Energy Resilience in the Caribbean

Ade Samuel and Wendell Samuel
10/30/2019

Paper presented to 51st Monetary Studies Conference. Held at the Eastern Caribbean Central, Basseterre, St. Kitts, November 19-22, 2019

Energy Resilience in the Caribbean

By
Ade Samuel and Wendell Samuel

Introduction

The Caribbean is one of the most disaster-prone regions in the world, afflicted by flooding (which causes landslides), hurricanes, earthquakes and occasional periods of drought. The first three events have devastating effects on the region's energy infrastructure, especially on the distribution network and on end-user infrastructure. Climate change threatens to increase the frequency and severity of natural disasters hence resilience of the energy infrastructure will become even more important in the years ahead. Like general economic resilience a key part of enhancing infrastructure resilience is the investment in structural resilience that takes place ahead of the occurrence of a natural disaster. Since energy pervades all aspects of the economy, strengthening resilience of the energy infrastructure will have knock-on effects on growth and on livelihoods, apart from its impact on the wellbeing of the society. This paper discusses the resilience of the energy infrastructure in the Caribbean looking at all aspects of resilience and presents some ideas on how resilience can be enhanced.

A recent International Monetary Fund Executive Board paper has proposed a Disaster Resilience Strategy (DRS) for small states (IMF 2019). The DRS proposes that countries focus on ex ante action in three areas of resilience building (i) structural resilience; (ii) financial resilience; and (iii) post disaster recovery. Structural resilience refers to ex ante investments to strengthen infrastructure while financial resilience is achieved by putting in place financial arrangements in advance of natural disasters. The forward-looking focus of the DRS finds resonance in the discussion of energy resilience of this paper.

The term resilience is not always clearly defined. In this paper we will adopt the definition used by the United States National Infrastructure Advisory Council—resilience is the capacity of a system to continue functioning in the event of a natural disaster and its capacity to recover quickly after the event. Accordingly, resilience has four closely related dimensions. (i) robustness, (ii) resourcefulness, (iii) recovery and (iv) adaptability. Robustness refers to the ability of the system to withstand shocks. This robustness is built in ahead of time and represents the investment in hardening the infrastructure and building in flexibility. Resourcefulness is the key to managing through an event making required adjustments as needed. This involves investment in people and putting in the training and simulations ahead of time to assist with critical decision making in a crisis. Recovery as the name suggests is the capacity to recover quickly in the aftermath of an event. This requires hardening of infrastructure, but it also involves having critical spare parts on hand and enough redundancy to deal with recovery issues as well as deliver on expected mandates.

Adaptability refers to the ability to learn from an event and build these lessons into the system so that it enhances resilience the next time around.

There are a few considerations that need to be addressed in enhancing resilience in the energy sector. First as opposed to other types of infrastructure like bridges, sea defenses, roads etc., there is a much larger emphasis on operational resilience, in power generation and distribution which goes beyond the mere hardening of the infrastructure. Second, with a significant amount of long-lived and very costly assets it may take many years to bring about the adjustment needed to build resilience. Progress in some aspects of resilience building would need to be incremental as new capacity comes on stream to effect a shift to more resilient energy sources. A wholesale shift would be prohibitively expensive. A recurring question for small states is the tension that arises concerning whether a country should build back better or build back faster. Building back faster gets critical systems back up and running more quickly and avoids economic loss and prolonged hardship. On the other hand, building back better takes time. Nowhere is this tension more evident, than for energy because of the its pervasiveness in economic activity and daily life. The urgency to get power back up and running usually forces countries to build back faster and hence lose the benefits of building back better. Finally, as small states strive to build resilient energy systems, they must bear their climate change mitigation goals in mind to try to shift to more renewable sources of energy while ensuring economic resilience of their energy systems.

Following the introduction Section I of the paper discusses resilience as it applies to the energy sector in the Caribbean. It treats resilience in a holistic manner looking at all aspects of resilience building. Section II of the paper discusses some of the main considerations in building energy sector resilience in the Caribbean. Some ideas for enhancing energy resilience in the Caribbean are discussed in section III, identifying low hanging fruits but also discussing some more intractable, medium-term issues. The final section provides some concluding remarks.

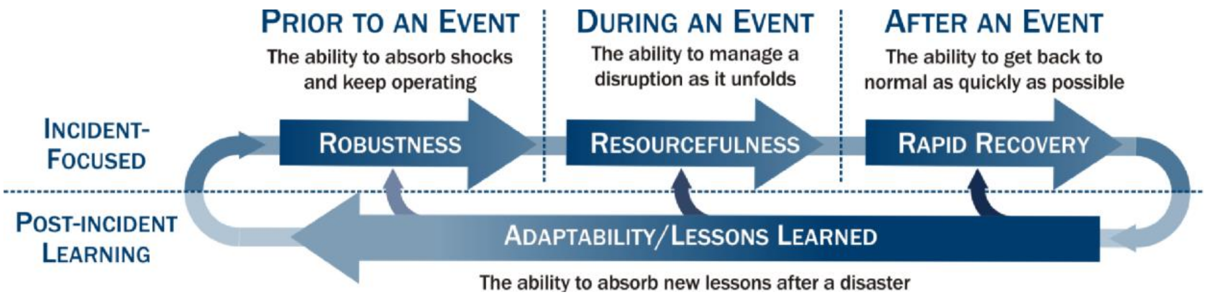
Section I

What do we mean by resilience in the energy sector?

The concept of resilience has received a significant amount of attention in recent years and has been applied in a variety of contexts. Consequently, the meaning of resilience has become diffused and imprecise. For this paper we adopt the definition used by the United States National Infrastructure Advisory Council, which encompasses the notions of continued efficient operation, quick recovery and learning and adaption following a disruptive event. This gives resilience the related dimensions of robustness, resourcefulness, recovery and adaptability discussed below. Since natural disasters like hurricanes and earthquakes are the most disruptive events in the Caribbean, we will pay close attention to these phenomena.

With a significant amount of assets for power generation and distribution, the energy sector is extremely vulnerable to hurricanes and flooding that results in landslides. The distribution system consisting of poles, miles of electrical cabling, transformers, and other assets are usually the first to sustain damage during hurricanes. Electricity generation plants and other assets are also vulnerable to such events. As countries move to adopt renewable sources of energy, the power generation infrastructure is exposed to even greater vulnerability. Finally, the end-user interface is also important because even if the energy companies do a good job in ensuring the energy infrastructure remains usable after a disaster, consumers still need to be able to accept power. It is therefore critical that resilience addresses all aspects of the energy infrastructure.

Elements of a Resilient Infrastructure



Source: National Infrastructure Advisory Council (2010).

Figure 1: Elements of a Resilient Infrastructure

Robustness is the capacity to continue efficient operation or remain standing in the event of a disaster. This can be achieved through ex ante hardening of infrastructure to make it able to withstand low-probability more severe events like catastrophic hurricanes. Studies have shown that investment to harden infrastructure well ahead of potential disasters has a huge pay-off—one dollar spent on strengthening infrastructure is estimated to save about 7 dollars in damage avoided. Ex ante spending yields returns in terms of reducing lost downtime and production compared to rapid rebuilding in the post disaster period (Clarke and Dercon 2016). For the economy as a whole, it increases growth prospects as hotels and factories can come back on stream more quickly avoiding dislocations and bottlenecks which can be costly to output. A second way to achieve robustness is through redundancy. Investment in redundant systems allows for energy infrastructure to maintain normal operation even if some hardened infrastructure fails. Ideally these two strategies should be used together to achieve maximum resistance to uncertain events.

Resourcefulness is the ability to manage through a disaster, ensuring that operations continue efficiently during the event. This involves real time decision making, for example whether it is necessary to shut down parts of the system to avoid costly damage that could delay recovery. This capacity inheres from the investment in selection and training of the workforce charged with operating the infrastructure. While this activity takes place during the event, a key part of this takes place ex ante in the form of training, communication systems, scenario simulations, drills, and ensuring that the appropriate persons are in place. Moreover, this aspect of resilience also encompasses ex ante considerations made during the design of energy infrastructure. Diversity among different types of generation sources, incorporation of sufficient battery storage, and distributed system design are all hallmarks of resourceful and resilient energy systems. These factors allow for increased agility in terms of maintaining generation capacity in the face of disruptive events.

Rapid Recovery is the capacity to get operations back to normal with a minimum amount of delay. While the recovery refers to measures taken after the event to ensure a speedy return to normalcy, as with the other components of resilience, ex ante preparation is indispensable. Well-designed contingency and business continuity plans are needed to ensure quick recovery from natural disasters. Also important is the identification of key resources that would be needed for recovery and ensuring their availability ahead of time. In the case of the Caribbean, there are well-established processes where electricity linesmen from other countries are mobilized to assist the stricken countries to get electricity poles and power lines back up very quickly. It may also be necessary for countries to have stocks of spare parts to minimize delay as imports may be delayed in the post disaster period.

Adaptability refers to the learning and making changes based on the experiences during and after the event. Reviews following the event are critical to identifying which measures worked and which did not during the event. These would inform how the procedures, training, personnel deployment and contingency and business continuity plans need to be adjusted in light of the experiences. They also provide important input into the medium to longer-term decisions about hardening the infrastructure

Section II

Some Considerations for Energy Resilience in the Caribbean

The resilience framework discussed above points to some interesting aspects of resilience building including the role of time. Energy infrastructure is characterized by large quantities of long-lived and costly assets—power plants, distribution networks, etc. This means that process of strengthening resilience would be time intensive, as assets depreciate as changes would need to be incremental. This is even more true in cash-strapped, high-debt, Caribbean countries since they do not have the resources available to make the requisite investment for a more rapid shift. The only exception would be in the event of a catastrophic event that requires replacement or near replacement of the entire infrastructure.

Energy infrastructure is different compared to regular infrastructure projects like roads, bridges, sea defenses etc., which mainly require physical maintenance to ensure that they function, resilience in energy infrastructure is more complex. It involves physical maintenance, training and skills development of the personnel to keep systems running and needs to consider the interdependencies with other cross-sectoral services. The physical maintenance of energy infrastructure varies according to the component. Resilience in generation capacity requires maintenance of both the plant and machinery while the distribution network requires maintenance of the poles and lines sub-stations, transformers etc., A key part of the line maintenance is the clearing of trees and over hanging branches to help minimize the effect of falling trees on power lines. DOE (2018) notes that the bulk of power line disruptions in Puerto Rico arise from falling trees and branches and recommended a program of regular, periodic clearing of over-hanging vegetation.

Energy resilience requires consideration of the interdependence between the energy sector and other utilities to minimize the cascading effects of the loss of electricity power. The importance of staff selection, training and business continuity exercises has already been discussed. However, these simulation exercises would be meaningless if they did not consider how the electricity system impacts and is impacted by other utilities. The main interdependencies are:

(i) Fuel services: Fuel and lubricants are required for the generation of electricity and for powering of transport. Meanwhile, fuel pumps are driven by electricity thus disruption in one can have cascade effects on the other.

(ii) Communication and information technology services: During a hurricane the loss of communication services could be partly related to the loss of electricity. This then creates a negative feedback loop involving the electricity sector as critical information technology services may delay the recovery of electricity services and communications between units in the electricity sector breaks down.

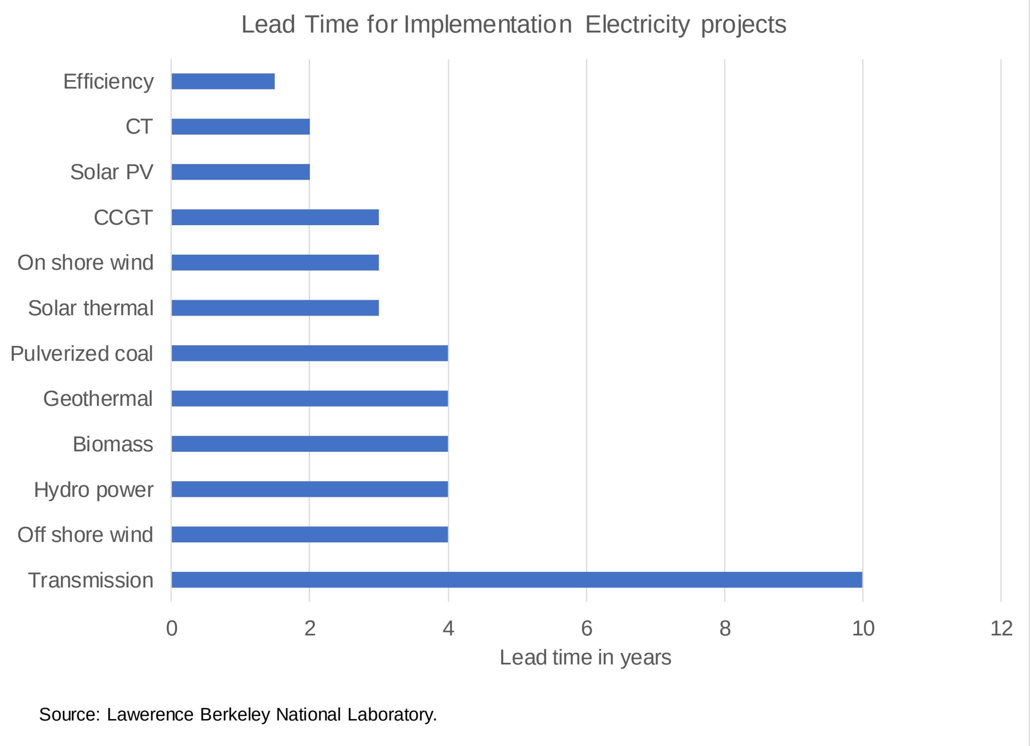
(iii) Water and wastewater systems: The electricity system provides power for water pumping stations, and at the same time the water system may provide cooling electricity turbines.

(iv) Banking and finance: Banks and other financial institutions are heavily dependent on electricity and communication and information technology services. Not only would disruption of electricity affect the speed with which baking services are restored for population at large, but financial transactions that affect the recovery of the electricity sector may also be delayed for example wiring funds to acquire critically needed spare parts.

Long-lived assets and lead-time for investments

Electricity companies have a significant amount of long-lived assets, which implies that adjustments in the sector would be slow. The longevity of assets also differs between generation and distribution, and across the energy mix. For example, hydro power plants have greater longevity than oil-fired plants. With the predominance of long-lived assets large-scale changes in the sector are likely to be prohibitively expensive. In addition, most Caribbean countries currently have very high debt levels. Accordingly, under normal conditions enhancement of resilience will need to be incremental.

Long lead-times for electricity investments also suggest that resilience building in the sector will be slow. Figure 2 shows the lead time for investment in various electricity projects. Projects in the distribution system have the longest lead time while projects that enhance efficiency have the shortest gestation period. These suggest that resilience building projects dealing with the efficiency of electricity and those that address the human resource constraints could be low-hanging fruits, while other investments could take place over the medium-term.



Source: Lawerence Berkeley National Laboratory.

Figure 2: Lead Time for Implementation of Electricity projects

Near destruction of the electricity system in a natural disaster could create conditions for complete replacement. If a natural disaster causes significant damage to the electricity system, countries would need to weigh the cost of costly repairs and retrofitting against the cost of starting over from scratch. In this case the disaster provides an opportunity to rethink the energy system and put in modern resilient energy infrastructure. Such opportunities are often few and far between. The Community of Greenberg Kansas turned disaster into an opportunity when a tornado destroyed 95 percent of the housing in [2007]. They rebuilt the community around a modern resilient energy efficient model using renewable energy resources.

Vicious Recovery Circle

Energy infrastructure is one area where the common disaster recovery tension between 'build back better' and 'build back faster' is most apparent. In order to strengthen resilience, building back better is the objective. After a disaster, strengthening resilience requires rebuilding infrastructure to withstand more intense hurricanes and for the most part, this is what countries do. However, in the case of energy infrastructure there is usually an urgency to get power back up and running as quickly as possible. Since energy is a critical input for many societal goods and services, to drive productive activities, hospitals, and bringing a sense normalcy back daily life. The emphasis is usually on speed rather than seeking long-term more resilient solutions. Most policy makers in the region know that if power lines were underground, they would be better able to withstand windstorms and power would be back on more quickly. However, running lines underground would take a very long time and would be extremely expensive. Thus, in the aftermath of a hurricane most countries simply opt to replace the poles and power lines, leaving the energy distribution system just as vulnerable to next hurricane. Thus, countries go through the cycle of replacing poles and power lines only to repeat the process soon after.

In order to break from this cycle of subsistence recovery, stepwise changes in energy infrastructure need to be made following the aftermath of natural disasters. Isolated microgrids can be established gradually, starting by linking the most critical loads like hospitals, communications and water sanitation. This enables those essential societal functions to be recovered more quickly and potentially share power between one another in periods when generation capacity is temporarily diminished. The development of such microgrids also serves as a step toward increasing resilience through the broader application of a distributed systems approach to energy infrastructure within the Caribbean.

Section III

Source Diversification/Incorporation of Renewables:

Many Caribbean countries have proposed significant scale up of investment in renewable energy generation as part of their commitments under the Paris Climate agreement. The achievement of these climate mitigation goals would also help increase resilience of the energy infrastructure if properly planned. The implied diversification of the energy matrix along with the adoption of distributed systems could increase resilience, while the modular framework of some new technology could help facilitate investment. We explore some of these options in this section.

Geothermal:

Geothermal power is generated by taking advantage of the existing temperature gradients within the various layers of the earth's crust. Geothermal power can be generated in areas of thin crust within the earth's surface that contain sufficiently high temperature gradients and rock surface that is able to transmit fluids (permeable). These geothermal reservoirs are classified into two categories based on the mechanism of heat transfer demonstrated within them, convective and conductive. Convective hydrothermal reservoirs are areas within the earth's crust where heat is carried toward the surface by naturally occurring fluids (liquids or steam). This convective cycle is driven by magma present within the crust of high heat flows from the mantle in areas of thin crust. The magmatic heat source system is most common form of these convective reservoirs. These magmatic systems generally contain high temperatures. Areas that have rapid crust expansion can develop these magmatic reservoirs, however intermediate temperatures are generally observed in these systems.

Conductive hydrothermal systems develop in areas where high heat flows combined with thermal decay of isotopes in insulating sedimentary layers to create hot rock. This hot rock can then transfer heat to surrounding aquifers to develop hot aquifers and springs. These conductive resources generally exist at low to intermediate temperatures, but recent exploration has found that higher temperature conductive resources exist within the earth's crust.

Electrical power is generated from these resources using a Rankine turbine system. In the case of high temperature reservoirs, high pressure steam is extracted directly from the geothermal reservoir and is passed through a turbine. The passage of this steam rotates the turbine and turns a generator which generates electrical energy. In the case of intermediate or low temperature reservoirs, a binary turbine is used where the energy from the geothermal reservoir is used to heat a low boiling point working fluid that passes through a turbine.

Geothermal resources tend to decline in output over time. This can occur for a variety of reasons including decreases in temperature and decreasing saturation of steam. The variability of the available geothermal resource has also limited standardization of parts for generation plants. Plant parts generally need to be tailor made to operate effectively with the available resource at different locations. This fact makes upfront capital input high for geothermal projects. Degree of mineralization of the geothermal resource also impacts the generation capacity. Generally speaking, the higher the mineralization the lower the generation capacity because there is less heat that can be readily converted to work (WER Geothermal 2016).

Hydroelectric (wave):

Wave power generation takes advantage of surface motion of the ocean or pressure fluctuations below the water's surface in order to generate electricity. Wave energy can only be employed effectively in areas where wind blows with sufficient consistency and force to provide continuous waves along a shore line.

There are several designs and configurations that are being tested to most effectively take advantage of the wave energy source. There are four overarching configurations that are currently employed. The first of these four is described as a terminator device. These devices are oriented perpendicular to the wave direction and are generally onshore or nearshore (some floating offshore terminators have been developed). An example of a terminator device is the oscillating water column (OWC). This device allows water to enter through a sub-water surface opening. The water enters a chamber where air is trapped, the water level in the chamber then oscillates as waves pass through the OWC. As the water level increases the air in the chamber is then forced through a turbine which can be turned to generate electricity. Most of these terminator devices are rated at 500 kw to 2 MW depending on geometries and wave conditions.

Another potential configuration is the attenuator. Attenuators are multi-segmented structures that are oriented parallel to the wave direction. They are anchored to the ocean floor at the head by a mooring. Waves run along the attenuator and the structure bends in accordance with varying water levels observed. This bending results in flexing at the points where the segments within the attenuator connect. Hydraulic pumps or other converters present at these connection points convert the resulting mechanical energy into electrical energy. The electricity generated is then stepped up and transmitted to other devices by a connecting line. Point absorbers are also common wave energy devices. These devices function as floating buoys with components that move relative to one another. As waves pass by the components bob up and down with wave height. This motion is used to drive either hydraulic pumps or electromechanical components to generate power.

Overtopping devices collect water from waves in reservoirs. These reservoirs function like dams and when released gravity causes the water to flow back into the ocean. This falling water can drive turbines to generate power. Special devices can be constructed to flow wave water through internal turbines in order to generate power.

The general drawbacks of these types of technologies include limited equipment accessibility leading to high maintenance costs because of the remote location of offshore devices. Moreover, the most efficient of these devices operate at about 30 percent efficiency, but this efficiency is improving as newer technologies are developed.

Wind (onshore and offshore):

Wind power takes advantage of moving air currents to produce electrical energy. The basic technology used to convert wind energy to electrical energy is well established. Wind turbines use rotary engines to convert rectilinear flow to shaft rotation using airfoils. The shaft work is then converted to electrical energy using a generator.

Even though the technology is well established, there is still significant work being conducted to overcome implementation challenges and improve the performance of wind turbines. One of these key areas of exploration is the development of offshore wind technology. Ocean winds tend to blow harder and more consistently than on land. This is an important factor because the amount of energy that can be produced from a wind turbine is proportional to the cube of the wind speed. This relationship makes offshore locations desirable for the implementation of wind technologies.

The technology used in offshore wind projects is similar to the technology used in onshore developments. Many of the modifications made with respect to the turbines and generators in offshore projects have to do with developing components that can handle the specific environmental challenges in the ocean. These include corrosion resistant parts and reinforced foundations that can withstand powerful waves, hurricane force winds. The projects are also generally designed with built-in service cranes. New projects are being developed that can take advantage of the wind resource in parts of the ocean that are too deep to be accessed with current wind technology. These developments include floating turbines or more innovative foundations that are viable in deeper waters.

Conventional offshore wind projects are very site specific and must account for the wind resource available as well as conditions within the sea bed below. In shallow areas monopiles are the common foundation configuration used. A steel pile is driven into the sea bed, generally between 80 and 100ft below the mudline. This pile supports a tower and a nacelle. The nacelle is a casing that contains the generator, gearbox, and remaining electrical components for the turbine. The turbines also contain a wind sensor connected to a yaw drive that orients the turbine toward the wind in order to generate as much electricity as possible.

Offshore turbines are generally larger than their onshore counterparts with tower heights of greater 200 ft and rotor diameters typically between 250 and 430 ft. Monopiles are generally used in water depths of between 15 and 100 ft. Tripod and jacket configurations can be used is depths or situations where the use of monopiles is not practical. Electricity generated in these turbines is sent to a central power station using cables that are embedded in the seabed. The power collected at this central station can then be fed back into the grid using similarly embedded cables. These cables and the process of embedding them are a major up-front capital cost that can depend to the soil and rock content of the sea bed as well as the distance from shore of the project and the distance between turbines.

Biomass:

The term biomass encompasses a wide range of materials including various wood types, agricultural residues, and animal and human waste. These materials can be converted into various types of energy and can be used as fuel for heating, electrical power generation, as well as combined heat and power applications. Each of these applications requires biomass components with particular characteristics. Woody biomass like wood chips and pellets is generally combusted directly or gasified to produce synthesis gas. This gasification process involves heating biomass in the presence of less oxygen than is necessary for complete combustion. Both direct combustion and gasification can be used to generate electricity. Agricultural residues like corn stover, (byproducts remaining after harvest), sugar cane bagasse and wheat straw residues can be used to generate heat energy by direct combustion or converted into fuel through anaerobic digestion. This digestion process involves using bacteria to decompose biomass components in the absence of oxygen and capturing the evolved organic natural gas. Wet biomass material (human and animal wastes) can be converted into gas with a lower energy content using anaerobic digestion. Most other types of biomass can be converted into fuel in the form of boil-oil employing the process of pyrolysis (rapidly heating material in the absence of oxygen).

Direct combustion systems feed biomass components into a furnace where they are combusted with oxygen in excess and the heat generated is used to create steam. This steam is then expanded through a turbine to generate electricity in a configuration similar to those employed in solar thermal power generation systems.

Biogas is generally produced though one of two processes anaerobic digestion or landfill gas collection. Anaerobic digestion involves collecting off-gas from the decomposition (performed by microorganisms) of wet biomass like manure and waste water. This off-gas generally contains a 60-40 mixture of Methane and CO_2 these gases can then be treated and used to produce electricity. Landfill gas collection systems functions through a microbial decomposition process that occurs at the bottom of landfills as compression caused by added waste materials creates an anaerobic environment. The off-gases from this process, which are generally 40 to 60 percent methane with the balance compromised of predominantly carbon dioxide, can be collected and used as a biogas energy source.

Solar (PV and thermal):

Solar energy has become one of the preeminent sources of renewable energy. The two overarching categories for its application are direct use heating (solar thermal) and conversion of light energy into electricity using the photovoltaic effect (solar PV).
In the case of solar PV, a semiconductor device is used to convert light into electricity. A major benefit of the technology behind these solar PV systems is their modular nature. Solar power systems can be designed and scaled to meet a wide variety of energy needs. The largest PV power systems in the world produce for power distributors (largest located in California and can produce up to 579 megawatts).

The amount of power produced by photovoltaic arrays is subject to fluctuations based on operating conditions and field factors (ambient temperature, sun's geometric position, etc.). Intermittence is one of the most significant hurdles to overcome in the development of solar power systems. This intermittence manifests on several time scales. In recent years, several advancements in the technology supporting solar power have help address some of these intermittence concerns. Solar tracking using auto-adjusting mounting equipment increases array generation capacity by increasing sun exposure. Meanwhile "microinverters" coupled with individual panels in an array increase array performance in the event that arrays are partially shaded. Finally, advances in battery technology help address intermittence issues through energy storage and compensating for temporal lags between energy supply and demand.

Solar power systems generally incorporate additional equipment in order to most effectively take advantage of the energy gleaned from sunlight. Inverters are used to convert the direct current (DC) that is produced form photovoltaic cells to alternating current (AC) which is used in most local transmission as well as household appliances. A single inverter can be employed for an array or "microinverters" can be coupled to each of the panels in an array. Microinverters allow for the independent operation of panels, which is beneficial in various scenarios such as if one of the panels in an array is shaded. Meanwhile single inverters are generally less expensive and easier to cool.

Concentrating solar power (CSP) is another development to increase the power produced in solar energy systems. In the case of CSP mirrors are placed across the project site and oriented in such a way that they reflect sunlight back to a receiver. The receiver then converts the solar energy into electricity using PV devices or thermal devices depending on its design. There are several configurations through which CSP can be employed. One is the "Trough" system in which large parabolic mirrors are used to focus sunlight onto series of pipes. The heat built up (temps as high as 750 F) in these pipes can be used to boil a working fluid. The resulting steam can then be used to power a conventional turbine/generator. Another possible configuration is the "Power Tower" configuration in which focusing reflectors are positioned along the ground of a project site and they redirect light toward a central receiver placed atop a tower. The heat built up (temps as high as 1050 F) at the receiver can be used to boil working fluids to power turbines. Another alternative configuration is the "Dish/Engine" configuration. In this case reflective mirrors are used to direct sunlight to a receiver much like in the case of the power tower, however, the mirrors along with the receiver are part of a single assembly that can track the sun throughout the day. These orientations can be applied to either solar thermal or PV applications to increase the system's effectiveness.

Increasing Energy Resilience through distributed systems approach:

Identifying options for renewable generation technologies that could be incorporated into energy systems within the Caribbean addresses one major concern regarding the development of energy infrastructure. The other major concern is how these technologies can be incorporated to improve the infrastructure's overall resilience. Of the existing options to address this issue the most commonly cited approach the implementation of distributed systems i.e. microgrids.

The U.S. Department of Energy defines a microgrid as "a group of interconnected loads and distributed energy sources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid". This approach to the design of energy distribution systems is a pivot away from the unidirectional flow model employed in the past to an integrated flow model (simplified schematic shown in Figure 3). These systems offer increased flexibility in terms of load management using centralized controllers that can optimize the flow of generated power between connected loads and back-up energy storage resources. In the simplified case these systems often incorporate power generation from renewable resources like solar or wind as well as more traditional energy sources like natural gas generators. This design approach helps mitigate some of the intermittence issues associated with renewable technologies as excess energy generated from these resources can be diverted to storage to be used during periods of higher demand. Moreover, the integration of several generation sources allows for disruptions in the power supplied by one source to be offset by power from the remaining energy sources.

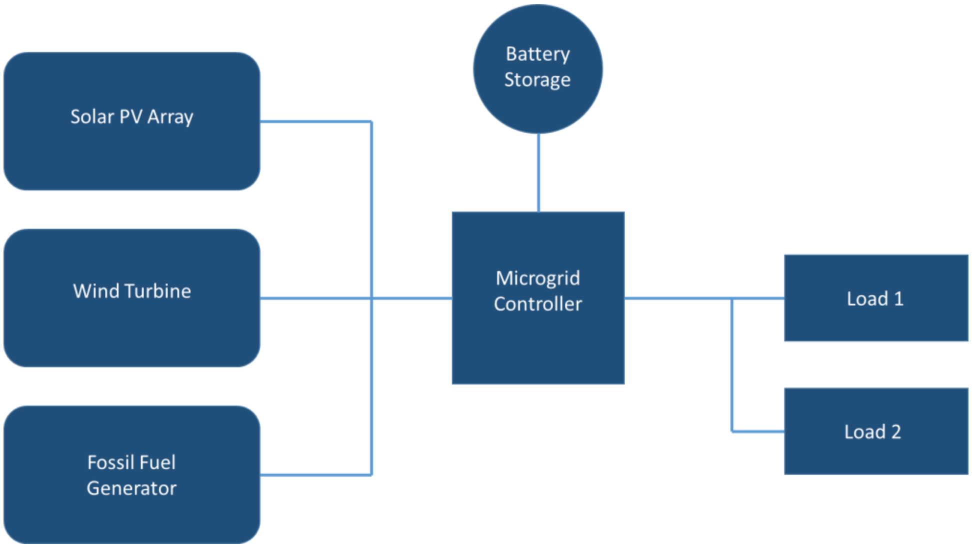


Figure 3: Sample Microgrid Configuration

Microgrids also serve to provide increased resilience to power infrastructure. In the event of a major grid outage effectively islanded microgrids can continue to provide power to critical loads (i.e. hospitals, rescue service centers, etc.) and prolong the period that traditional backup generators can provide power to these loads. Several researchers from the National Renewable Energy Laboratory as well as The City University of New York documented experimental results to support these assertions in 2017. Their work simulates a catastrophic storm event affecting a portion of New York City (below 42nd Street in Manhattan), and performs analyses to compare how long power could be supplied to a critical load with and without the use of a renewable energy hybrid system (REHS) –microgrid. They found that coupling a REHS with a finite fuel supply generator more than tripled the time for which the critical load could be supplied when compared to using a generator on its own. The calculated value of this increase in resilience corresponded to 14 percent of capital costs for the installation of the system.

There is a myriad of approaches to developing effective microgrids varying from developer to developer and site to site as installations are often tailored to address specific situational needs. However, there are a few common threads that can be identified across the span of microgrid development projects that serve as hallmarks for successful installations. Extensive literature exists examining each of the presented design attributes for distributed energy systems. What follows is a brief discussion of these factors and how they contribute to energy resilience.

The first of these determining factors is the effective sizing of grid components to meet power demand. Though it may seemingly go without saying, the process of properly sizing to meet demand requires extensive foresight. Projects should be sized, or have the capacity, to fulfill power demands for connected loads over the entirety of their life cycle. Developers have different approaches for designing to meet this constraint. Some developers oversize their systems making an initial capital investment in anticipation of eventually reaching system capacity as demand rises. Modular system design offers an alternative to this approach and is gaining more prevalence particularly among smaller developers. These modular systems can be rapidly scaled as demand increases and can be flexible enough to incorporate new loads and/or generation sources. This flexibility along with the fact that modular systems do not require as significant a capital investment based on a singular a priori demand estimate is driving interest in the modular design approach. Moreover, this agility in system design offered by modular microgrids adds an aspect of adaptability to existing energy infrastructure, increasing overall resilience.

Another of these common threads in successful microgrid implementation is effective load selection. Intermittency of demand is a major challenge to microgrid development. Customers with power demand that fluctuates throughout the day, like residences or retailers, can drive up infrastructure costs as additional storage is needed to account for excess power generated in periods of low demand. With energy storage being one of the more expensive microgrid components these resultant cost shifts can often significantly hamper project success. Developers look toward loads with more consistent power demand to avoid incurring these costs. They strive to incorporate anchor loads like hospitals or productive use loads (i.e. small business or manufacturing units) and have these less-variable loads serve as the basis of their systems at least during the early stages of development.

Finally, a key attribute of successful microgrids, particularly where resilience is concerned, is grid autonomy. Microgrids need to be properly islanded from the existing grid to reap resilience benefits in the event of a major grid service interruption. Along those lines, black start capacity is a crucial precondition from resilience promotion through distributed energy systems. Resilient microgrids must incorporate some method of self-contained start up without the use of external power sources. Maintaining the autonomy of these distributed energy systems allows for their incorporation to add robustness and resourcefulness to existing energy infrastructure while adding to the capacity for rapid recovery.

Economic Resilience

Economic resilience of the energy sector refers to its ability to manage through and recover from economic shocks. For the energy sector the main external economic shock is the volatility of oil prices which affects the cost of fuel to generate electricity. The variability of prices, especially in the absence of an automatic pass-through to electricity prices could also erode the financial position of utility companies in the short term and over the medium term could result in a deficiency of investment to ensure efficient generation and distribution of power. Meanwhile, automatic pass-through of fuel prices could squeeze the budgets of lower income households and reduce competitiveness of domestic industries.

Cheaper and more reliable electricity could help unlock the full potential of the economy and help realize savings on oil imports. Investment in new energy infrastructure would boost economic growth. Stronger growth would inhere from higher investment during the construction phase as investment boost local demand for labor and construction materials. Over the medium term, cheaper more reliable electricity would also boost growth. McIntyre et al (2017) show that energy investment could boost economic growth in the Caribbean by 0.1 to 0.8 percent over 5 years. Investment in energy resilience will cause the external current account to deteriorate initially given the high import content of investment, but the external current would improve over the medium term with the reduction of fuel imports.

Meanwhile such investment would also reduce the inflationary impact of volatile oil prices. It is estimated that oil prices account for about [40] percent of the variability in inflation in the Caribbean—a large part of which flows through electricity prices. Moreover, the increase in electricity prices absorb a significant portion of real incomes lower-and-middle-income households. The pass through of energy prices to inflation results in an appreciation of the real effective exchange rate as higher inflation pushes up wages and unit labor cost. This is particularly important in countries with fixed exchange rates where the exchange rate cannot adjust to offset external shocks and monetary policy is impotent to offset second round effects including higher wages and cost of intermediate inputs.

Enhancing the resilience of energy infrastructure could also help reduce the volatility of electricity prices as well as lower fiscal risks. Figure 4 illustrates the impact of higher oil prices on electricity prices. The volatility in global oil prices is clearly reflected in domestic electricity prices as many utility companies have incorporated automatic pass through of increased fuel prices to consumers through fuel surcharges. In a few Caribbean countries the pass through is not fully automatic for example Guyana where there is a delayed response which affects the finances of the power company, and Suriname and Trinidad and Tobago where energy prices are highly subsidized. The current dependence on oil imports exposes the fiscal position to sharp increases in oil prices which would depress demand, reduce tax revenues and increase transfers to electricity companies where such transfers exist. In the absence of alternative energy sources, electricity dependence on thermal power generation will continue and their finances will remain exposed to oil price fluctuations, creating vulnerability for the fiscal accounts. Diversifying the energy matrix towards renewables reduces these risks.

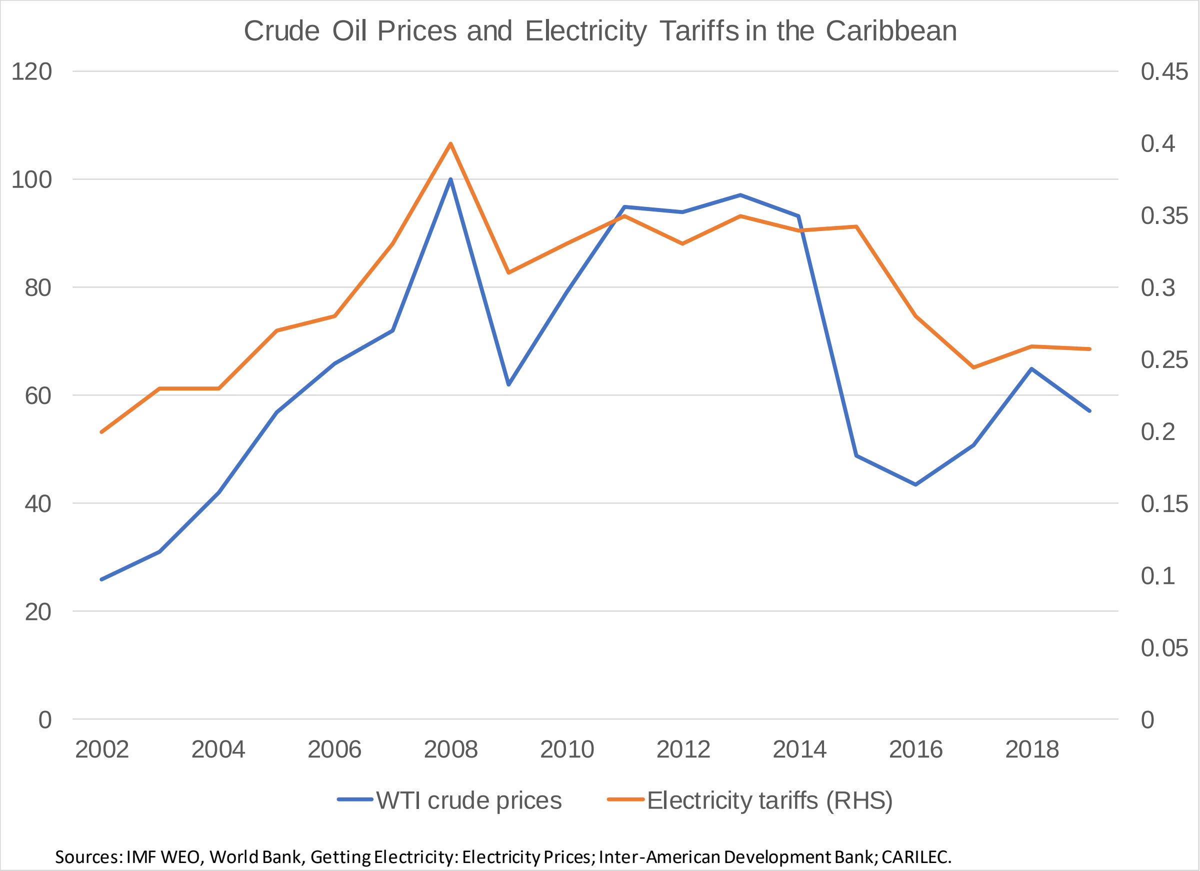


Figure 4: Crude Oil Prices and Electricity Tariffs in the Caribbean

Building more resilient energy infrastructure is costly and where undertaken by governments could significantly increase already high debt levels. The IDB estimates that on average, it would cost Caribbean Countries about 7 percent of GDP to undertake the needed investment in energy infrastructure over the period 2018-23. This average belies the wide spread in investment needs, which ranges from 3.3 percent of GDP in Belize to 12 percent of GDP in St. Lucia. Such investments could prove to be a challenge for countries with very little fiscal space. In order to limit public sector borrowing and encourage large scale private investment in infrastructure, governments can seek to implement such large energy infrastructure projects as Private Public Partnerships (PPP). If this option is chosen, it would be essential to strengthen the project and debt management framework in view of the risks that PPPs can pose, particularly in the presence of sovereign guarantees. In this regard, the adoption of international best practices in the management of PPPs to manage potential risks of contingent fiscal liabilities is warranted, utilizing technical assistance to design the legal, accounting and fiscal risk management frameworks.

Case Studies:
With concerns regarding power generation technologies and resilient energy infrastructure having been addressed more generally as they pertain to the region, it now becomes pertinent to examine the specific scenarios facing different nations within the Caribbean. Despite the common grouping of these countries in global policy spheres, their prospective energy situations can vary drastically. A one size fits all approach in this region will surely fit none. So, it is important to bear in mind the nuances that set these islands apart when looking to develop effective policy. In the section that follows we present two case studies exploring the energy pictures in St. Lucia and Trinidad and Tobago.

Trinidad and Tobago

The islands of Trinidad and Tobago are an excellent example of diversity in energy outlook within the Caribbean. Due to extensive onshore and offshore shale gas resources the nation finds itself in a drastically different position with regards to the development of its energy infrastructure than those of other Caribbean islands. This gas reserve provides the vast majority of the of the nation's generation capacity, 99% as of 2013 (IDB) and has shifted the country's import/export balance in the energy sector. Most Caribbean countries find themselves relying on fuel oil imports to meet their generation demand and are thus susceptible to fluctuations in oil prices. Trinidad, on the other hand, meets its energy demand almost exclusively through domestic supplies of natural gas. Moreover, they have the capacity to export their excess gas making them one of the region's few potential net energy exporters.

Understanding of this context provides important perspective when looking at the energy infrastructure goals put forward by the Trinidadian government. As part of the Caribbean Sustainable Energy Roadmap and Strategy (C-SERMS) Trinidad proposed a target for electricity generated from renewables of 5 percent of peak demand (or 60 MW) by the year 2020. This target is rather modest when compared to other Caribbean islands who generally aim for at least 20 percent power generation from renewable sources in the same time frame. However, Trinidad's favorable position with regards to domestic generation capacity reduces the impetus for incorporation of renewables.

Trinidad and Tobago has very little trade incentive to diversify its energy mix. The nation does, however, still have potential to increase the resilience of its energy infrastructure through the implementation of microgrids. Trinidad can increase its capacity to cope in the wake of disaster events by linking critical anchor loads in a distributed energy system that incorporates renewable generation sources. This path of diversification/renewable promotion for the sake of resilience is distinct from most of the Caribbean. It, however, allows for Trinidad to move toward increasing renewable generation capacity and infrastructure resilience in a manner that fits the situational imperatives driving the nation's energy policy decision making.

St. Lucia

The island of St. Lucia provides a telling contrast to Trinidad and Tobago in terms of their respective energy policy stances. Having historically been an agrarian economy dependent upon agricultural exports, worsening cost positions and increased competition have prompted the government in St. Lucia to turn its focus toward tourism as a means to foster economic growth. Electricity is supplied reliably throughout the island, however St. Lucia's installed generation capacity at present consists almost exclusively of fossil fuel-based technologies. The resulting demand for fossil fuels to fulfill energy consumption needs is met by importing crude oil, making energy prices and more broadly the nation's economic prospects sensitive to fluctuations in oil prices. This energy/economic condition is rather common throughout the Caribbean, but St. Lucia serves as a rather extreme example given that their installed renewable generation capacity is among the lowest in the region.

St. Lucia's lack of renewable power generation is made even more glaring when looking at the nation's survey of viable renewable resources. St. Lucia has the broadest range of renewable energy resources at its disposal of nations surveyed as part of the C-SERM. McIntyre and others (2016) reports that St. Lucia (much like many other Eastern Caribbean Islands) has a geothermal resource significant enough to meet baseload power demand for the island as well as viable solar, wind, hydro, and biomass resources. Policy makers from the island have set energy targets that aim to address this deficiency. With the nation's existing energy infrastructure nearing its limits and consumption rates continue to increase government officials are looking to increase domestic generation capacity while simultaneously improving environmental and economic sustainability within the energy sector. As part of the C-SERM, St. Lucia was aiming to increase its renewable generation capacity to 35 percent by the year 2025 (and to 50 percent by 2030). This shift would have resulted in an implied oil import reduction of 22 percent and an 11 percent implied reduction of the national electricity bill by 2025. Since committing to these goals St. Lucia, in coordination with external lenders, have commissioned an exploratory drilling project aimed at characterizing the geothermal resource that is available on the island. The project will entail the drilling of 3 to 5 wells (each 2000 meters deep), with shared geo-technical services and infrastructure to conduct necessary analyses. If results from this characterization suggest that the geothermal resource is suitable for power generation, then the nation's joint public and private utility LUCELEC plans to invest in the development of a 30 MW geothermal power plant. Coupled with the planned development of the more intermittent renewables (wind and solar), this plant would allow for St. Lucia to vastly surpass its renewable power generation targets.

Enhancing resilience in the energy sector in St. Lucia could result in a significant increase in debt levels. The IDB estimated that undertaking the minimum required changes would cost about 12 percent of GDP. Assuming that the projects are implemented over a 5-year period with some frontloading of the projects, the public debt would rise to almost 75 percent of GDP (from 67 percent) and remain elevated for several years thereafter. The medium-to-long-term (MLT) will increase while the short-term debt declines slightly. The debt service ratio would also rise to around 17 percent of GDP and remain close to that level over the next decade. The rise in the debt would be partially offset by higher growth generated by more resilient cheaper electricity as well as the reduction in the economic volatility that would come from international energy prices.

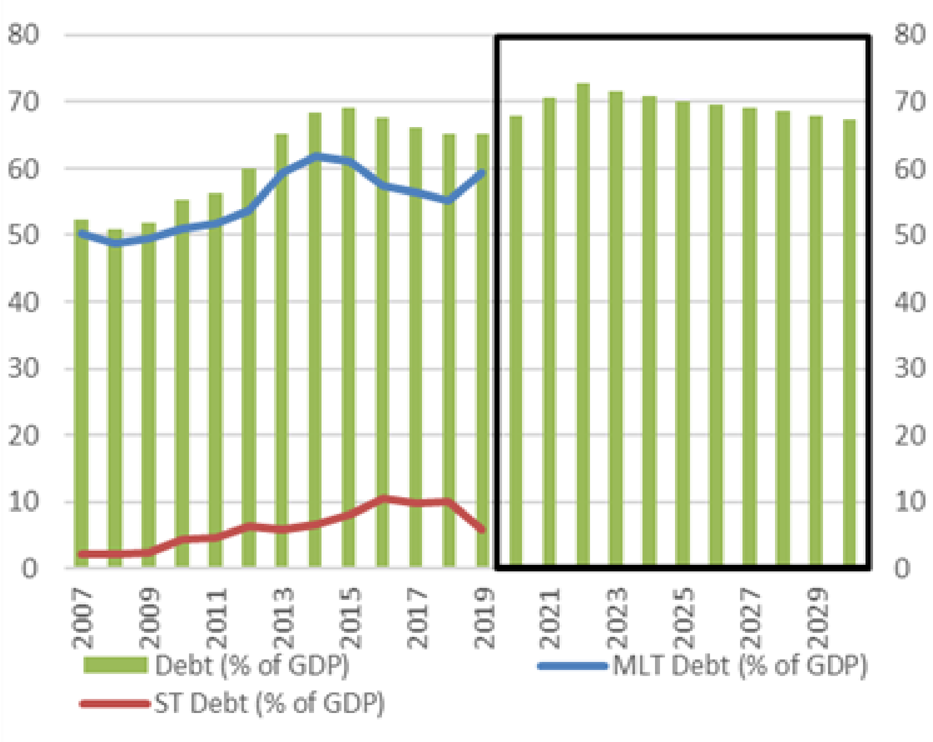


Figure 5: St. Lucia. Public Debt-to-GDP Ratio, 2007-2030

The rise in debt can also be mitigated by encouraging private sector investment and implementing a fiscal resilience framework. As discussed in the previous section public private partnerships could help reduce the level of investment governments have to undertake. A fiscal resilience framework that embeds a fiscal rule could also help reduce the growth of the fiscal deficit and hence the increase in the public debt.

Conclusion

The increasing frequency and severity of tropical storms and hurricanes increases the urgency of enhancing the resilience of the energy infrastructure. Indeed, hundred-year storms are becoming so prevalent that a reclassification of such storms might be necessary. A recent IMF Board paper proposed a Disaster Resilience Strategy (DRS)for small states that urges a focus on ex ante actions building overall resilience of the economy. Enhancing resilience of the energy sector is no different as the bulk of the initiatives, like hardening infrastructure, strengthening operational resilience and training must take place well before a disaster occurs.

Enhancing resilience means strengthening 4 interrelated components: or; robustness, resourcefulness, recovery and adaptability. Building robustness implies hardening the physical infra-structure and strengthening operational frameworks. Resourcefulness is embodied in those charged with ensuring that infrastructure remains running through the event and requires selection and development of human resources. Although recovery takes place after the event, ex ante business continuity planning is essential to speed up the recovery process. Adaptive learning from the experiences of previous events is key to ensuring that mistakes and vulnerabilities of the past are not carried into the future.

Peculiarities of energy infrastructure throw up some important considerations for resilience enhancing investments. Its pervasiveness in economic activity means that energy infrastructure is different from roads, bridges and sea defenses since operational resilience may be just as important as hardening infrastructure. Energy sector assets are long-lived which could mean that adjustments in the physical plant will be slow, hence placing more emphasis on enhancing operational resilience in the short run. The tension between building back better and building back faster is exacerbated by the integral role of energy use in economic activity and social wellbeing. Often, the balance is tilted towards speed of recovery sacrificing resilience. Building resilience in the energy sector would need to take into consideration its significant interdependence with other utilities.

Achieving Caribbean countries’ climate mitigation goals could help enhance resilience. These goals already call for significant shifts toward renewable energy sources and diversifying the energy mix. The shift to renewable energy sources opens opportunities to enhance resilience by building in redundancy and diversification of energy sources. This coupled with the use of modular micro-grid technology could enhance the robustness, and resourcefulness of energy systems. An added benefit of modular implementation technology is that it allows energy investments to be less front loaded and take place more quickly than the traditional energy infrastructure.

Enhancing energy resilience could help improve the overall resilience of Caribbean economies. Reducing the dependence on imported fuel for electricity generation lowers the volatility of the economy to global energy prices. It also improves the external current, lowers the volatility of inflation and could help improve competitiveness by lowering energy prices and the pass-through to the real effective exchange rate.

References

Anderson, Kate, et al. “Quantifying and Monetizing Renewable Energy Resiliency.” *Sustainability,* vol. 10, no. 4, 2018, p. 933., doi:10.3390/su10040933.

Clarke, Daniel Jonathan; Dercon, Stefan. (2016). Dull disasters? How planning ahead will make a difference (English). Washington, D.C.: World Bank Group.

IRENA, (2014) *Wave Technology Brief. www.irena.org,* www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf.

McIntyre, A, and others (2016). Caribbean Energy: Macro-Related Issues. IMF Working Paper, WP16/53, 2016.

“Microgrid Definitions.” *Microgrid Definitions | Building Microgrid*, building-microgrid.lbl.gov/microgrid-definitions.

Molyneaux, L and Others (2012), “Resilience and electricity systems: A comparative analysis”, Energy Policy No.47, 2012 pp.188-202.

Preston, Benjamin L., and others (2016). Resilience of the U.S. Electricity System: A Multi-Hazard Perspective, US DOE, 2016.

Robert, Fabien Chidanand, et al. “The Critical Role of Anchor Customers in Rural Microgrids: Impact of Load Factor on Energy Cost.” *2017 International Conference on Computation of Power, Energy Information and Communication (ICCPEIC),* 2017, doi:10.1109/iccpeic.2017.8290401.

Robinson, Mike, and Walt Musial (2006). “Offshore Wind Technology Overview.” US Department of Energy.

Singh, G. K. “Solar Power Generation by PV (Photovoltaic) Technology: A Review.” *Energy,* vol. 53, 2013, pp. 1–13., doi:10.1016/j.energy.2013.02.057.

“Solar Photovoltaic System Design Basics.” *Energy.gov,* energy.gov/eere/solar/articles/solar-photovoltaic-system-design-basics.

“Solar Photovoltaic Cell Basics.” *Energy.gov,* energy.gov/eere/solar/articles/solar-photovoltaic-cell-basics.

"Solar Photovoltaic Technology Basics." *Energy.gov*, energy.gov/eere/solar/articles/solar-photovoltaic-technology-basics.

United States Department of Energy (USDOE) (2018). Energy Resilience Solutions for the Puerto Rico Grid, USDOE, June 2018.

U.S. Department of Energy Federal Energy Management Program. "Biomass for Electricity Generation." *WBDG*, www.wbdg.org/resources/biomass-electricity-generation.

U.S. Department of Energy Federal Energy Management Program. "Biogas." *WBDG*, 8 Mar. 2016, www.wbdg.org/resources/biogas.

World Bank (2017) St. Lucia: Renewable Energy Sector Development Project, World Bank, May 2017.

World Energy Council (2016) World Energy Resources-Geothermal 2016, World Energy Council, 2016. pp. 3-21.