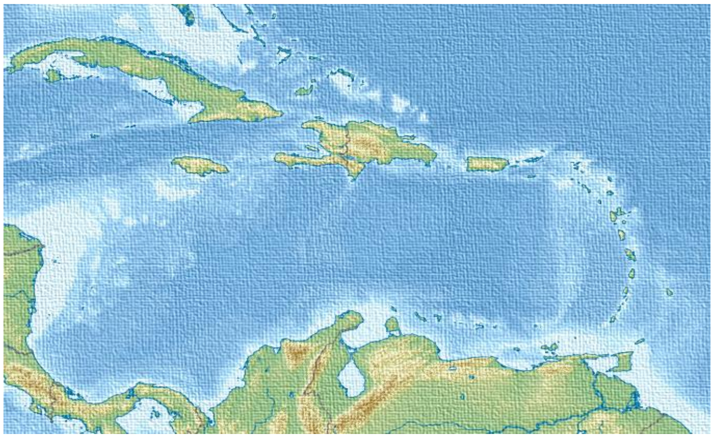

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Economic Commission for Latin America and the Caribbean

Policy Brief
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Building a climate-resilient power sector in the context of the Caribbean small island developing States' energy transition

Introduction

In Caribbean small island developing States (SIDS), electrical power outages are frequent in the aftermath of major weather events. While local service disruptions often last a few days after these events, nationwide power grid failures lasting several weeks, or months have resulted in enormous social and economic impacts. In 2017, Hurricane Maria left 90 per cent of the population of Dominica without access to electricity for over four months (Commonwealth of Dominica, 2020) and caused a systemwide collapse of Puerto Rico's power grid that took 11 months to be entirely restored (Campbell, 2018) (see map 1). In 2022, Puerto Rico was again left in the dark for several weeks after Hurricane Fiona's landfall (Lakhani, 2022). These events highlight the vulnerabilities of the subregion's power sector and demonstrate the lasting, compounding, and increasingly frequent impacts of extreme climate disasters in Caribbean SIDS.

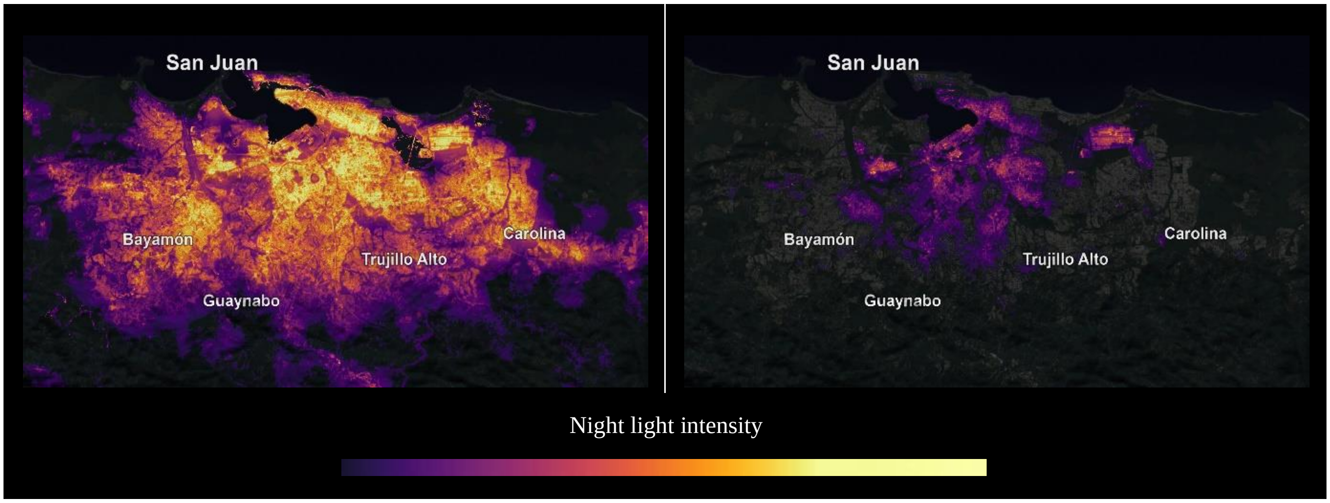
Improving routine infrastructure maintenance is a cost-effective measure to reduce the power sector's vulnerabilities to climate change (Nicolas and others, 2019). However, the increasing threats posed by climate hazards require more systematic approaches that mainstream resilience into traditional planning practices of the power sector.[1]

Key recommendations

- **Improve routine maintenance of the power infrastructure**
- **Mainstream climate resilience into traditional power sector planning**
- **Map and prioritize the power needs of critical infrastructure for disaster risk response and recovery strategies**
- **Strengthen human and institutional capacities to produce energy statistics and other relevant climate disaster-related data in a timely and accessible way**
- **Promote a multiple-stakeholder approach for power sector resilience planning**
- **Scale up and accelerate the incorporation of renewables into countries' energy mix**
- **Incorporate climate resilience into industries' standards, codes and regulations**
- **Review and update electricity sector policies, institutional arrangements, legislation, and regulations to attract private investments**

[1] In this policy brief, the power sector consists of the electricity sector.

Map 1: Night light intensity in San Juan, Puerto Rico, before Hurricane Maria (left) and average night light intensity two months after the storm (right)



Source: NASA (2018).

Power sector resilience consists of the "ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions to the power sector through adaptable and holistic planning and technical solutions" (Lee and Stout, 2019). This policy brief focuses on the power sector resilience to climate hazards – referred to here as climate resilience. It provides recommendations on how Caribbean SIDS can improve their power sector's climate resilience in the context of climate change and transition towards increased use of renewable energy sources.

Background

Current characteristics of the energy sector in Caribbean SIDS expose and increase their vulnerabilities to disasters. Some of these are: national power sectors operated by a single utility, centralized generation, high reliance on fossil fuels, low transmission and distribution efficiency, and high electricity tariffs (Flores and Peralta, 2020). As indicated in figure 1,[2] plants fuelled by oil and natural gas represented the highest share of electricity installed capacity in the subregion in 2021, with renewables accounting for just 18.7 per cent. That dependency on imported fossil fuels leads to extremely high tariffs in the subregion, averaging US$ 0.33/kWh — three times higher than the average in the USA (Rozenberg and others, 2021).

The subregion is undergoing an energy transition towards increasing the use of renewables. Almost all Caribbean SIDS have a renewable energy target.[3] Antigua and Barbuda, Barbados, Dominica, Grenada, Guyana, and Saint Kitts and Nevis have pledged to achieve a 100 per cent renewable energy target by 2030 (CCREEE, 2021). In the past seven years, the increased use of solar photovoltaics (PV) and wind power has been driving up the share of renewable sources in the Caribbean energy mix. Three main drivers are pushing that transition: dependence on high-cost imported fossil fuels; decreasing costs of renewable energy technologies; and international commitments targeting greenhouse gas emissions reduction (Walker and de Paula, 2022).

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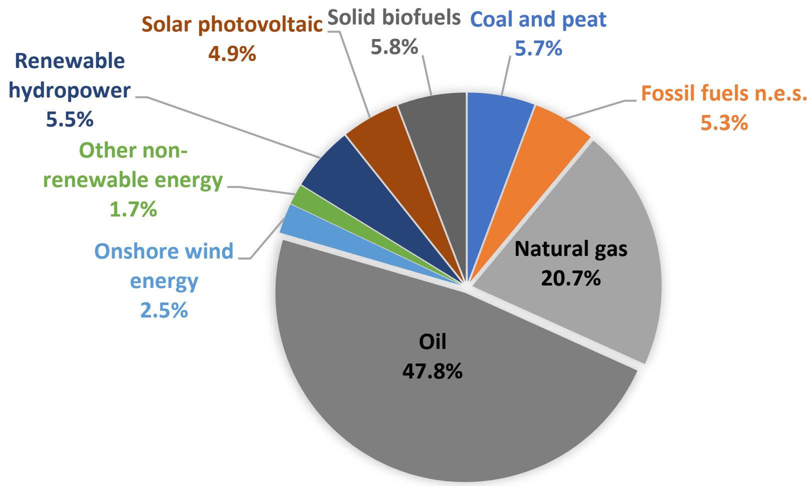
[2] The data in the graph refers to Antigua and Barbuda, Bahamas, Barbados, Belize, Cuba, Dominica, Dominican Republic, Grenada, Guyana, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, and Trinidad and Tobago. The 2.79 MW of biogas, 0.01 per cent of the subregion's energy mix, is not represented in the graph.

[3] Targets set by Trinidad and Tobago and Saint Vincent and the Grenadines have expired in 2021 and 2020 respectively and have not yet been updated (CCREEE, 2021).

Figure 1: Installed electricity capacity in Caribbean SIDS, per technology (2021)



Source: IRENA (2022); *n.e.s.: not elsewhere specified.

The increasing use of renewable sources in the Caribbean is resulting in the restructuring of the electricity sector. The model where a single utility controls nearly 100 per cent of the generation and transmission and distribution is giving way to a more decentralized system with independent power producers and self-generation by households and businesses. Legislative changes have introduced more competition, requiring more robust regulatory agencies. While a more decentralized grid can contribute to increased resilience in the power sector, it will also need the engagement of a broader range of stakeholders in the planning process.

Multi-hazard risks to Caribbean small island developing States' power sector

Caribbean SIDS' power sector has become increasingly more vulnerable to climate hazards due to the effects of climate change. However, other threats need to be taken into consideration. Diagram 1 shows the main potential hazards affecting the power infrastructure, which can occur simultaneously. For instance, an increase in average temperature for several days (a natural hazard) can lead to a peak in electricity demand; if the transmission and distribution infrastructure is undersized (a technology hazard), the chances of fires in substations increase significantly. Achieving resilience requires systematically understanding, identifying, and addressing the multi-hazardous, compounding, and cumulative nature of threats to the subregion's power security.

Hurricanes are the dominant climate hazard in the Caribbean (Nicolas and others, 2019). Other extreme weather events resulting from climate change also pose significant threats, such as flooding, landslides, extreme heat, and droughts. Slow onset events[4] – such as the continuous increase in air and water average temperatures – must be acknowledged and factored into planning for a more resilient power sector. As ambient temperatures rise, thermal conversion efficiency will decline and impact the generation output of thermal power plants by 0.45 per cent to 0.8 per cent for every 1°C of global temperature increase. The efficiency of PV modules can also drop by about 0.5 per cent for every 1°C increase in temperature (Nicolas and others, 2019). The derating[5] of transmission and distribution lines, and equipment under higher temperature averages will also increase.

[4] Slow onset events "evolve gradually from incremental changes occurring over many years or from an increased frequency or intensity of recurring events" and include increasing temperature, desertification, loss of biodiversity, land and forest degradation, glacial retreat, sea level rise, ocean acidification, and salinization (UNFCC, 2012).

[5] Derating refers to a decrease in capacity (EIA, n/d).

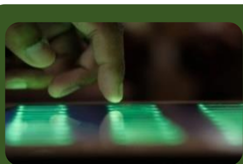
Diagram 1: Key threats to the power system infrastructure

Natural hazards

- Climate hazards: slow onset events-related hazards (changes in precipitation, increase in water and air temperatures, sea level rise), and extreme weather events (hurricanes, storms, floodings, landslides, heat waves, droughts).
- Other natural hazards: volcanic eruptions, earthquakes, tsunamis...

Technological hazards

- Accidents, such as a fire in a substation, caused by failures due to faulty equipment or aging or undersized transmission and distribution infrastructure.



Human-caused hazards

- Accidents resulting from unintentional actions;
- Malicious events, a result of deliberate and harmful human actions, such as physical terrorism or cyberattacks.

Source: Elaborated based on Lee and Stout (2019).

The overall rise and more frequent peaks in energy demand for air-conditioning and refrigeration services are also direct impacts of these slow and steady changes in climate patterns. The International Energy Agency estimates that every 1°C increase in global temperature will result in an additional 25 per cent increase in cooling demand until 2050 (IRENA, 2021). Sea level rise leading to loss of land in highly populated coastal zones will require the relocation of both human settlements, where a substantial share of energy demand is located, and generation, and transmission and distribution infrastructure.

The specific characteristics of a country's power system also need to be considered. Countries with different energy generation mixes can be under very different levels of risk exposure under the same climate conditions. For instance, Belize has 28 per cent of its electricity installed generation capacity coming from hydropower – the largest share in the subregion (IRENA, 2022). As a result, Belize's electricity generation capacity is relatively more exposed to changes in precipitation patterns, droughts, and competing water requirements for irrigation and human consumption. Antigua and Barbuda has 83 per cent of its electricity generation capacity coming from plants powered by fossil fuels (IRENA, 2022) and will be affected by the efficiency loss of thermal power plants – as most of other Caribbean SIDS. The state of conservation of generation and transmission and distribution infrastructure can also impact the sector's ability to withstand extreme weather events and vary vastly across countries and islands. A study carried out with firms in the tourism sector in the Caribbean created a power infrastructure reliability index based on reported power outage frequency and length. The three countries with the lowest performance in this index are: the Dominican Republic, Antigua and Barbuda, and Sint Marteen (Erman and others, 2021). An unreliable power provision can indicate existing problems related to infrastructure inadequacy, aging, and poor maintenance, affecting the power sector's resilience to climate events.

Table 1 summarizes critical climate trends and parameters for Caribbean SIDS and the most significant and likely impacts on the three domains of the power sector value chain: (i) generation, (ii) transmission and distribution, and (iii) energy demand.

Table 1: Selected climate trends and parameters and implications to Caribbean SIDS' power sector

Climate change trends	**Parameter change**	**Impact on electricity system domains**		
		Generation	Transmission and distribution	Demand
Rising global temperature	Air temperature	**Efficiency:** modest reduction in efficiency of solar PV modules and thermal power plants (derating). **Capacity:** additional generation capacity required due to higher demand, including seasonal peaks. **Potential:** decreasing hydropower potential due to increased evaporation losses from reservoirs.	**Reduced network efficiency:** modest increase in network losses and line sag reducing available capacity (also dependent on other variables such as wind); derating of transmission and distribution equipment.	**Cooling:** increasing air-conditioning and refrigeration requirements.
	Water temperature	**Cooling efficiency:** lower efficiency of thermal plants with water-based cooling technologies. **Potential:** lower generation potential due to ecological constraints on water temperature being fed back into water bodies.		
Changing patterns of precipitation, humidity (including drought) and winds	Water availability	**Potential and output:** partial output reduction or complete shutdown of thermal plants due to insufficient availability of cooling water; changing hydropower potential due to changing patterns of precipitation; dusty conditions resulting from drought affecting solar PV efficiency; altered wind patterns - direction, speed, and availability – potentially impacting wind power generation; drought conditions affecting the crop production required for biomass and biofuels. **Peak and variability:** increasing variations in hourly or seasonal peaks of hydropower generation because of increased anomalies in precipitation patterns.	**Physical risks to grids:** damage to assets due to direct or indirect impacts of heavy precipitation and landslides.	**Cooling:** increasing air-conditioning and refrigeration loads due to a rising level of humidity in hot weather. **Water supply:** higher electricity demand to provide drinking and irrigation water in cases of drought.
Sea level rise	Sea level rise	**Physical risks to generation:** requirement to relocate existing generation facilities in coastal areas. **New assets:** limited availability of appropriate locations for new generation.	**Physical risks to grids:** increasing vulnerability to coastal erosion and floods, linked to substations often located near main generation plants and load centres in coastal areas. **New assets:** limited availability of appropriate locations for grid development.	**Fresh water supply:** increasing adoption of more energy intensive methods (e.g. desalination) to provide water due to saltwater intrusion.
Extreme weather events	Hurricanes and storms	**Physical risks to generation:** physical damage to solar PV due to flying debris, strong winds and hailstorms; physical damage to onshore and offshore wind turbines and blades due to flying debris and strong winds; risks to thermal generation plants with high cooling towers due to strong winds; flooding resulting from storm surge damaging power generation infrastructure. **Supply chain:** disruption of fuel supply chains for thermal plants when transportation network is compromised. **Potential and output:** crop damage affecting biomass and biofuels production.	**Physical risks to grids:** damage to transmission and distribution lines and tall components of substations due to flying debris, falling trees, strong winds and corrosion due to saltwater; faults caused by flooding of transformers and substations due to storm surges.	
	Floods	**Physical risks to generation:** physical damage; hydropower turbine abrasions and efficiency decrease due to an increased sediment load after floods or landslides caused by storms; plant failure due to flood overtopping of dams and spillway damages by debris.	**Physical risks to grids:** damage to transmission and distribution equipment due to direct or indirect impacts of flooding, such as undermining tower foundations, rock falls and landslides, damage to transmission and distribution lines and substations due to direct or indirect impacts.	
	Heat waves	**Efficiency:** reduced efficiency of solar PV modules and thermal plants. **Cooling:** potential service disruption of thermal power plants due to high water temperatures.	**Transmission efficiency:** substantial reduction in line capacity or failure due to increased sag or cable capacity caused by heat dissipation limitations; derating of capacity to prevent transformer overload; de-energizing lines to prevent fires.	**Cooling:** substantial increase in air conditioning and refrigeration demand, intensified by thermal inertia of buildings.

Source: Elaborated based on IEA (2021) and Nicolas and others (2019).

Incorporating resilience requirements into power sector planning

Mainstreaming resilience into power sector planning tools and methodologies seeks to improve traditional approaches. It ultimately contributes to ensuring a country's energy security to achieve its sustainable development priorities. While this policy brief focuses on climate hazards and the impacts of climate change on the power sector, an integrated approach to mainstreaming resilience must systematically consider all threats described in the previous section.

Traditional power sector planning approaches focus on forecasting grid expansion needs according to current and projected electricity demand over a specific time horizon. The integrated resource plan is a well-established planning approach that considers demand and supply aspects, and transmission and distribution resource options to meet a calculated demand forecast. The development of potential scenarios associated with mathematical optimization tools is part of this integrated planning approach, allowing the choice of a preferred least-cost plan. The integrated resource plan also seeks to align sector planning with sectoral priorities and strategic objectives, and the jurisdiction's policies, regulations, and sustainable development goals. As an iterative process, the integrated resource plan requires regular updates that feed monitoring and evaluation data into the planning process (CCREEE, n/d).

There is no one-size-fits-all approach to incorporating climate resilience into traditional power sector planning. Processes need to be adaptable and build on existing planning frameworks and practices. Some examples of planning frameworks that support climate resilience and mitigation in the electricity sector include: low emission climate resilient development strategies; integrated electricity planning approaches – such as the integrated resource plan ; and local climate action plans (Cox and others 2017). Other methods emphasize multi-jurisdictional collaboration and the participation of various stakeholders in planning for a more resilient power sector (Hotchkiss, 2019). By mainstreaming climate resilience, any established methodology needs to combine a multi-stakeholder holistic approach that identifies, assesses, and incorporates climate hazards into the physical and operational planning of the grid infrastructure. This approach needs to include developing mitigation measures at different geographic scales to prepare and respond to shocks and stresses on the system.

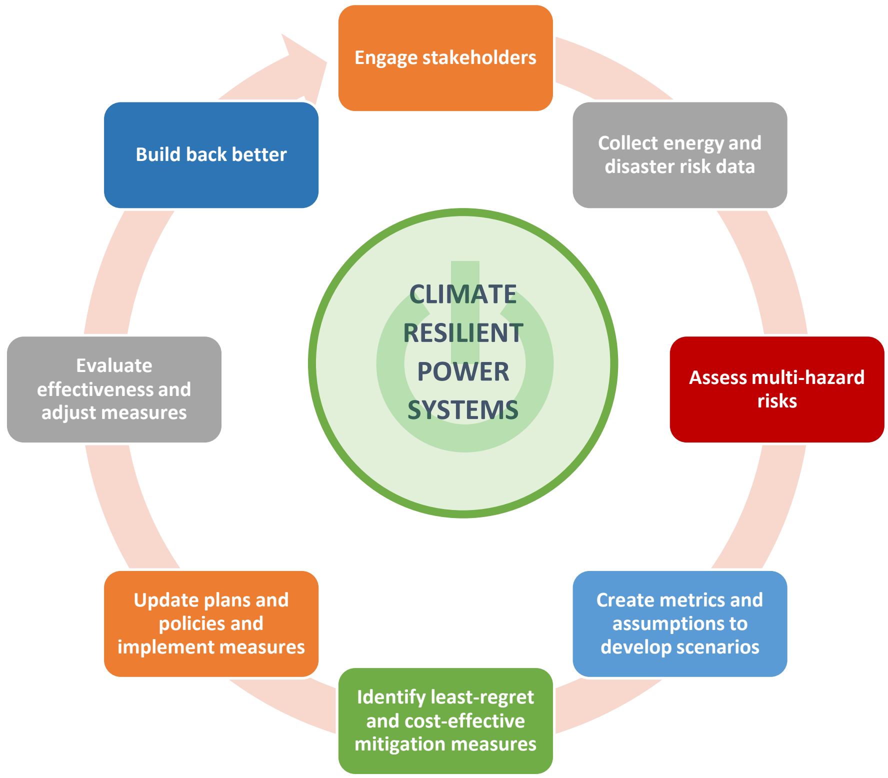
Figure 4 provides a non-exhaustive framework containing the steps that can support climate resilience mainstreaming into power sector planning.

Building on the traditional integrated resource plan, the Integrated Resource and Resilience Plan (IRRP) is one method that brings the resilience element into the sector's planning process. CARICOM member States endorsed the IRRP as a preferred mechanism to guide planning in the electricity sector. While the traditional integrated resource plan aims to develop a "least-cost plan", the IRRP seeks to create a "least-regret plan" by incorporating a multi-hazards analysis (CCREEE, n/d). Belize, Guyana, Jamaica, Saint Kitts and Nevis, and Trinidad and Tobago have already engaged with the Caribbean Centre for Renewable Energy and Energy Efficiency (CREEE) Climate Resilience Programme to develop IRRPs. In the scope of that initiative, CCREEE also supports human and institutional capacity building to improve systems modeling and planning by governments and utilities.[6]

One crucial aspect for the successful development and implementation of the IRRP and any other integrated planning methodologies is the collection of energy statistics and multi-hazard risk data to develop scenarios and plans based on informed assumptions and appropriate demand forecast models.

[6] More information on the Integrated Resource and Resilience Plan (IRRP) can be accessed: https://www.ccreee.org/irrp/.

Diagram 2: Mainstreaming climate resilience into power sector planning



Source: elaborated based on Lee and Stout (2019) and IEA (2021).

The accuracy of these planning outputs relies on the quality and availability of the data employed in the process. In traditional sector planning, both normative data (energy acts, power sector regulations, energy policies, economic development policies, decarbonization goals, and adaptation plans) and sectoral technical data (electricity consumers, socioeconomic statistics, historical consumption or sales data, generation plant information, transmission infrastructure details, distribution system information, risks, and historical reliability) are crucial (Parle, 2022). Mainstreaming climate resilience into power sector planning requires incorporating additional data and information concerning climate and other hazards and vulnerabilities into that planning process. This critical step calls for close integration with stakeholders, such as environmental authorities, meteorological offices, national emergency agencies, public service providers, urban and physical planning practitioners, and others that can provide additional data.

Open data platforms and machine learning tools applied to big data are used to develop predictive maps of countries' and regions' power systems when critical datasets are unavailable.[7] For instance, the National Renewable Energy Laboratory (NREL) utilizes geographic information systems (GIS) to produce maps, analyses, models, applications, and visualizations that inform energy planning and production.[8] Given the spatialized nature of risks and vulnerabilities, geospatial data is vital to adequately assess multi-hazard risks, develop appropriate mitigation responses, and build back better after disasters.

[7] See the World Bank Group's open data platform for the energy sector: https://energydata.info.

[8] See the USA's National Renewable Energy Laboratory (NREL) platform on geospatial data science for the energy sector: https://www.nrel.gov/gis/index.html.

Technologies and technical solutions for building climate resilience

This section explores technologies and technical solutions that can be considered by governments, utilities, communities, individuals, and businesses when assessing cost-effective and least-regret measures to improve Caribbean SIDS' power sector climate resilience.

Renewable energy sources – promoting renewable energy sources can shield the subregion from global price shocks and build its power sector's resilience. Firstly, the nature of these sources – renewable, inexhaustible, and locally available – allows countries and communities to secure access to electricity in the aftermath of extreme weather events when the fossil fuels supply chains may be interrupted due to damaged ports and roads, but also due to damaged transmission and distribution lines. After Hurricane Fiona struck Puerto Rico in 2022, the work of charities promoting solar PV panels' installation in households and businesses' roofs came into evidence as a successful case of using renewables to foster energy resilience (Espalda, 2022). Secondly, renewable sources allow for a more decentralized and off-grid distributed generation of electricity – particularly solar PV – bringing generation much closer to the consumer and drastically decreasing the requirements for transmission and distribution lines, the most vulnerable segment of the electricity value chain during disasters. Thirdly, a diversified renewable energy matrix is inherently more resilient because it allows countries to be less exposed to shocks affecting one fuel or energy source. For instance, countries relying on hydropower can supplement their energy mix with wind or solar PV during drought conditions.

Energy storage solutions – the application of these technologies – such as batteries, flywheels, compressed air energy storage, and pumped hydro storage – can have multiple goals in the power system. Traditionally, batteries are used as an uninterrupted power source to support strategic infrastructure and equipment that require a stable critical load, such as computer servers and medical equipment. More recently, storage solutions have been fundamental to support a more aggressive uptake of renewables. The inherently intermittent nature of these sources requires energy storage solutions to ensure grid stability when solar or wind power is unavailable or suboptimal. Storage is essential for off-grid applications, where electricity supply from the main grid cannot provide that stability when there is no wind or sunshine. Most importantly, storage solutions can provide or add backup capabilities to the grid in the event of service disruption or grid failure during or after an extreme weather event. In 2017, a 20MW of battery storage employed in the Dominican Republic during Hurricanes Irma and Maria supported grid stability, frequency control, and critical reliability services of the interconnected power system (Elgqvist, 2021).

Mini-grids and microgrids – a microgrid can be defined as a local cluster of energy resources that can operate independently from the primary grid to service single or multiple nearby customers (ThinkMicrogrid, 2021). While the conceptual differentiation between mini and microgrids varies – emphasis can be put on differences in scale or level of connectivity with the primary grid – both can offer an additional level of autonomy to customers, particularly when they are connected to the main grid and serve as a redundant system. This solution can address the needs of certain facilities mapped as critical or strategic infrastructure by resilience power sector planning – for instance, hospitals, airports, telecommunication companies, shelters, water and sanitation plants, and essential government offices. They can provide redundancy in case of grid failure when associated with renewable energy sources and energy storage technologies.

Smart grids – are "an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users" (IEA, 2022). Multiple hardware and software are required to create smart or smarter grids: smart meters and inverters, computer software, forecasting models, and other two-way communication and system management equipment (Cox and others, 2017). Smart grids seek to create a more efficient and resilient power grid through the real-time collection, analysis, and processing of data on energy generation, transmission, distribution, and consumption, which then inform the operation of the grid. During extreme climate events, smart grids can more easily and rapidly divert and prioritize electricity supply, averting service disruption. It can also respond more quickly to the inherent load variations associated with renewable sources or any other sources of fluctuations, creating a more stable network.

Hardening existing infrastructure – while it is virtually impossible to avoid damages caused by extreme weather events such as category five hurricanes, there is mounting evidence of how technical specifications and solutions can improve the resilience of power systems. In the wake of Hurricanes Irma and Maria, structural engineers assessed why specific solar PV systems survived or failed during the storms in the Caribbean, pointing out several common characteristics among failed systems. This evidence can support measures to improve the installation of solar PV systems to avoid future large-scale damage. The research indicated that increasing solar PV systems' resilience to withstand category 5 hurricanes could increase engineering, procurement, and construction costs by 5 per cent to 5.5 per cent compared with the standard category three baseline. The study also showed the importance of creating multi-stakeholder (solar PV suppliers, equipment providers, installers, utilities, consumers) collaboration to ensure that clear industry standards, codes, and regulations are developed and implemented by professionals and practitioners (Burgess, Locke and Stone, 2020). Research and development involving industry players, utilities, and national and regional educational institutions can produce the necessary practical expertise to develop new or probe existing standards, codes and regulations so they can be suitable for the unique characteristics of Caribbean SIDS.

Policy recommendations

Key recommendations for the consideration of member States and other relevant stakeholders in the energy and disaster risk management sectors:

- Include improved and regular maintenance of power insfrastrucutre as a priority measure in disaster risk reduction and preparedness strategies. This highly cost-effective measure can reduce the vulnerability of power infrastructure to climate disasters.
- Mainstream climate resilience into traditional power sector planning, considering the multi-hazardous nature of vulnerabilities occurring along the power sector value chain - generation, transmission and distribution, and demand – while addressing national and local specificities of the power infrastructure.
- Map and prioritize the power needs of critical infrastructure for disaster risk response and recovery strategies, such as telecommunications, hospitals and health facilities, water supply and sanitation, refrigeration for the food sector, shelters, and transportation.
- Strengthen human and institutional capacities to collect, process, analyze and disseminate appropriate energy statistics and other relevant climate disaster-related data in a timely and accessible manner. This measure should incorporate the spatialized nature of risks and infrastructure vulnerabilities and explore innovative alternative sources and platforms to fill data gaps.
- Promote a collaborative multiple-stakeholder approach at all stages of the resilience-building planning and implementation process. This process requires a dialogue between traditional energy players – utilities, energy sector authorities, regulators, large-scale consumers – and other interested stakeholders, such as environmental authorities, meteorological offices, public service providers, national

emergency agencies, urban and physical planning practitioners, and others.
- Scale up and accelerate the incorporation of renewable energy sources into the electricity generation mix as a key climate adaptation measure, updating expired renewable energy targets when required.
- Incorporate climate resilience into the energy industry's quality standards, building codes, and other sectoral regulations, employing national research and development institutions and capabilities to explore and test the suitability and cost-effectiveness of technologies and technical solutions.
- Review and update the power sector's policies, institutional arrangements, legislation, and regulations to attract private investments and competition to finance the additional costs required by building climate resilience in the power sector.

Conclusion

Climate-related disasters pose a considerable and increasing threat to the integrity and efficiency of the Caribbean power sector. Proactive planning measures must systematically identify and mitigate multi-hazard risks, particularly regarding the growing effects of climate change. Methodologies that mainstream climate resilience into traditional power sector planning — such as the Integrated Resource and Resilience Plans (IRRP) — are the ideal platform to promote a data-driven and multi-stakeholder collaborative dialogue. Traditional energy sector stakeholders and other relevant players must be involved in this process and fully understand, assess, and act on the wide-ranging implications of a warming planet's short- and long-term effects on the entire power sector value chain.

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