

Framework for decentralized energy and enhanced resilience on islands

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Key messages

- Many island states are facing growing energy insecurity because of increased hydroclimatic risks, combined with dependence on imported energy and centralized grid infrastructure.
 - Our research suggests, however, that there are many actions island states can take to limit these risks. By following a five-step framework, countries can assess the resilience of their power systems and shift to more decentralized, renewable and reliable forms of energy production.
 - Decision-makers can improve islands' crisis preparedness by including decentralized renewable energy systems in their contingency planning.
 - The design of energy system solutions must be tailored to specific contexts. This requires analysis of local variations and potential trade-offs between different types of costs and resilience improvements.
 - Informed decision-making requires accurate models. In turn, accurate models require effective collaboration between researchers, energy authorities and grid operators.
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Introduction

As a result of the climate crisis, many island nations face fast-growing and unprecedented threats to their critical infrastructure. Decision-makers need to learn more about emerging technologies and new approaches to limit the risks, including which solutions are appropriate for islands.

This policy brief presents a five-step framework for strengthening energy systems facing hydroclimatic risk. The framework is especially suitable for islands and low-lying states, although the findings can also be useful for decision-makers in diverse situations.

We developed the novel framework by exploring the role of decentralized energy systems in reducing the risk of power infrastructure failures. The framework's stepwise approach means it is possible to locate vulnerable points in a network and identify appropriate solutions. We used the case of Cuba to test the modelling framework and, based on this experience, we make three policy recommendations to enhance energy security for high-risk island contexts.

The role of decentralized energy systems for island states

Island states are particularly exposed to hydroclimatic hazards such as hurricanes, floods, sea-level rise, and drought. As the climate crisis unfolds, these extreme events are projected to increase and intensify, disrupting energy systems in unforeseeable ways. The remote location of many islands aggravates the situation, especially if they only have access to a limited set of local energy sources and turn to expensive imports of fossil fuels.

The fact that most island nations rely on centralized energy infrastructure can add to these difficulties (Winters et al., 2022). Although centralized systems can be highly effective under normal circumstances, they are vulnerable to disruption: if one part of the connected system ceases to function, the ripple effects can be enormous. Many of these infrastructure systems are also becoming more fragile due to aging.

All these factors combined mean that many islands face rapidly growing risks of energy insecurity. In addition to the immediate impacts on the energy supply, this can affect the economy more widely and hinder sustainable development.

Renewable energy technologies are becoming more competitive compared with fossil fuels (IRENA, 2023). These technologies offer a means to harness local clean energy sources and diversify island states' energy systems, making them more robust (Vezzoli et al., 2018). When configured in a decentralized structure, one of the main advantages of renewable energy systems is that it is possible to add redundancy so that power generation becomes more reliable (Vezzoli et al., 2018). There are, however, few relevant studies that include aspects like reliability and robustness in assessments; most consider only cost-effectiveness and function without examining how systems respond to disruptions (Hammer & Veith, 2021).

Our proposed framework focuses on how decentralized renewable energy (DRE) systems can help ensure a stable electricity supply when a power system experiences a single-point failure with cascading effects. We applied this framework to the case of Cuba, an island state highly vulnerable to climate impacts, extreme weather events and natural disasters. It is also a country marked by a high degree of international isolation in terms of economy and technology, which is relevant of the framework.

A five-step framework to enhance power system resilience

The framework combines an assessment of power infrastructure vulnerability with the design of cost-optimal DRE systems, and evaluates the designed systems using metrics to measure their resilience. The framework consists of the following five steps:

Step 1. Create a synthetic electricity network to identify vulnerable hotspots

The first step in the modelling framework is to identify hotspots susceptible to power supply disruptions from system failures. To do so, a synthetic network is created that mimics the topological features of the electricity distribution system, for example using OpenStreetMap data. Nodes in the system represent points of electricity demand from residential, commercial, and industrial consumers, as well as supply from power stations.

For each node, different aspects of vulnerability are calculated through demand-weighted network centrality metrics, using the Python library NetworkX and the network analysis software igraph. Each metric provides insights into how important any given node is for the network's connectedness by measuring different types of node connectivity. Nodes that score high on the centrality metrics are critical for the function of the entire network. These nodes are therefore considered disruption hotspots, where disturbances could lead to significant impacts such as interrupted power supply.

Step 2. Disruption analysis

In the second step of the framework, the disruptive potential of the most vulnerable hotspots is assessed. In each hotspot, critical nodes and their neighbouring nodes are removed stepwise to assess how single-point failure can propagate through the network. The framework assumes that power failure spreads through network links without back-up systems. The disruptive potential is measured as the total demand that is affected as power failure spreads. The municipality with the most disruptive node can then be selected for targeted solutions to enhance resilience.

Step 3. Modelling to test technical solutions

A computational approach is the most effective way to identify cost-effective DRE solutions. In the third step of the framework, the globally recognized standard tool for optimizing microgrid designs, HOMER Pro (Hybrid Optimization of Multiple Energy Resources Pro), is used to design decentralized system solutions tailored to the municipality containing the most disruptive node. The HOMER Pro optimization is based on the availability of renewable energy resources, DRE technology costs and grid interactions. It involves analysis of the following:

- **Economics and financial soundness:** analysing overall expenses, returns, and long-term economic viability.
- **Energy production and consumption:** including potential surpluses or deficits.
- **System performance:** scrutinizing overall efficiency, reliability, and resilience of the decentralized system under various conditions.
- **Renewable technology:** component-specific metrics provided a granular understanding of each component's functionality and efficiency within the decentralized energy system.

Different DRE system architectures can be explored, such as ancillary and back-up systems, exemplifying different degrees of decentralization. For example, an ancillary

system can be configured to meet the full anticipated electricity demand of the municipality identified in step 2 while remaining integrated with the central grid, which allows exchange of electricity with the main power grid. In contrast, a

4. Finding the best local approach

The fourth step in the framework involves integrating contextual factors into the modelling. The design of solutions must be based on the specific local context because the result will vary depending on local regulations, international trade regimes, and the distance from production facilities, among other factors. Contextual considerations could, for example, be reflected in the modelling as limited access to certain technologies, or in the costs of certain technologies.

5. Evaluation of resilience improvements

In the final step of the framework, the modelled DRE system solutions are evaluated based on their ability to improve power system resilience, particularly in maintaining a continuous power supply. This evaluation compares the power supply with and without the deployment of these solutions, in both normal conditions and during disruptive events. The goal is to assess the potential of these solutions to improve resilience in everyday operations as well as in the face of disruptions.

Lessons learned from the case of Cuba

Applying the framework to the case of Cuba provides key insights into how DRE technology solutions can improve the resilience of power systems in island states. Our results from the first two steps in the framework show that, out of the 10 hotspot municipalities in Cuba with the highest disruption potential, seven belong to the city of Havana.

Under steps three and four in the framework, the modelling of technical solutions for both ancillary systems (AS) and back-up systems (BS) includes solar photovoltaic (PV), wind power, battery storage and biomass generators. To highlight the context-specific opportunities and challenges associated with integrating DRE system solutions into Regla's power system, these system architectures are explored under two scenarios. One is a global scenario that analyses global costs for DRE technologies, and the other is a Cuban scenario, in which the US embargo against the country incurs higher investment costs and limited access to DRE technologies. This leaves four modelled systems in total: AS1 and BS1 under the global scenario, and AS2 and BS2 under the Cuban scenario.

Looking at the results from steps three and four, the cost-optimal solutions for each scenario in Table 1 show distinct trends in installed capacities and costs. Costs of the ancillary systems and back-up systems under the Cuban scenario are generally higher than under the global scenario: capital investment costs are about 5-40% higher and differences in the levelized cost of electricity (LCOE) are even more pronounced. More generally, AS emerges as a better option compared to BS in terms of LCOE, but it brings challenges in the form of higher upfront costs.

Table 1. Techno-economic output of the solutions modelling

	Global scenario		Cuban scenario	
	AS1	BS1	AS2	BS2
Installed PV (megawatts)	156	21	53	24
Installed biomass generators (megawatts)	1	1.5	0.5	3.5
Installed wind turbines (megawatts)	147	10.5	148.5	6
Capital costs (millions of USD)	404	61	426	86
Levelized cost of electricity (USD per megawatt hour)	9	107	34	155

The results from the fifth and final step of the framework show that all modelled DRE system solutions improve resilience by ensuring a more continuous power supply. These improvements are greater during disruptive events, with supplied loads up to 66% (AS1) and 56% (AS2) higher than the loads supplied in everyday operations. Such differences are less pronounced in BS1 and BS2. Meanwhile, ancillary systems are more affected by the contextual factors of the Cuban scenario than back-up systems, which means they supply less load than under the global scenario.

Conclusions and policy recommendations

The results of applying the five-step framework in Cuba suggest that municipalities with high concentrations of electricity demand from large buildings and industries are more vulnerable to single-point power system failures and their cascading effects. It seems possible that in such municipalities power systems can become more resilient through DRE systems that help ensure a more continuous power supply. The case of Cuba indicates that DRE systems can help improve power system resilience on a day-to-day basis, in particular by reducing the risk of power system failures.

When choosing energy system set-ups it is, however, important to consider trade-offs. Robust solutions that increase resilience may incur substantial initial investments even if operation costs are relatively low. At the same time, there can be significant benefits to society if investment in a vulnerable area strengthens the infrastructure in dense urban environments and critical economic sectors.

Applying the framework in Cuba demonstrated how context-specific factors influence which DRE system solution is most suitable. By making context-specific assumptions for Cuba, we found a different mix of renewable technologies were suitable than would have resulted had we used assumptions based on the global average. come with higher costs and less potential for resilience improvements. This suggests that there are no one-size-fits-all solutions; to be relevant, the analysis must involve expert inputs together with accurate data to ensure that the model reflects real-world conditions and plausible trends.

Based on these conclusions, we recommend that decision-makers should:

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- recognize how distributed renewable energy systems can make power systems more resilient and develop coordinated strategies to increase renewable capacity in the energy mix and contingency planning processes.
 - ensure that grid expansion and contingency planning account for the wider socio-economic impacts of implementing decentralized renewable systems to improve resilience.
 - foster collaboration between researchers, local energy authorities, grid operators and other relevant stakeholders to build better models, informed by more accurate data, increasing their relevance to policy and decision-making.

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