts.

Next steps in the island's energy transformation toward a 100 percent renewable electricity system include solar farms, additional energy storage, and energy efficiency. The island is also exploring local algae resources grown in the large salt flats on the island to create biofuel, which could then be used in existing generators. This could allow Bonaire to operate a 100 percent renewable electricity system with on average 40 to 45 percent of annual electricity generation from wind and 55 to 60 percent from biodiesel.

RENEWABLES AS REPLACEMENT— NOT DISPLACEMENT

Bonaire was presented with an opportunity to build a new renewable electricity system when the existing diesel power plant was destroyed. This is in contrast to most cases profiled in this casebook where diesel generators are typically partway through their operating life when a renewable transition begins. Existing generators often remain a part of a transitioning renewable microgrid, especially as renewables are incrementally added to the system, and may even remain as backup power for a transformed system that operates mostly with renewables. However, if some or all of the existing diesel resources in a system are completely shut down before the end of their available lifetime, grid operators must accelerate the depreciation of existing diesel generators and incur those added costs into their overall energy transformation plan. Bonaire had no such constraints and, although they chose to use diesel generators to support the newly constructed wind turbines, they were able to design their electricity system around renewables—not the other way around.



KODIAK, ALASKA, UNITED STATES

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
13,000	*75,000 kW*	*27,800 kW*	*99.7%*	*$0.14/kWh*	*$0.15/kWh*

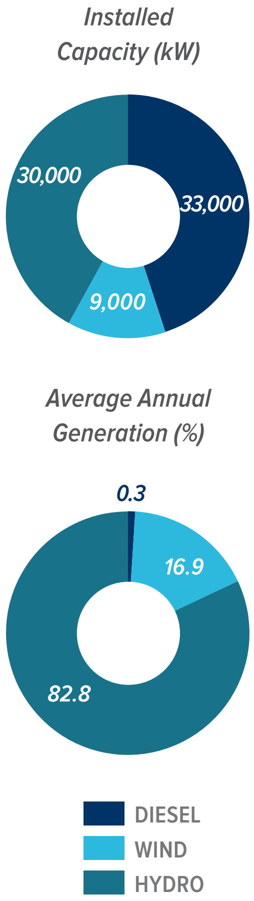
THE BOARD OF the Kodiak Electric Association (KEA) cooperative set a vision statement in 2007 to cost-effectively generate 95 percent of its electricity from renewable resources by 2020. While the community of Kodiak, an Alaskan island and the second-largest island in the United States, has been utilizing hydro resources since 1984, the board's vision drove the addition of multiple wind farms and a third hydro turbine, enabling the community to achieve an average annual renewable penetration of 99.7 percent. These new components were added in various steps after assessing how much renewable energy the system could handle and what limitations existed at various levels of renewable penetration.

The community had to overcome several challenges to develop the system. Kodiak's remote location made wind turbine transport and installation difficult. There were issues related to the timeline of funding, system design, and turbine construction (which, due to extreme weather variations, needed to take place in the summer). In addition, KEA had little knowledge on how to manage grid frequency and voltage issues inherent to intermittent wind resources at a time when there weren't many examples to draw from. Kodiak's 3 MW (2 MWh) gel lead-acid battery contributes to the stability of the system, and KEA recently added two 1 MW flywheel systems. The flywheel will take over some of the workload from the battery, which currently charges and discharges around 1,000 times each day. The pairing of multiple types of storage that operate on different time scales effectively matches system needs, especially when variable renewable penetration is high. KEA faces additional operational challenges because of Kodiak's wet and windy climate, which can cause excess water to collect inside the turbine hubs.

Kodiak's economy relies heavily on the relatively electricity-intense fishing industry. Stable electricity rates resulting from the new renewable system have led to an expansion in the fishing industry, creating more jobs and tax revenue for the local government. The addition of the flywheel will also enable a much larger crane to be operated at a major shipping pier without negatively impacting microgrid operation. Since the crane has a highly fluctuating load that can peak at 3 MW (18 percent of the average KEA load), the flywheel provides spinning reserve that can handle these large, fast changes in load when the crane is in use.

MULTIPLE BENEFITS FOR COMMUNITY MEMBERS

The addition of more renewable resources has reduced KEA customer rates 3.6 percent since 2000. Relying less on diesel fuel also makes the rates more stable, since prices are not as closely tied to the fluctuating price of diesel fuel. Now that the wind turbines have been added and the system is over 99 percent renewable, the community is saving around $4 million per year. Along with lower electricity rates, residents can now cost-effectively switch from oil as a heating fuel in their homes to electric heat pumps. This option saves money for residents of Kodiak and contributes to a more efficient overall system.



Installed Capacity (kW)

Average Annual Generation (%)

EL HIERRO, CANARY ISLANDS, SPAIN

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
11,000	*35,000 kW*	*7,600 kW*	*100%*	*$0.15/kWh*	*$0.17/kWh*

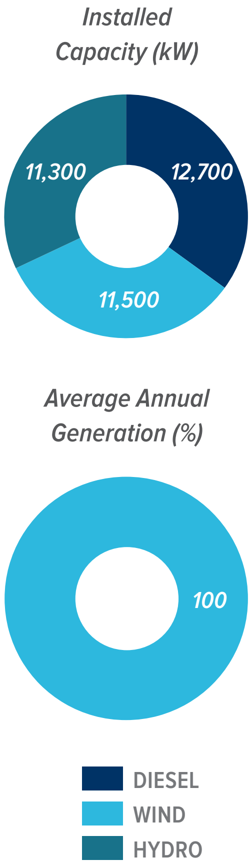
THE ISLAND OF El Hierro, the smallest of the Spanish Canary Islands, has recently completed a shift to generating 100 percent of its electricity from renewables. The transition, driven by El Hierro's residents, was linked to environmental concerns and the significant burden of high electricity demand from the desalination plant. Desalination and its energy requirements are a main concern due to the island's reliance on agriculture as a primary economic activity (exporting pineapples and mangoes) in an extremely dry climate. Combining wind with pumped storage hydro created a renewable microgrid capable of meeting the island's unique energy needs.

The project was jointly funded by the local utility Endesa, the Spanish government, and the Canary Institute of Technology. Although the transition offered many low-carbon benefits, developers also had to consider how the new system would impact the island's physical environment and find wind turbine locations that did not conflict with the Canary Islands' status as an environmentally sensitive, protected territory.

The 100 percent renewable electricity system is part of a wider island program in sustainable development. Other measures underway include increasing energy efficiency and an island-wide shift from internal-combustion-powered vehicles to electric ones. As a part of this expansion into sustainable transportation, the local government has begun to incentivize electric vehicle purchases, while utility Endesa is studying development, implementation, and maintenance of a network of charging stations. The current renewable system meets all of the electricity demands on the island.

LOW-COST STORAGE: PAIRING WIND WITH PUMPED STORAGE HYDRO

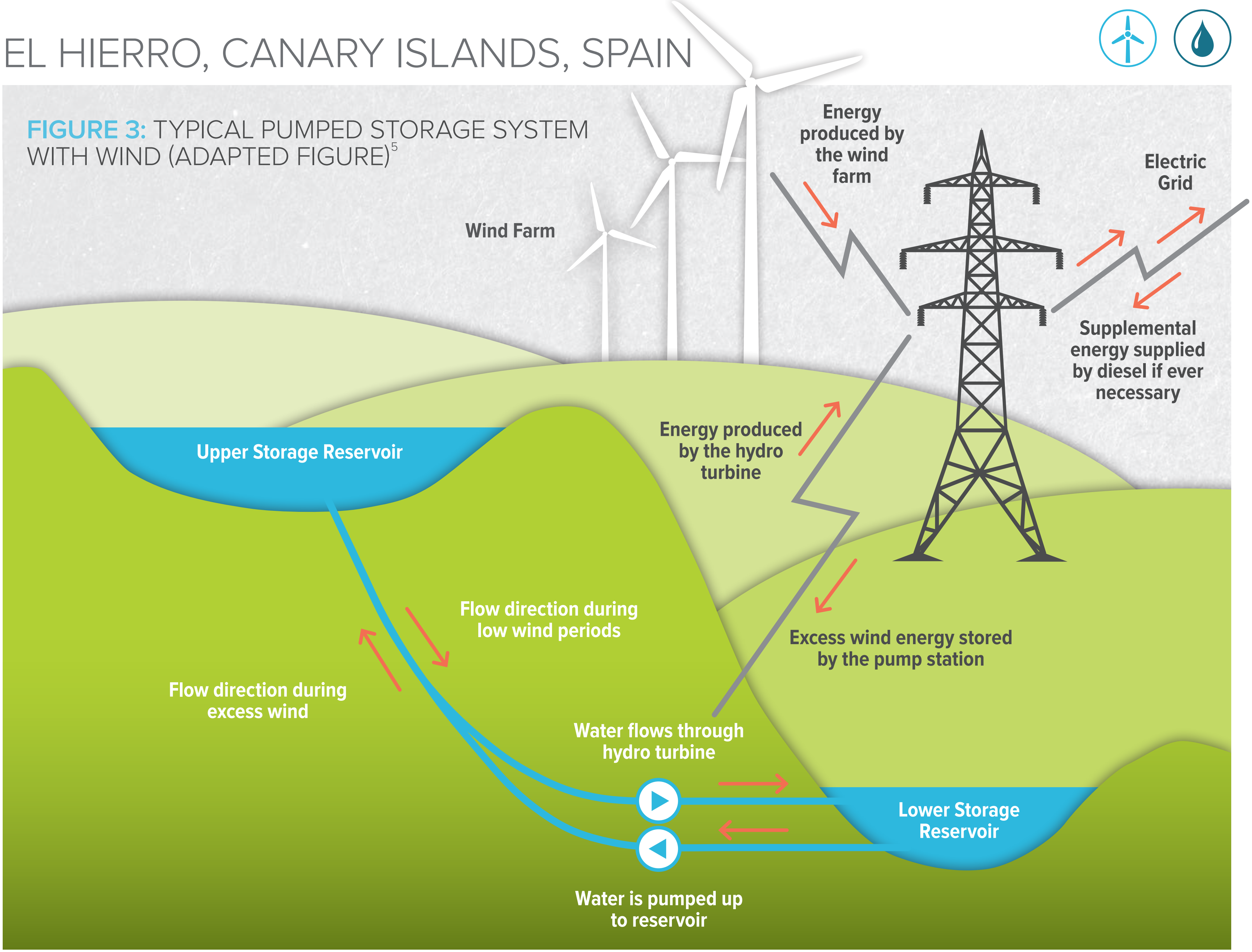
During times of abundant wind, El Hierro's immediate electricity needs are met by wind generation, and excess electricity is used to pump water up to a large storage lake. When the wind dies down and can't meet the electricity needs of the community, the water is released and hydro-powered turbines supply the needed power. The island includes a location ideal for this type of energy storage: an extinct volcano crater where water can be pumped to a height of 700 meters. While this arrangement doesn't suit all locations, El Hierro is demonstrating the success of pairing these two renewable options. The size of the renewable energy system—including the water storage location, the electricity-generating pumps used when the water is released, and the wind farm—was determined based on the projected electricity demand in 2030. This ensures that the system can continue to provide renewable electricity to the island and its residents in the years to come.


Installed Capacity (kW)

Average Annual Generation (%)

EL HIERRO, CANARY ISLANDS, SPAIN

FIGURE 3: TYPICAL PUMPED STORAGE SYSTEM WITH WIND (ADAPTED FIGURE)[5]



FALKLAND ISLANDS, UNITED KINGDOM

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
2,500	*8,580 kW*	*3,200 kW*	*33%*	*$0.30/kWh*	*$0.30/kWh*

SOME THREE HUNDRED miles off the southern Patagonia coast of South America, the Falkland Island archipelago is home to an abundant wind resource (4.5 m/s on average) and a community with a long-term goal to harness that vast energy potential. Beginning in 2007, installation of several wind farms increased annual electricity generation from wind to one-third of annual consumption.

When adding wind to the system, a key part of the strategy involved having the same group own both the wind farm and the conventional power plant. The utility took a novel approach to integrate deeper penetrations of wind and to maintain diesel generator loading and efficiency. On the Falkland Islands, wind turbines are given a set-point target power and vary the pitch of their blades to maintain that output. With consistent, predictable output from the wind turbines, diesel generators continue to run without large fluctuations in their loading (thereby maintaining generator efficiency) unless there is a significant change in the wind speed. Since the local utility operates both the diesel generators and wind farm, it was able to design this control strategy and enhance overall operation of the system.

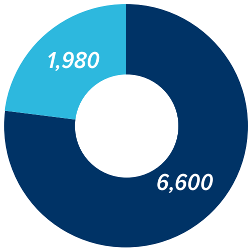
One challenge during the transition was allowing a period of time to train staff to operate the new wind farm control desk. The utility delivered all projects on time and on budget, despite potential risks around the fluctuating currency exchange rates and the islands' remote locations.

Adding wind has not changed the reliability of this stand-alone system, which on average experiences just one or two outages per year. The system includes a small flywheel in order to further increase the efficiency of the wind-diesel hybrid system. Although the utility conducted both hydro and solar power experiments, the wind resource on the island greatly exceeds the potential resource for either of these two technologies. The Falkland Islands are therefore considering how to further utilize the wind, including considering additional energy storage and heat pump technologies.

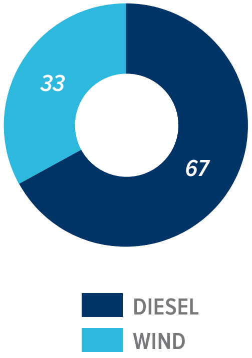
REDUCING RATES FOR ISLAND RESIDENTS

In this system, as in many renewable systems, energy produced by the wind turbines directly displaces energy that would need to be generated from diesel fuel. This means that less fuel has to be transported to the islands and paid for by the community. On average, the wind farms reduce diesel fuel use by 1.4 million liters per year, creating a savings for the community that translates directly to customers' electricity bills. As a result, since 2007 the residents of the Falkland Islands have seen a $0.12/kWh decrease in their electricity rate, from $0.42/kWh to $0.30/kWh.

Installed Capacity (kW)



Average Annual Generation (%)



KING ISLAND, TASMANIA, AUSTRALIA

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
1,800	*8,840 kW*	*2,500 kW*	*65%*	*$0.19/kWh*	*$0.19/kWh*

JUST SOUTH OF MELBOURNE sits King Island, one of the many islands belonging to Tasmania in the Bass Strait. First sighted by explorers in 1798, the island was not officially settled until the 1900s, but is now home to approximately 1,800 residents and a story of transformative renewable energy. The King Island Renewable Energy Integration Project has helped the island transition from diesel to renewable-based electricity. Over the past 20 years, the island's utility, Hydro Tasmania, has been installing renewable energy systems, along with enabling technology such as energy storage, on the island, which now relies on renewables for 65 percent of annual electricity needs. The transition was driven by economics since the cost of producing power from diesel generators alone exceeded the utility's revenues.

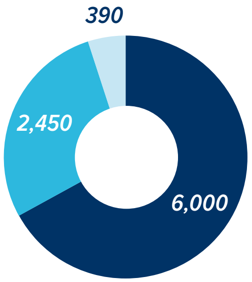
Using a stepwise approach, Hydro Tasmania has overcome many renewable integration challenges to incorporate more renewable resources into the system. The first wind farm was built 18 years ago as a first step in the energy transition process. When it became clear that additional wind could not be easily added to the existing system, Hydro Tasmania incorporated a 1.5 MW dynamic resistor to allow the island's existing wind turbines to contribute greater amounts of renewable energy and regulate system frequency. These advances provided reserves that help to avoid problems during a quick shift in wind availability, and pushed the diesel generators to their minimum loading level, enabling higher levels of renewables in the system. As Hydro Tasmania sought to obtain further contribution from the existing renewables, additional technologies became necessary, including two 1 MW flywheels, which work in concert with the dynamic resistor to allow the system to run with the diesel generators completely off—sometimes for up to 22 hours a day. The flywheels also ensure that the system can shut down safely in the event of a system disruption. Finally, the microgrid now includes a 1.5 MWh battery that augments the performance of both the dynamic resistor and the flywheel by sustaining diesel-off operation through periods of reduced renewable generation.

By combining various renewable resources, storage, and control techniques, King Island has reduced CO_2 emissions by more than 50,000 tons to date, while improving reliability and power quality. Hydro Tasmania is also experimenting with biodiesel blends in order to further reduce the amount of oil used to produce electricity on King Island.

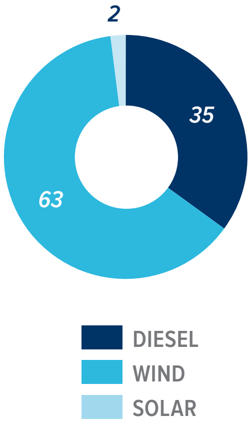
PAIRING RENEWABLES WITH SMART METERS

Along with increasing the amount of renewable resources in its King Island system, Hydro Tasmania has incorporated smart meters with switching capability, deployed into the community on a voluntary basis. Smart meters allow the utility to monitor customer energy use in real time, including hot water loads and any local PV production. The utility monitors and controls up to several interruptible loads in each participating home or business, including water heaters and heating and cooling systems. Having real-time information about these loads allows the utility to control and flexibly dispatch them as a virtual power plant. Thanks to the program's success, Hydro Tasmania is investigating the expansion of the smart meter program to additional customers on King Island beyond the 110 initial volunteer participants.

Installed Capacity (kW)



Average Annual Generation (%)



MARBLE BAR & NULLAGINE, AUSTRALIA

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
600	*2,748 kW*	*820 kW*	*30%*	*$0.19/kWh*	*$0.22/kWh*

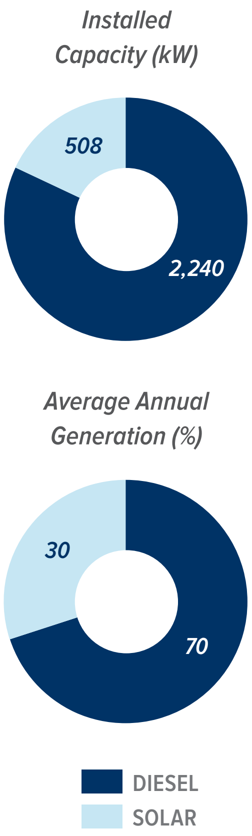
MARBLE BAR AND NULLAGINE, two remote towns with adjacent aboriginal communities located in Western Australia, were originally settled in the late 1800s during a gold rush. In 2008, the power stations for these grids were in need of replacement. Horizon Power, a utility company that operates 34 islanded microgrids and four connected power systems in Australia, decided to incorporate renewable resources in the updated system as a test case for what is possible. No other nearby towns had included renewables in their systems at that time. The project was funded partially with a government grant and partially by Horizon Power. The utility worked with power and automation engineering company ABB and SunPower to design and build a system for each town that includes single-axis tracking solar PV, diesel generators, and a kinetic flywheel.

Flywheels, heavy revolving wheels that maintain momentum and store kinetic energy to enhance system stability, are often used alongside wind turbines. However, in Marble Bar and Nullagine, flywheels enable the grid to operate on very high penetrations of the local solar resource when it's sunny. The flywheel allows the system to ride through short fluctuations (for example when a cloud passes), and also allows time for diesel generators to be turned on when there is a significant drop in solar availability or a large increase in load. However, the flywheel must continue spinning in order to maintain overall system operation, even during the night when no solar power is available, which results in additional parasitic losses. As seen in several other cases, a flywheel often pairs better with wind than with solar due to wind's comparatively higher capacity factor.

Although residents did not see a change in electricity rates, the system has brought other benefits to Marble Bar and Nullagine. First, the system is now more reliable, and renewables act as a hedge against increasing oil prices. Second, these two towns are recognized as leaders in renewable integration, and Horizon Power has been able to share its knowledge of how to design and build a renewable system with other communities around the world through the Isolated Power System Developers Forum.

LEADING FIRST WITH ENERGY EFFICIENCY

Along with including solar as a source of electricity generation in the new system, both Marble Bar and Nullagine incorporated new levels of energy efficiency. As a result of a customer engagement campaign, the residents of these remote communities have an increased appreciation for how much energy they use on a daily basis. Many residents spend a significant amount of their income on electricity. Horizon Power provided energy efficiency audits to households throughout the community prior to the integration of the solar system along with educational materials about energy usage and training sessions in the local language. The energy audit processes and educational information ensured overall buy-in of the new system. Community members also had the opportunity to name the new solar systems in each town.


Installed Capacity (kW)

Average Annual Generation (%)

CORAL BAY, AUSTRALIA

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
140	*2,915 kW*	*600 kW*	*45%*	*$0.19/kWh*	*$0.22/kWh*

CORAL BAY IS HOME to the Ningaloo Reef, where coral starts right at the shore, forming Australia's only fringing reef. This small community's chief activities are tourism and fishing, local industries that, until 2006, were powered entirely by isolated diesel generators. In 2006, the small, remote Australian community made a big change.

Previously, residents in this community relied on their own individual generators to provide electricity without a connected system, similar to the Isle of Eigg in Scotland. The new electricity system, while not connected to Australia's larger grid, interconnects local residences and buildings, and is powered by 45 percent wind (on an annual basis). The new system was grant-funded, and developed through a power purchase agreement (PPA) with the generating utility, Verve Energy. In order to balance the intermittent wind resource, the system incorporated two technologies: low-load diesel generators, and a 500 kW flywheel. The low-load generators are able to operate down to 10 percent of their rated load with minimal penalties to efficiency, which allows more of the available wind energy to be utilized (see Figure 4 on the next page for a comparison of traditional and low-load diesel generator efficiency curves). The flywheel, part of ABB's PowerStore solution, provides stability to the overall system. Overall, the system can use up to 97 percent wind power instantaneously, and powers 45 percent of the community's loads from wind power annually. Although there's no baseline to compare electricity rates directly (since there was previously not a connected system), the cost for individuals has gone down since they are no longer paying for fuel to run their own generators.

The addition of the system was not without challenges. Many residents were wary of wind turbines being located so close to town, but a well-designed community education process brought everyone on board and generated buy-in on the project. Furthermore, construction was difficult due to the remote location, where getting people on-site to build the system required several days of travel. Currently, one full-time park employee is located on-site to provide day-to-day support.

HURRICANE-PROOF WIND TURBINES

Another interesting feature of the Coral Bay system is the use of Vergnet wind turbines, eight of which are installed near the community. The entire turbine can be tilted and lowered to the ground in the event of dangerous weather. This process can be completed by two people in less than an hour, and once lowered the turbine can survive up to 300 km/h wind gusts—equivalent to a Category 3 hurricane—without any damage.[6] The turbines can then return to normal operation once extreme weather passes. This same tilting approach can be used to perform routine maintenance on the wind turbine blades. Vergnet wind turbines currently operate in places where high winds and hurricanes are a concern, such as at the Maddens Wind Farm on Nevis Island in the Caribbean.

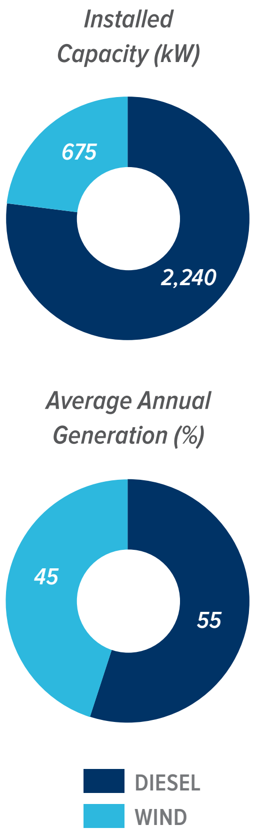
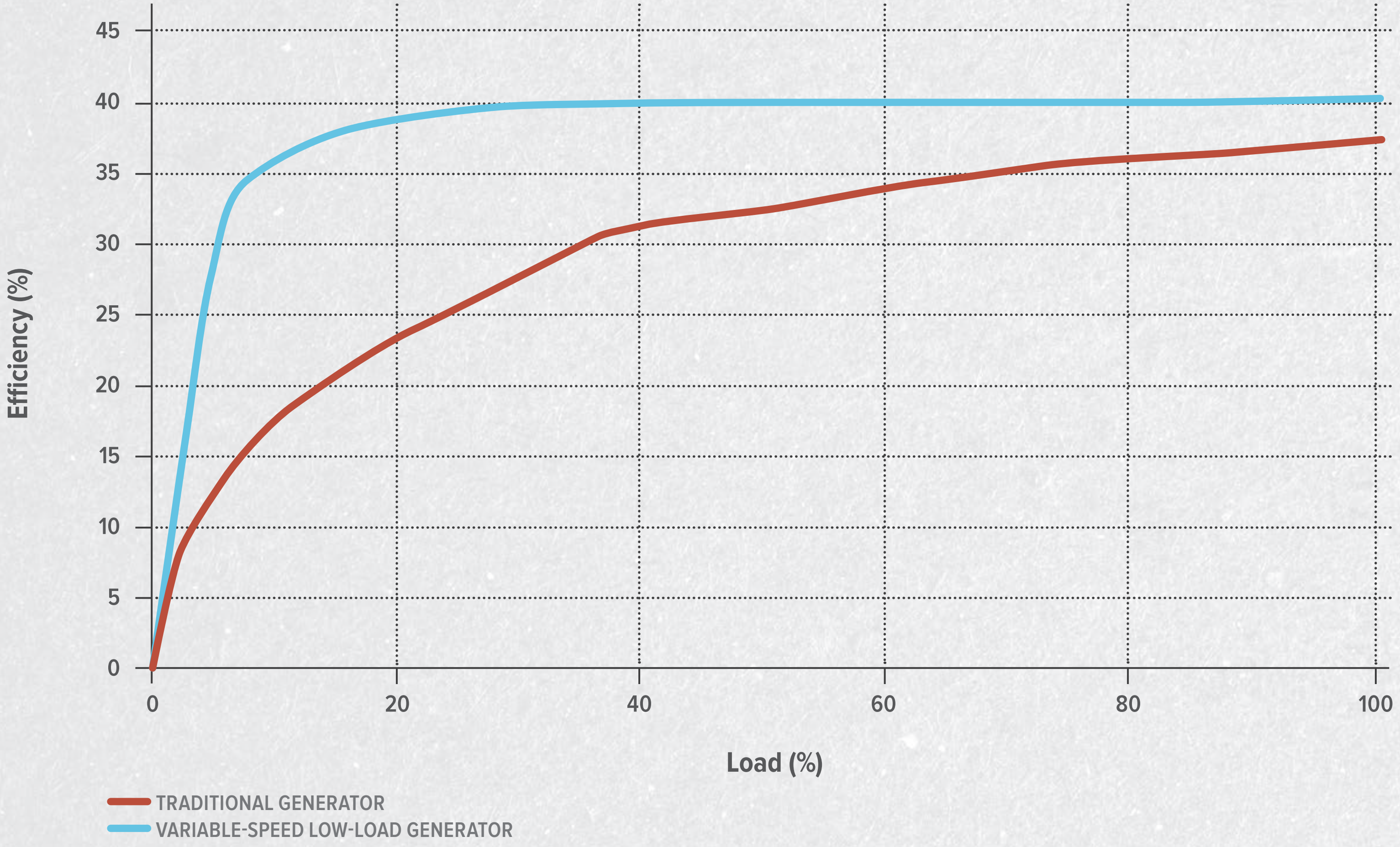


FIGURE 4: EXAMPLE OF TRADITIONAL AND VARIABLE-SPEED LOW-LOAD DIESEL GENERATOR EFFICIENCY CURVES.



ISLE OF EIGG, SCOTLAND, UNITED KINGDOM

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
100	*250 kW*	*60 kW*	*87%*	*$0.31/kWh*	*$0.31/kWh*

THE ISLE OF EIGG is a small island off the coast of Scotland known for its beauty, wildlife (on average 130 bird species are recorded on the island each year), and renewable electrification project. Prior to 2007, island residents generated power at homes and businesses using diesel generators. Furthermore, the buildings and their diesel generators were stand-alone systems: no multi-building microgrid existed on the island prior to the transition. Recognizing the drawbacks that come along with a non-interconnected electricity system driven by diesel alone, the community created an integrated plan for a new, connected, all-island electricity system. Community members were involved throughout the process. “What makes it work so well is that it’s ours [the electricity system],” says John Booth, formerly a Director of the Isle of Eigg Heritage Trust and Volunteer Project Manager for the system.

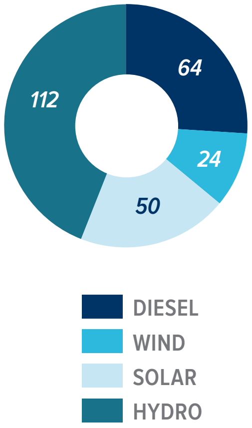
Leadership from within the community is a unique feature of the Isle of Eigg’s electricity transformation. When residents decided that a diverse, connected electricity system would be better than each home having its own individual generator, they quickly realized that building their own system would be cheaper than creating an electrical connection to the mainland grid. They also decided to power their new system almost entirely with the island’s abundant renewable resources—rain, wind, and sunshine. Since this was a brand new system combining three different renewable sources of electricity, the community was forced to learn by doing as it transitioned—applying for grant funding, securing permission to build, finding a contractor to design and build the system, and training local residents on how to operate and repair the now renewable microgrid.

The system also includes a 720 kWh battery bank in order to guarantee that electricity will be available at all times. When there is extra power available from renewable resources and the battery is already fully charged, the system automatically activates heaters that pre-heat community buildings keeping them warm and dry. Residents have reaped many new benefits from the system, the most prevalent of which is reliable power availability. Before the microgrid, individual buildings were at risk of power outages in the event of diesel generator failure. With an interconnected microgrid, risk of power outages at individual homes has been reduced. Isle of Eigg residents are also now using local energy resources and much less diesel fuel. A team of local residents has been trained to maintain the system, which includes four part-time maintenance personnel, forestry jobs to harvest biomass, and two “green project managers,”[7] ensuring reliable electricity for all community members.

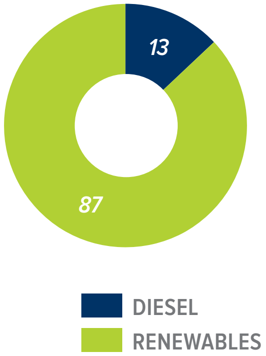
A UNIQUE APPROACH TO MANAGING ELECTRICITY USE

On the Isle of Eigg, community members agree to use electricity responsibly; each home and small business is capped at an instantaneous peak demand of 5 kW, while larger businesses and buildings can use up to 10 kW at once. Residents prepay for their electricity ahead of time via cards that slot into their electricity meters and are available for residents to purchase once per week. It’s rare that anyone exceeds their maximum demand limit using this system, which has resulted in additional cost savings since no truck rolls are necessary to shut down or reactivate building electricity access.

Installed Capacity (kW)



Average Annual Generation (%)



NECKER ISLAND, BRITISH VIRGIN ISLANDS

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
60	*2,160 kW*	*400 kW*	*80%*	*$0.24/kWh*	*$0.24/kWh*

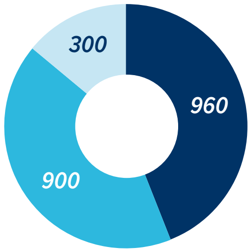
IN 1978, ENTREPRENEUR Sir Richard Branson made a bid to buy a small Caribbean island. As a part of the Commonwealth Law, non-resident landlords were required to build a resort on the island or the government could reclaim ownership. At the time he purchased the island, Sir Richard Branson took a risk as he lacked the funds to develop it immediately. Over time, he made a home out of Necker Island, and situated Necker as a test bed for an energy transition.[8] Prior to 2014, diesel fuel was the only resource used to generate electricity for island staff and visiting guests. In 2014, Richard Branson set down a path to phase out the use of all diesel fuel on the island. Thus far, 300 kW of solar photovoltaic (PV) have been installed with a single 900 kW wind turbine, a 500 kWh battery, and advanced microgrid controls planned for installation in 2016.

Necker is not only working to bring as much renewable energy online as possible (with a current 75 percent renewable energy penetration target), but to deliver the additional 25 percent of diesel reduction by the integration of energy efficiency and smart controls. The goal is to reach 100 percent reduction in diesel fuel use. In addition to increasing the supply of renewable energy, Necker's system designers and contractors are retrofitting existing buildings with more efficient AC units and upgrading insulation of many of the buildings while adding smart controls to further reduce diesel consumption. Through these approaches, the island benefits from actually reducing usage, not just adding generation, pushing Necker Island to the forefront of what is possible with a renewable microgrid. With the addition of solar, the island is already seeing diesel fuel savings of 15 to 20 percent annually. Once wind and storage come online in the near future, those savings will increase. The owner and developer of the new system, NRG, plans to incorporate deeper levels of energy efficiency to reduce overall energy demand, which will move beyond the 75 percent renewable energy goal.

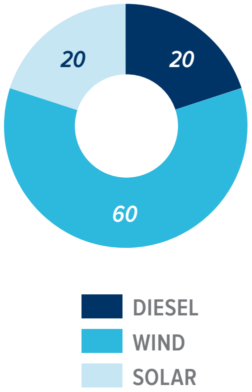
Currently, the Smart Island Economies team is supporting island partners in developing strategies for transitions, including a process for open tenders to independent power producers and energy efficiency providers for the region. Accordingly, Necker Island was the first island to issue an RFP for design and construction of its new system as a part of the Smart Island Economies program.

SUCCESS THROUGH AN INCREMENTAL PROCESS

The addition of 300 kW of solar on Necker Island reduced diesel use by 15 to 20 percent. The various renewable resources, energy storage, and controls are being implemented in phases so that the impact of each technology can be measured and validated before the next phase of the transition begins. In addition, developers used an off-site programmable load bank to create a virtual version of the system in order to test different scenarios before actually installing renewable resources and controls.



Installed Capacity (kW) - Planned



Average Annual Generation (%) - Projected[v]

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[v] *For this example, these are projections for when the planned projects are completed in 2016.*

MAWSON STATION, ANTARCTICA

POPULATION	INSTALLED CAPACITY	PEAK DEMAND	AVG. ANNUAL RENEWABLE GENERATION	AVG. RESIDENTIAL RATE	AVG. COMMERCIAL RATE
30	*1,150 kW*	*450 kW*	*50%*	*N/A*[vi]	*N/A*

IMAGE: © JUSTIN CHAMBERS/AUSTRALIAN ANTARCTIC DIVISION

MAWSON IS THE oldest surviving, continuously operated research station south of the Antarctic Circle, and is the most distant of the three main Antarctic stations operated by the Australian Antarctic Division (AAD).

Two unique features made this station an ideal place to incorporate renewables for electricity generation. First, its remote location makes reliable delivery of diesel fuel difficult. Second, the wind resource in and around Mawson is outstanding. In 2002 and 2003, the AAD built two wind turbines at Mawson Station, serving on average thirty researchers. Before installation began, the AAD completed an environmental impact assessment to ensure that the benefits of adding wind turbines outweighed potential negative ramifications including impacts on wildlife and visuals.

Mawson's remote location and cold climate led to several challenges while preparing for and installing two Enercon 300 kW wind turbines. The installation needed to bring in a 100-ton crane, requiring the provision of a larger than typical icebreaking ship. Once the turbine components reached Antarctica, bridges at the station had to be strengthened to bear the weight of the vehicles transporting the turbine.

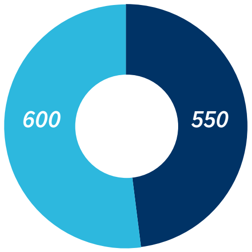
Interestingly, Mawson Station's electrical loads go beyond thermal comfort, lighting, and plug-loads. The station also includes some luxuries for residents, such as a spa and a sauna, which require relatively large amounts of electricity compared to other day-to-day uses. In order to maximize fuel savings, the AAD worked to educate people about using these amenities only when wind energy is readily available, rather than at times when the diesel generators would need to turn on.

In 2014 alone, the wind turbines generated enough electricity to reduce Mawson's diesel consumption by 288,000 liters, directly saving the AAD $263,000 in fuel costs. The AAD also gained greater flexibility in scheduling resupply ships; instead of requiring a shipment of diesel fuel at least once per year to meet the station's needs, the AAD can now send a refueling shipment every other year. The success seen at Mawson Station is already spreading, and other nations with operations in Antarctica have incorporated renewable resources for electricity generation.[9] Furthermore, the now 10-year old wind turbines are still operating at high levels of efficiency—even in the tough winter climate.

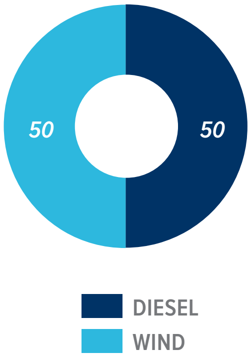
RENEWABLES FOR HEATING IN A HARSH CLIMATE

The wind turbines created an additional impact on Mawson's heating supply that's of note for other remote microgrids with large heating requirements. Before adding wind to the system, two diesel generators powered Mawson Station and extra heat from these generators heated many of the station's buildings. With the addition of wind, just one diesel generator runs for most of the year. This slashes the diesel requirement, but it also removes the extra heat source from the now rarely used second generator. In response, the AAD added an electric boiler to the system in tandem with the wind turbines. With any extra power available from the wind turbines, the electric boiler preheats water to heat buildings. The boiler is also connected to Mawson's system with a smart inverter, which provides voltage and frequency support to the microgrid. The result is similar to having additional spinning reserves, since the boiler can ramp its output up or down quickly when there is a shift in available wind.

Installed Capacity (kW)



Average Annual Generation (%)



[vi] *Since Mawson is a research station, the Australian Antarctic Division covers all costs, and rates are not charged to specific customers for electricity use.*

GLOSSARY OF KEY TERMS

04

GLOSSARY OF KEY TERMS

AVERAGE ANNUAL RENEWABLE GENERATION—The percentage of electricity in a system that is generated from renewable resources over the course of a year; this is the definition of renewable penetration used in this casebook.

AVERAGE COMMERCIAL RATE—The average rate that a commercial customer pays for electricity today (after the renewable transition).

AVERAGE RESIDENTIAL RATE—The average rate that a residential customer pays for electricity today (after the renewable transition).

DYNAMIC RESISTOR—A large resistive load, which can be varied rapidly. On King Island, a dynamic resistor is used to absorb excess wind generation rather than spill it through shutting down or throttling back wind turbines. Since the resistor can be adjusted rapidly, this effectively converts spilled wind into "spinning reserve" that can be used to supplement diesel generation. Maintaining the power balance between generation and demand in this way allows the resistor to maintain system frequency.

ELECTRIC HEAT PUMP—A device that uses electricity to move heat from a cool space (such as outdoors) to a warm space (such as indoors), and can be used as an alternative to a furnace.

ENERGY STORAGE—Technologies including but not limited to batteries, pumped hydro, and/or flywheels that store energy to perform work at a later time. Storage applications range from managing second-to-second variations in power output to storing energy over multiple days.

FLYWHEEL—A rotating mechanical device used to store kinetic energy.

INSTALLED CAPACITY—The total size of the various installed sources of electricity generation, in kilowatts.

MICROGRID—While the term "microgrid" is often used to describe many different things, in this casebook we use it to refer to small electricity grids supplying island and remote communities, with no connection to a larger electricity grid.

PEAK DEMAND—The highest electricity demand experienced by a system at a single point in time, in kilowatts.

PROGRAMMABLE LOAD BANK—Test equipment that emulates electric loads in order to perform functional tests of batteries and power supplies, such as solar panels. Being programmable allows tests to be automated, and allows changing load profiles to be used for testing the power source.

RELIABILITY—The ability to deliver electricity to all points of consumption, in the quantity and with the quality demanded by the customer.

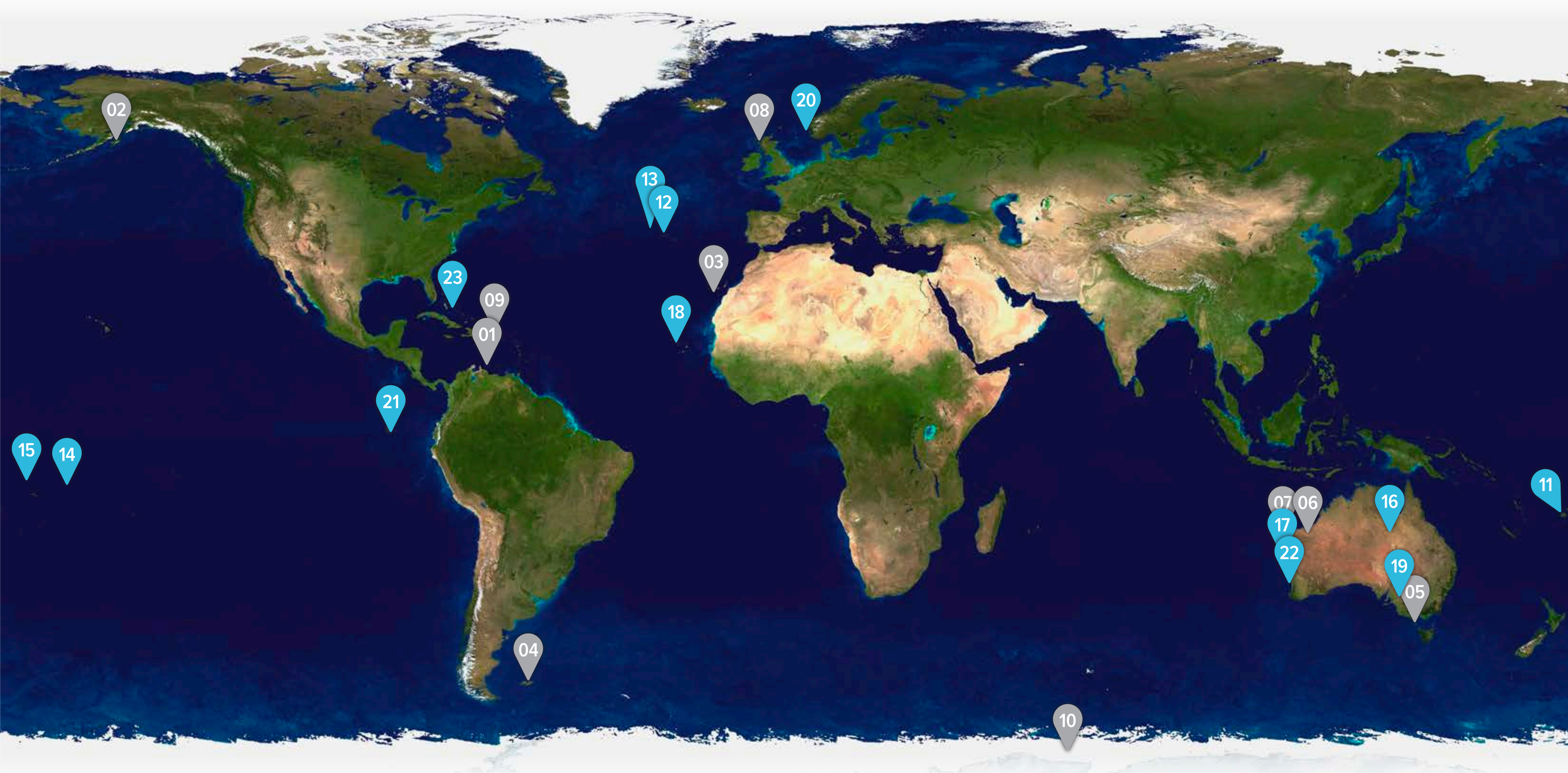
RESILIENCE—The ability of the electricity system to resist failure and rapidly recover from breakdown.

SPINNING RESERVE—Extra generating capacity that is immediately available to meet an increase in load while also helping to maintain system frequency.

APPENDICES

05

APPENDIX A: ADDITIONAL ISLANDED OR REMOTE MICROGRIDS



01: Bonaire, The Netherlands
02: Kodiak, Alaska, United States
03: El Hierro, Canary Islands, Spain
04: Falkland Islands, United Kingdom
05: King Island, Tasmania, Australia
06: Marble Bar & Nullagine, Australia
07: Coral Bay, Australia
08: Isle of Eigg, Scotland, United Kingdom
09: Necker Island, British Virgin Islands
10: Mawson Station, Antarctica
11: Fiji
12: Graciosa Island, Portugal
13: Flores Island, Portugal
14: Northern Cook Islands, New Zealand
15: Tokelau, New Zealand
16: Ti Tree, Kalkaringdi, Lake Nash, Australia
17: Denham, Australia
18: Monte Trigo, Cape Verde
19: Hopetoun, Australia
20: Ultsira, Norway
21: Floreana, Galapagos, Ecuador
22: Rottnest Island, Australia
23: Over Yonder Cay, Bahamas

APPENDIX A: ADDITIONAL ISLANDED OR REMOTE MICROGRIDS

FIGURE 5

COUNTRY	CITY	POPULATION	AVERAGE ANNUAL RENEWABLE GENERATION (%)	AVERAGE RESIDENTIAL RATE ($/kWh)	AVERAGE COMMERCIAL RATE ($/kWh)	OVERALL GRID CONNECTION	BASELINE GRID YEAR	INSTALLED CAPACITY (kW)	PEAK DEMAND (kW)
Fiji		881,000	60	0.08	0.19	physical islands	1980	159,000	150,000
Portugal	Graciosa Island	5,000	70	0.17	0.15	physical island	2013	9,600	2,200
Portugal	Flores Island	3,900	50	0.17	0.15	physical island	2009	6,080	2,000
New Zealand	Northern Cook Islands	1,441	95	0.45	0.64	physical islands	2014	2,286	151
New Zealand	Tokelau	1,400	100			physical island	2011	1,727	214
Australia	Ti Tree, Kalkaringdi, Lake Nash	1,139	30	0.22	0.26	remote grids	2012	2,400	770
Australia	Denham	800	50	0.22	0.32	remote grid	1997	2,410	1,200
Cape Verde	Monte Trigo	600	95			remote grid	2011	47.3	3.75
Australia	Hopetoun	350	40	0.16	0.32	remote grid	2006	3,440	650
Norway	Ultsira	212	100			physical island	2003	1,255	55
Ecuador	Floreana, Galapagos	200	100	0.091	0.092	physical island	2009	159	50
Australia	Rottnest Island	100	40	0.42		physical island	2005	1,240	560
Bahamas	Over Yonder Cay	0	96			physical island	2009	1,075	400

APPENDIX B: LIST OF INTERVIEWEES

CASE LOCATION	ORGANIZATION	INTERVIEWEE
Bonaire, The Netherlands	Contour Global	Roy Montero
Kodiak, Alaska, United States	Kodiak Electric Association	Darron Scott
El Hierro, Canary Islands, Spain	Gorona del Viento	Christina Clavijo
Falkland Islands, United Kingdom	Falkland Islands Government	Glenn Ross
King Island, Tasmania, Australia	Hydro Tasmania	Simon Gamble
Marble Bar & Nullagine, Australia	Horizon Power	David Edwards
Coral Bay, Australia	ABB	Juergen Zimmerman
Isle of Eigg, Scotland, United Kingdom	Isle of Eigg Heritage Trust	John Booth
Necker Island, British Virgin Islands	Virgin	Adam Simmonds
Mawson Station, Antarctica	Australian Antarctic Division	David Waterhouse

ENDNOTES

[1] *Renewable Energies for Remote Areas and Islands (Remote)*, p. 18—22, IEA-RETD, April 2012. http://iea-retd.org/wp-content/uploads/2012/06/IEA-RETD-REMOTE.pdf; and *Remote Microgrids: Commodity Extraction, Physical Island, Village Electrification, and Remote Military Microgrids: Global Market Analysis and Forecasts,* Navigant Research, 2013.

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[3] C. Barton, L. Kendrick, and Malte Humpert. “The Caribbean has some of the world’s highest energy costs- now is the time to transform the region’s energy market,” InterAmerican Development Bank, 2014, http://blogs.iadb.org/caribbean-dev-trends/2013/11/14/the-caribbean-has-some-of-the-worlds-highest-energy-costs-now-is-the-time-to-transform-the-regions-energy-market/

[4] J. Enslin, *“Grid Impacts and Solutions of Renewables at High Penetration Levels,”* Quanta Technology, http://quanta-technology.com/sites/default/files/doc-files/Grid-Impacts-and-Solutions-of-Renewables-Executive-Summary.pdf

[5] J.I. San Martin, I. Zamora, J.J. San Martin, V. Aperribay, and P. Eguia, “Energy Storage Technologies for Electric Applications,” *International Conference on Renewable Energy and Power Quality (ICREPQ’11),* April 13-15, 2011, http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html

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[7] “The Ashden Awards for sustainable energy,” *Ashden Awards Case Study Isle of Eigg Heritage Trust, Scotland,* May 2010.

[8] L. Murray, “How Richard Branson bought Necker Island,” *Virgin Entrepreneur, 2015,* http://www.virgin.com/entrepreneur/how-richard-branson-bought-necker-island

[9] A. Schwartz, “Antarctica Turning to Solar, Wind Power,” *CleanTechnica,* January 2009, http://cleantechnica.com/2009/01/22/antarctica-turning-to-solar-wind-power/

ROCKY MOUNTAIN INSTITUTE

CARBON WAR ROOM