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Decentralized solutions for island states: Enhancing energy resilience through renewable technologies

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ABSTRACT

Decentralized grid solutions could be a feasible alternative to improve resilience and mitigate cascading effects in island states. Our study explores approaches that reduce the risk of infrastructure failures and promote decentralized utility planning in islands. A novel framework is proposed to conduct a power system resilience assessment by integrating vulnerability assessments and energy system modelling approaches through network analysis. The framework is applied to an island context, where vulnerability to hydroclimatic hazards, geographic isolation, restricted access to energy sources, small population bases inadequate for substantial infrastructure investments, dependence on imported energy, lack of energy source diversification, and fragile ecosystems have exacerbated energy insecurity. As a case study, we have applied the framework to Cuba. We simulate disruptions in vulnerable network nodes in Cuba to determine the municipalities that are most impacted by the simulated cascading failures. We designed and optimized the lowest cost decentralized solutions to increase resilience either by acting as the baseload electricity source or as a complementary backup system to complement in case of a power outage. Then, the resilience of the designed system was assessed using power system resilience metrics. The study results show Regla municipality in Cuba as the most vulnerable hotspot for electricity distribution. Upon the different system comparisons, ancillary systems outperform backup systems in enhancing power system resilience, especially in the context of a disruptive event, supplying up to 53 MWh/day more, although they have higher investment costs. Based on this research, resource planners and policymakers can understand vulnerable node points and prioritize the necessary investments for the preferred system choice to alleviate impacts of energy insecurity on the Island States.

1. Introduction

Electricity is the cornerstone of modern society, powering everything from hospitals and schools to communication systems and emergency services. Yet for Island States (IS), the promise of consistent, resilient electricity remains elusive. Not only are these IS facing economic constraints and fuel shortages [1], but they are also increasingly susceptible to hydrometeorological hazards such as hurricanes, floods, and droughts—events that are projected to increase and intensify due to climate change [2]. Such events often lead to catastrophic failures in IS already fragile grid-based electricity distribution systems. The impact of these vulnerabilities cascades into various sectors, exacerbating energy insecurity and hindering sustainable development [3]. Network-based models have been developed to evaluate cascading vulnerabilities in infrastructure systems by explicitly accounting for interdependencies among individual infrastructures or components through graph theory [4,5]. For electrical distribution systems, topological centrality metrics from network analysis has been applied to predict grid vulnerabilities [6] and flow-based approaches have been developed to simulate supply-demand balance after disruptions [7,8].

IS are a distinct group of countries and dependent territories that face unique social, economic, and environmental vulnerabilities [9]. One of

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the challenges they face is access to, and the cost burdens of, energy. Most IS are heavily reliant on imported fossil fuels, creating supply risks, and both direct and indirect costs associated with climate change [10]. Island states often continue to rely on centralized energy production and supply systems [11], even though these systems may not be the most robust in the face of rising hydroclimatic risks. Centralized systems, while efficient under normal conditions, can become vulnerable to extreme weather events like hurricanes, sea-level rise, and prolonged droughts [12]. This is particularly the case of aging infrastructures whose functions are increasingly decaying [13]. The persistence of centralized systems is often due to factors like historical infrastructure investments, limited financial resources for extensive overhauls, and a lack of alternatives. However, as hydroclimatic risks intensify with climate change, island states must increasingly consider diversifying infrastructure systems [14].

Decentralized renewable technologies emerge as a promising alternative with potential to harness clean energy sources, reduce dependency on fossil fuel imports and enhance energy access. The challenge, on the other hand, of shifting to a more decentralized energy system could be high upfront costs and a lack of suitable financing, absence of supportive regulatory frameworks, small energy markets that constrain the establishment of independent regulatory agencies, resistance by incumbent power companies to new technologies, limited technical capacity for working with new sources of energy including renewables, lack of negotiating capacity, low financial transparency and sustainability of utilities, and lack of long-term planning and political commitments [15].

While some studies have explored the optimization of decentralized grid energy systems for IS [16–18], these frameworks often focus on cost-effectiveness, energy efficiency, and 'business-*as*-usual' power supply scenarios. Such models are valuable for routine energy planning but might not fully account for the unique vulnerabilities of IS to hydrometeorological hazards and infrastructure issues. Many overlook the spatial aspect of vulnerability, potentially leading to designs that do not mitigate the effects of power disruptions in the places most exposed to events like hurricanes, floods, or earthquakes.

Our study aims to address these critical gaps highlighted in the introduction. To address the challenges, we do this in three ways. First, we introduce a replicable modelling framework that not only considers cost and efficiency, but also emphasizes power system resilience, which is crucial for IS facing frequent power disruptions. Second, we integrate network analysis into the design phase of decentralized grid energy systems to optimize their power distribution and reduce disruptions in vulnerable areas. Lastly, we evaluate the designed power system of the region by using power system resilience assessment metrics. For this evaluation, we draw upon Noebels [13], to define power system resilience as a power system's ability to withstand power outages, with least possible interruptions in the supply of electricity.

We test the framework for the case of Cuba, since it exemplifies many of the challenges inherent to IS. Positioned in the Caribbean, Cuba is frequently exposed to the direct path of hydrometeorological hazards. The island regularly confronts the wrath of hurricanes, tropical storms, and heavy rainfall events, which can lead to flooding [19]. Additionally, its position makes it susceptible to droughts and sea level rise, exacerbated by climate change [20]. These hazards are not only threatening the natural landscape of Cuba but are also making its electricity distribution system especially vulnerable. In this context, the study is guided by two research questions.

RQ1. Where are the most vulnerable geographic areas in multi-sectorial electricity service demands in Island States (IS)?

RQ2. What cost optimal combinations of technologies in decentralized solutions are the most suitable to enhance power system resilience in Island States (IS)?

The rest of the paper is structured as follows. Section 2 describes the study approach, detailing the methodology behind our modelling framework, and provides an overview of our chosen case study area. Section 3 showcases the outcomes from applying this framework to the case study area. The discussion in Section 4 critically evaluates both the results and the underlying modelling framework. Finally, Section 5 wraps up the paper with conclusions drawn from our research.

2. Methodology

Fig. 1 illustrates the research design for this study, as well as the different steps of our proposed framework. We assess disruptions and cascading effects of electricity infrastructure through network analysis (Module 1). We identify the vulnerable hotspots in the electricity infrastructure where decentralized technologies could increase power system resilience to help addresses critical infrastructure vulnerabilities (Module 1). Cost-optimization is further used in Module2 to assess the relevant technology mix of decentralized solutions for the identified vulnerable area. The concepts and data inputs are discussed in detail in the next sections.

2.1. Case study area

Cuba is an island nation situated in the Caribbean Sea, near the Gulf of Mexico and the Atlantic Ocean. The most densely populated areas in country are the cities of Havana and Guantanamo. Socioeconomically, Cuba has faced long-standing embargo conditions, primarily imposed by the U.S., restricting trade, investment, and financial transactions [21]. This economic isolation has impacted its infrastructure development, technological access, and energy sector [22,23]. As a result, Cuba presents a context influenced by both geopolitical constraints and inherent vulnerabilities as an island state, making it a fitting choice for a case study on electricity supply resilience in IS. Results from Cuba can be relevant to many other IS facing similar challenges, and our framework can be replicated for more tailored to the local context analyses.

Due to oil shortage, power outages has become a serious problem in some municipalities in Cuba. Currently, 84 % of Cuban electricity is mainly generated by oil. The main oil exporters for Cuba are Russia and Venezuela [24,25]. The case study focuses on analyzing the feasibility of integrating renewable energy sources into the country's electricity grid as a way to improve resilience and reduce fossil import dependency. Cuba's renewable energy sector has significant untapped potential, especially in the areas of biomass, solar photovoltaic (PV), and wind energy resources. The abundance of biomass resources in the country, such as marabu, sugarcane leftovers and agricultural waste, presents great potential for bioenergy generation [26]. Furthermore, Cuba's geographical location and temperature make it ideal for harvesting solar energy via PV systems (Bojan Stoijkovski, 2022, [27]). Wind energy is also a feasible renewable option due to the island's coastal regions and favourable wind patterns [28], but there are many practical difficulties in deploying these technologies on ground.

2.2. Analysis modules

The methodology employed in this study is organized into two principal modules aimed at addressing the respective research questions. Module 1 focuses on assessing critical electricity infrastructure and identifying areas with vulnerable infrastructure links. At the island scale, Module 1 utilizes infrastructure and population data to calculate electricity demand and to assess critical electricity infrastructure, identifying vulnerable areas. These outputs then inform Module 2, which focuses on the design and evaluation of cost-effective decentralized solutions tailored to the vulnerable area. The solutions' techno-economic performances and power system resilience improvements are also evaluated in this module.

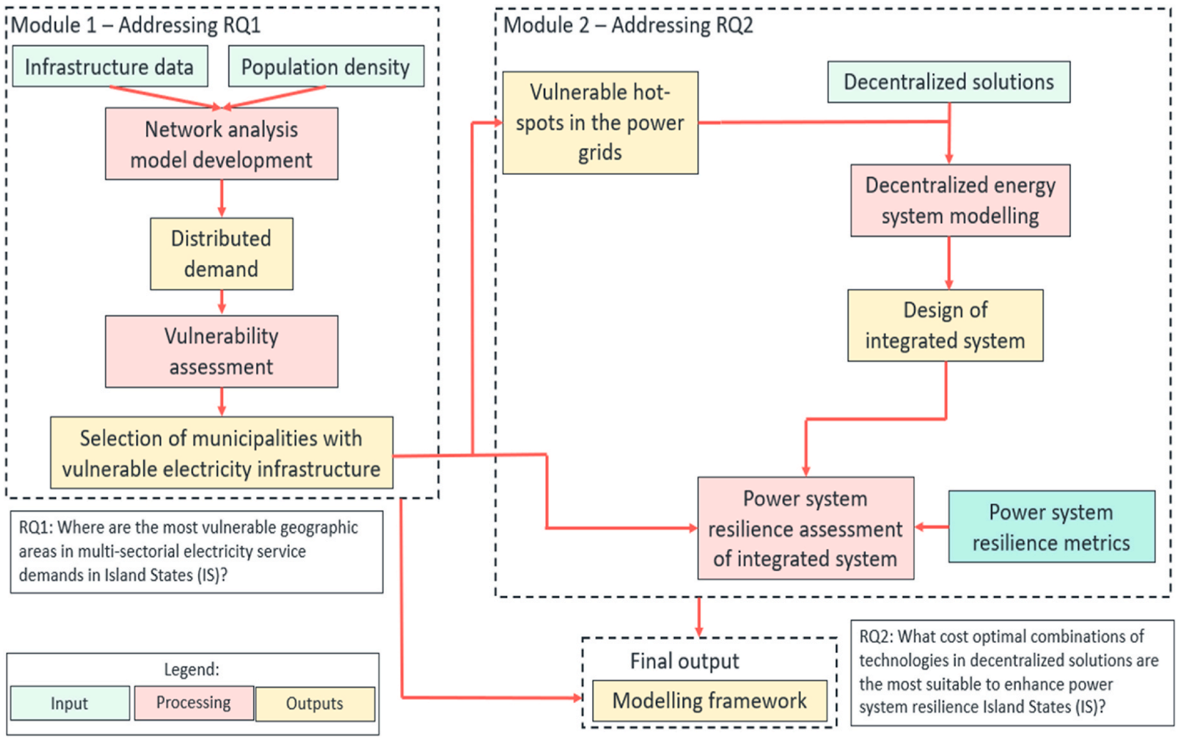

Fig. 1. Conceptual illustration of the research approach.

2.2.1. Module 1: vulnerability assessment of electric energy demand

The goal of the vulnerability assessment of electric energy demand is to identify areas where disruptions cause cascading effects, making them vulnerable hotspots that require attention for improving electrical energy provision and overall system resilience [5,29]. We apply a network-based model for hotspot identification due to its ability to simulate cascading impacts in electricity grids [30] and provide metrics to measure centralization and resilience [31]. The assessment involves 1) generation of a synthetic electricity network, 2) allocation of electricity demand and supply, 3) prioritization of nodes through network centrality metrics, and 4) identification of vulnerable hotspots through disruption analysis.

The first step involves creating a synthetic network [7] that mimics the topological features of the electricity distribution system using OpenStreetMap (OSM) data imported via the Python library OSMnx [32]. Nodes in this network represent road intersections and ends, including points of residential demand. Additional nodes are introduced to represent power demand from large commercial and industrial buildings and supply from power substations. Network edges, derived from OSM data, symbolize electrical cables in the distribution system.

Next, the allocation of electricity demand and supply is performed. Residential and non-residential demands are classified based on nodes representing cables and large buildings, respectively. Population density and per capita electricity consumption data are utilized to estimate residential electricity nodal demands through the Voronoi technique [33], as shown in Fig. 2. Non-residential demands are assigned using national-level electricity demand data by major economic sectors. Electricity supply is allocated as negative demands [34], with power substations serving as nodes for supply. Therefore, supply nodes have the inverse impact of demand nodes on the network model.

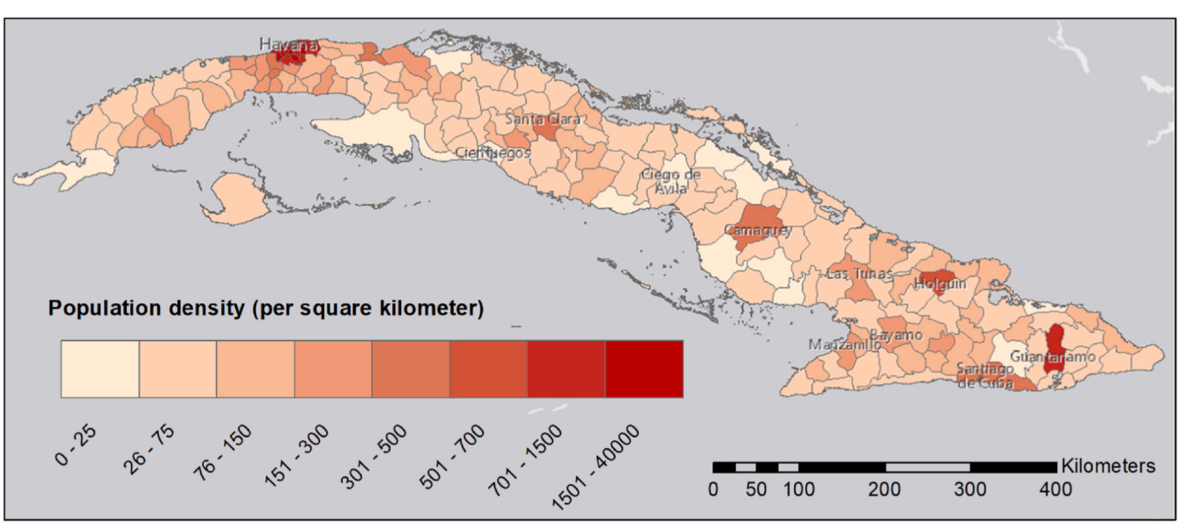

Fig. 2. Case study area (Cuba) including population density per square kilometer [35].

The third step involves node prioritization using network centrality metrics, which are theoretical node properties utilized to measure centralization. Four metrics—degree, eigenvector, betweenness, and closeness centrality [36–38]—are applied to analyse the network's structural properties. These metrics are calculated using Python libraries NetworkX [39] and igraph [40], considering regional electricity demands from each node as weights. Each metric provides insights into different aspects of vulnerability, and critical nodes are selected based on maximum values for each metric in each municipality.

The final step includes the identification of vulnerable hotspots through disruption analysis using a node removal technique. Critical nodes are further ranked by their disruptive potential in case of failures. The disruptive potential is assessed through a disruption analysis, involving a stepwise removal of critical nodes and their neighbours up to the 10th order of neighbourhood. This limit to the disturbance propagation process was defined as a compromise between computational constraints due to the large size of the grid and sufficient to cover reasonable network diameter at municipality scales. The assumption is made that failure, meaning power outage, spreads through network links without backup systems. In other words, failures in the critical nodes are assumed to lead to power outages in the neighboring nodes as a point of transmission is interrupted. An iterative algorithm has been developed to estimate the disruption by first removing the critical node and recording the impact on energy demand. Then, the algorithm proceeds to remove and record demands from subsequent order of neighbours. The total impacted demand is used as a criterion to evaluate node disruption. The municipality containing the most disruptive node is then selected as the most vulnerable for implementation of resilience-improving solutions.

2.2.2. Module 2: decentralized energy system modelling

The primary aim of energy system modelling in this study is to model and evaluate decentralized grid energy systems tailored to the specific needs and conditions of a selected region in Cuba. The methodology seeks to understand the cost optimal combination of renewable energy resources such as PV, wind, battery storage solutions, and possible integration of traditional biomass generators to ensure energy resilience, sustainability, and economic viability.

To facilitate the design of cost-effective decentralized energy solutions, a computational approach is employed using Hybrid Optimization of Multiple Energy Resources Pro (HOMER Pro). HOMER Pro is globally recognized as a standard tool for the optimization of microgrid designs and is well-suited for evaluating both decentralized grid and grid-connected energy systems. It simulates complex hybrid energy systems and microgrids, finding the least cost options by evaluating potentially hundreds of systems over the course of a year, utilizing various energy resources such as solar, wind, batteries, generators, and other energy sources [41].

In the evaluation of the proposed configurations of decentralized solutions, four key metric categories were used in Homer Pro and analyzed accordingly. First, economic metrics - Net Present Cost (NPC) and Levelized Cost of Electricity (LCOE) - were employed to evaluate the financial soundness of each setup, offering insights into overall expenses, returns, and long-term economic viability. Next, energy metrics were then assessed to understand energy production and consumption, including potential surpluses or deficits. Then, system performance metrics were scrutinized for overall efficiency, reliability, and resilience of the decentralized system under various conditions. Finally, renewable technology component-specific metrics provided a granular understanding of each component's functionality and efficiency within the decentralized energy system.

We modelled various scenarios tailored to Cuba to explore the challenges and constraints associated with integrating renewable energy technologies to the grid. Two main scenarios are devised: the global scenario and the Cuban scenario. The global scenario incorporates the global average cost of renewable energy technologies where the cost estimates are more accurate, while the Cuban scenario reflects average cost of renewable energy technologies adjusted to a Cuban context. The reason for choosing this approach is that, due to the US embargo, Cuba requires more investment for renewable technologies so this scenario analysis will help to uncover the financial burdens and to plan the resilient green energy transition for Cuba. The following Fig. 3 presents flow charts of the scenarios and sub scenarios explored in decentralized energy system modelling.

Under the global and Cuban scenarios, two sub scenarios have been modelled: Ancillary System (AS) and Backup System (BS) scenarios. In total there are four modelled scenarios which are global scenario (AS1 and BS1), and Cuban scenario (AS2 and BS2). In our scenarios, the ancillary system is configured to meet the full anticipated electricity demand of the chosen region, ensuring that the deployed decentralized energy system can supply 100 % of the region's energy needs. The system is connected to the central grid system to ensure a continuous and stable power supply and at the same time, the excess electricity produced from the decentralized system can be sold to the central grid. This helps to strengthen the current energy infrastructure of the region/island, increase the optimal utilization of the deployed energy system, and support the island's grid decarbonization. The backup energy system scenario is designed based on the average daily scheduled/unscheduled power outage of an island. Thereby, it is not dimensioned to provide entire regions' electricity demand. In the event of unexpected or scheduled power outages, the system seamlessly activates to meet selected demand requirements for specific hours per day and apart from that, the system remains inactive. As both AS and BS are dimensioned after the electricity demand and power outages at a regional level, the analysis considers these systems to be installed in the local distribution grid to which industrial and private consumers are connected. More specifically, the AS and BS are assumed to be installed at the point where the most critical node is located, acting as sources of electricity supply where the transmission is interrupted.

2.2.3. Module 2: power system resilience assessment

To evaluate the decentralized solutions' potential for power system resilience improvements, we make an assessment based on three performance-based metrics that measure power system performance in terms of electricity supply: supplied load, unmet load, number of people affected. These metrics are outlined within a broader framework of power system resilience to assess a power network's capacity to withstand and recover from various shocks and stresses [13].

We evaluate the power system resilience metrics for all scenario combinations described in Fig. 3, namely AS1, AS2, BS1, and BS2. We compare them with the evaluated metrics in a case without decentralized solutions, to assess the solutions' potential for improving power system resilience. This evaluation and comparison of metrics for each scenario, with and without the deployment of decentralized solutions, further extends to encompass a business-*as*-usual (BAU) case, and in a case where the power system is subject to a disruptive event (DIS). Comparing these cases allows an assessment of how the solutions' contributions to resilience improvements vary during power system failure. In other words, for each scenario combination, we make four evaluations: BAU with and without the deployment of the decentralized solutions and DIS with and without the deployment of decentralized solutions. In this assessment, the disruptive event is assumed to follow the node removal technique described in section 2.2., where failure is assumed to spread from the most disruptive node. All nodes subject to failure are assumed to be affected by complete power outage.

The same rationale for calculating the resilience metrics is applied to all cases. The supplied and unmet load are calculated as in Eqs (1) and (2):

$$\text{Supplied load} = \sum_{n} \text{Grid}_n + \text{Offgrid}_n \tag{1}$$

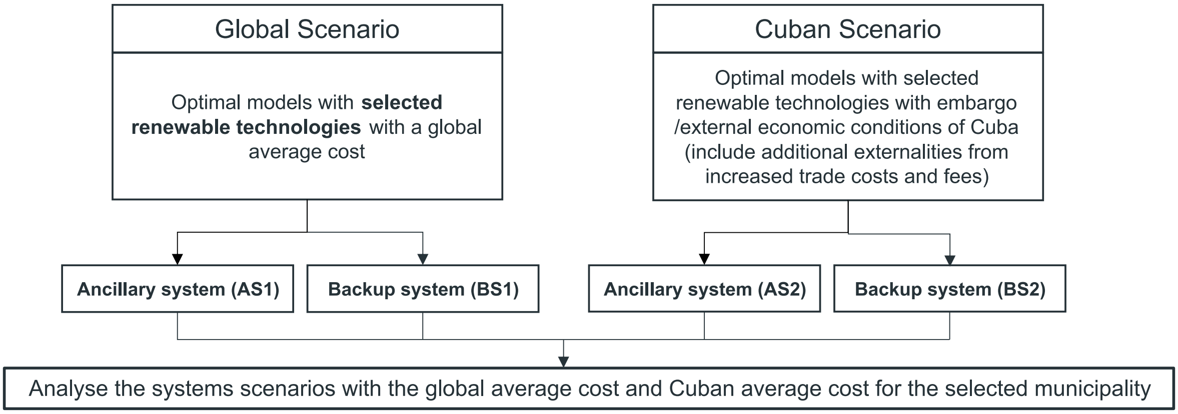

Fig. 3. scenarios for decentralized grid energy modelling.

where the total power supply from the grid and the decentralized solutions are summed for each node, *n,* in the system.

$$\text{Unmet load} = \sum_{n} \text{Demand}_n - (\text{Grid}_n + \text{Offgrid}_n) \tag{2}$$

where the unmet load is calculated as the sum of the difference between the demand and total power supply in each node, *n,* in the system.

The number of people affected by power outage is calculated for the nodes with residential demands. For these, the total power supply is divided by the number of residents to arrive at the average power supply per resident in each respective node. People are considered to be affected when the average power supply reached 0 kWh.

The power demand of each node, $Demand_n$, is retrieved from the vulnerability assessment described in section 2.2. Daily average demand data is used in the analysis. Each node is further subject to a daily power outage. Assumptions on daily power outage are further detailed in section 2.5. The amount of outage power in each node is assumed to be relative to the demand in each node.

The grid supply, $Grid_n$, is calculated as the difference between the power demand and the outage power of each node. The power supply from the decentralized solutions is retrieved from the energy modelling described in section 2.3. Similar to the power outage, the amount of power supplied from the decentralized solutions to each node is assumed to be relative each node's power demand.

2.3. Data collection

To understand the energy requirements of the selected region in Cuba and identify optimal solutions, we collected data on energy demand, the availability of renewable resources, and system components specific to the region. We then defined load profiles, evaluated the availability of renewables using historical weather data and literature reviews. Finally, we gathered detailed technical and economic information on potential components, such as photovoltaic (PV) systems, wind turbines, batteries, inverters, and traditional generators, for the selected region. The specifics of the data collection and analysis are further elaborated in the section.

For the vulnerability assessment through network analysis, this study utilized open-source data from OSM to gather information on the electricity grid, based on the street network, energy supply data, as well as the locations and spatial footprints of power substations and large commercial, public, and industrial buildings. Per capita residential electricity demand, total sectorial electricity demand and population density data at municipal levels were retrieved from National Statistics and Information Office (Oficina Nacional de Estadística e Información) [35] and the United Nations Department of Economic and Social Affairs [42]. The following Table 1 provides sectoral electricity demand of the Cuba which is used in the network analysis.

Table 1
Electricity demand per sector in Cuba [35,42]

Sector	Total Demand per Sector (2021, GWh)
Public	7211
Industry	3853
Storage	1860
Construction	129
Agriculture	276
Transport	266
Commerce	390
Others	2298
Total	**16 282**

The techno-economic parameters used in the modelling can be found in Table 2. The costs of renewable energy technologies for global average and the Cuban-specific da are obtained from reports, databases, and relevant literature. Table 2 compares cost data for both the

Table 2
Techno-economic data for energy modelling.

Input parameters	Assumptions	
	Global scenario	Cuban scenario
Solar PV – capital cost	857 $/kW [43]	1500 $/kW [44]
Solar PV – OM cost	10 $/kW/per year	23 $/kW/per year
Wind turbine – capital cost	1300 $/kW [45]	1769 $/kW [44]
Wind turbine – OM cost	13 $/kW (1 % of CAPEX/year)	35.38 $/kW (2 % of CAPEX/year)
Biogas generator – capital cost	3000 $/kW (Homer Pro)	3000 $/kW (Homer Pro)
Biogas generator – OM cost	0.10 $/operational hour (data retrieved in Homer Pro)	0.10 $/operational hour (data retrieved in Homer Pro)
Li-ion battery – capital cost	1394 $/kW [46]	1742.5 $/kW
Li-ion battery – OM cost	34.85 $/kW (2.5 % of CAPEX/year)	61 $/kW (3.5 % of CAPEX/year)
Converter – capital cost	300 $/kW (Homer Pro)	300 $/kW (Homer Pro)
Average biomass potential of the selected municipality	38 tons/day ([47,48]	
Annual average of solar GHI resources of Cuba	5.79 kWh/m2/day (data retrieved in Homer Pro)	
Average biomass price	24 $/ton	
Annual average of wind speed data of Cuba	6.31 m/s (data retrieved in Homer Pro)	
Discount rate	5 %	
Inflation rate	5 % [49]	
Project lifetime	25 years	
Grid sell price	0.076 $/kWh	
Grid purchase price	0.12 $/kWh [50]	

scenarios.

The solar and wind potential (NASA database), cost of biogas generator and convertor are retrieved from the in-built database of HOMER Pro software. Due to US embargo effect, based on the literature sources we identified that the overall technology cost in Cuba is 25%–40 % higher when compared to global average cost. Currently, Cuba does not have many battery storage systems so there is no data available. Therefore, missing data were derived from global average data. In this case we assumed that the battery cost would be 25 % higher than the global average due to embargo effect, but according to expert, in reality, it may be even higher than specified in our study.

We obtained the daily average electricity demand from the network analysis and we based our seasonal variations of the load profile on [51]. Furthermore, we incorporated data on the average power outage period in the selected municipality, which was obtained from newspaper articles. The grid outage is mainly considered for ancillary systems since the backup system does not connect with the central grid. Based on the different sources such as news articles, the study assumes that there will be 2-h power outage in winter and 4-h power outage in summer [52–54]. With this, we better understand Cuba's average load profile and power outages during summer and winter months and developed an own methodology to prepare the load profile data for the selected municipality in Cuba. For this study, we assume a consistent electricity use pattern for every day within a month.

Additionally, we discussed our assumptions with an expert in Cuba for getting feedback to validate our approach. This included information on electricity purchase and sale prices, technology costs for PV, and wind turbines, as well as details of renewable technology preferences, financial capability of the island, the overall island's power outage duration and patterns, the status of oil imports, and choices regarding decentralized energy systems and scenarios. The outputs related to our study from the interviews are explained in the discussion section 4.

3. Results

3.1. Vulnerable hotspots of energy demands

The generated synthetic electricity network in Cuba comprises 239 219 nodes and 581 833 links indicating points of demand and transmission cables. Most of the nodes (84 %) represent residential demands, derived from allocated population values. Fig. 4 shows the distribution of allocated population values per node, with mean, median and standard deviation of 55.66, 4.18 and 153.22, respectively. The distribution of nodes is shown in a logarithm scale due to the wide range of population values across the nodes, which spans several orders of magnitude. Urban areas do not necessarily have higher allocated populations because they are shared among a denser infrastructure. Daily residential electricity demand was allocated to nodes by employing a per capita consumption of 2.39 kWh/person/day [35], which is 73 % smaller than the global average [55].

Infrastructure types retrieved from geospatial data were grouped into sectors according to the available non-residential energy demand data in Cuba in 2021. The built area is predominantly occupied by the industry, public, and commerce sectors. The industry sector comprises industrial and manufacturing buildings, while the commerce sector corresponds to commercial, retail and service buildings. The public sector includes hospitals, schools, universities, and government offices. Demand benchmarks are calculated for each infrastructure type by dividing total demand per built area (Fig. 5). Agriculture and storage sector benchmarks are relatively higher than other sectors. Demands from large buildings belonging to other sectors include 38135 nodes and there are 242 supply nodes from power substations with average supply of 137 MWh/day.

To evaluate the cascading impacts of network disruptions on the electricity grid, a disruption analysis was conducted at each Cuban municipality for selected nodes with the highest centrality metric values. Fig. 6 shows the spatial distribution of the calculated network centrality metrics in Cuba. Degree and eigenvector centralities highlight

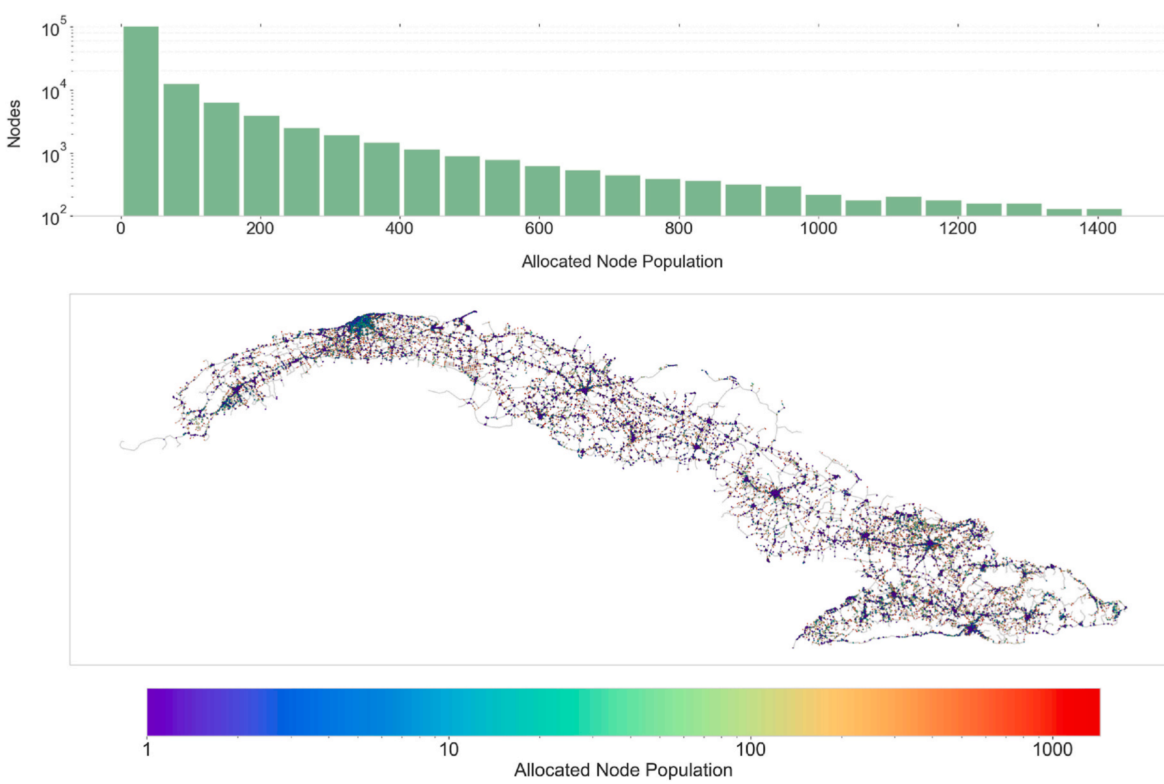

Fig. 4. Population allocated to network nodes.

Fig. 5. Retrieved non-residential built areas and estimated demand benchmarks.

nodes with higher demands due to high population density and concentration of industrial buildings. Betweenness centralities indicate nodes that topologically act as bridges between large groups and closeness centralities demonstrate nodes which are closer to others in terms of shortest paths. Nodes with higher centrality values are potentially the most disruptive in the synthetic electricity grid [6].

A normalized energy impact score was calculated as the sum of the demands from the disrupted nodes. Out of the ten municipalities with highest energy impact scores, seven belong to the city of Havana. The elevated demand in this city is attributed to large buildings, especially from the industrial sector. Among all municipalities in Havana, Regla is the one with largest demand disruption and has been selected to represent the vulnerable hotspot of energy demand for the consideration of decentralizing solutions.

Fig. 7 shows a cascading failure graph of the most disruptive node in the municipality, demonstrating that some industrial nodes have demands that can reach orders of magnitude above nodes from other sectors. Notably, all nodes affected by the cascading failure are demand nodes. Considering the total daily energy demands for all nodes within the municipality boundaries, it is noted that, apart from the industrial sector, public and residential demands also stand out in Regla.

3.2. Optimal solutions of decentralized grid energy solutions

This section details the outcomes of our modelling of a decentralized grid energy system in Regla Municipality, Cuba. Four scenarios were modelled to assess electricity contributions from PV, wind turbines, battery storage, and biogas generator: Global (AS1, BS1) and Cuban (AS2, BS2).

To design a decentralized energy system for scenarios, renewable technologies for Regla municipality have been chosen based on the potential for available resources. While the chosen technologies resemble both the AS and BS, there are key architectural differences between them, as presented in Fig. 8.

3.2.1. Electricity production and capacity required

We model decentralized electricity production systems in Regla municipality. In examining the AS scenarios, distinct trends in energy source contributions become apparent in both global and Cuban average scenarios. In AS1, PV provide a significant 33 % of the total electricity. However, in AS2, which reflects the Cuban average, PVs only contribute 14 %. Biomass generators play a minor role in both scenarios, but there's a slight increase in AS2, producing 0.98 GWh compared to AS1's 0.6 GWh. Wind turbines are key electricity sources in both scenarios. They're particularly dominant in AS2, contributing to 86 %, up from 67 % in AS1. In the BS1 scenario, PV systems and wind turbines contribute similarly, with 47 % and 52 % to the energy mix, respectively.

However, in the BS2 scenario, PVs dominate, accounting for 64 % of the total energy mix. This increase in PV contribution is accompanied by a rise in biomass generation, nearly doubling from 0.6 % in BS1 to 1 % in BS2. In contrast, the share of wind turbines significantly decreases in BS2, dropping to 35 %. Based on least cost optimization, both the AS and BS systems place significant emphasis on PV capacity, with the BS system, particularly BS2, showing a stronger reliance. While wind turbines are central to the AS system, especially in AS2, their importance is less pronounced in the BS scenarios. This is attributed to the capital cost and energy demand of each system. For instance, the AS systems cover 100 % of the energy demand, whereas the BS system only covers certain power outage hours per day, which mostly occur during sunny times. Consequently, the AS system has a greater wind capacity, while the BS system emphasizes more on PV capacity. Conversely, the typically marginal biomass generators have an enhanced role in BS, most evidently in BS2 because we designed to use the biomass generators only during the power outage time of the day.

The difference in energy source allocation between AS and BS scenarios is driven by, AS system focus on continuous energy supply for the entire region, leaning towards a combination of wind (predominantly in the Cuban context) and solar, while BS prioritizes cost-effective energy supply during power outages, favoring cheaper solar supplemented by biomass generation. Table 3 shows the electricity production and required capacity for the Regla municipality.

A salient feature across all modelled scenarios is the consistent generation of surplus electricity. It is expected that the magnitude of this excess varies considerably, with BS systems producing a surplus per year of 42 GWh (BS1) and 28.7 GWh (BS2) at the lower end and AS systems registering a substantial overproduction of 317.6 GWh (AS1) and 208 GWh (AS2) at the upper spectrum. However, when evaluating surplus relative to total electricity output of each scenario, BS1 has a larger share of excess production which is 104 %, BS2 72 %, AS1 9 % and AS2 0 % of its total electricity generated for Regla. This observation underscores the potential of the BS scenarios for excess energy storage or grid feed-ins even if this is not its main intended application.

We have further investigated self-sufficiency and excess capacity in the model results. Specifically, in scenarios AS1 and AS2, where the system needed to purchase electricity from the grid, quantified at 11 GWh for AS1 and 43 GWh for AS2. Interestingly, while these scenarios required external power procurement, they also exhibited significant surplus electricity at certain times of the day or year. This led to remarkable grid sales, with AS1 having the capacity to sell 269 GWh and AS2 235 GWh back to the grid. This indicates a potential for both self-sufficiency and revenue generation. By carefully managing energy production and consumption, Regla can not only meet its energy needs but

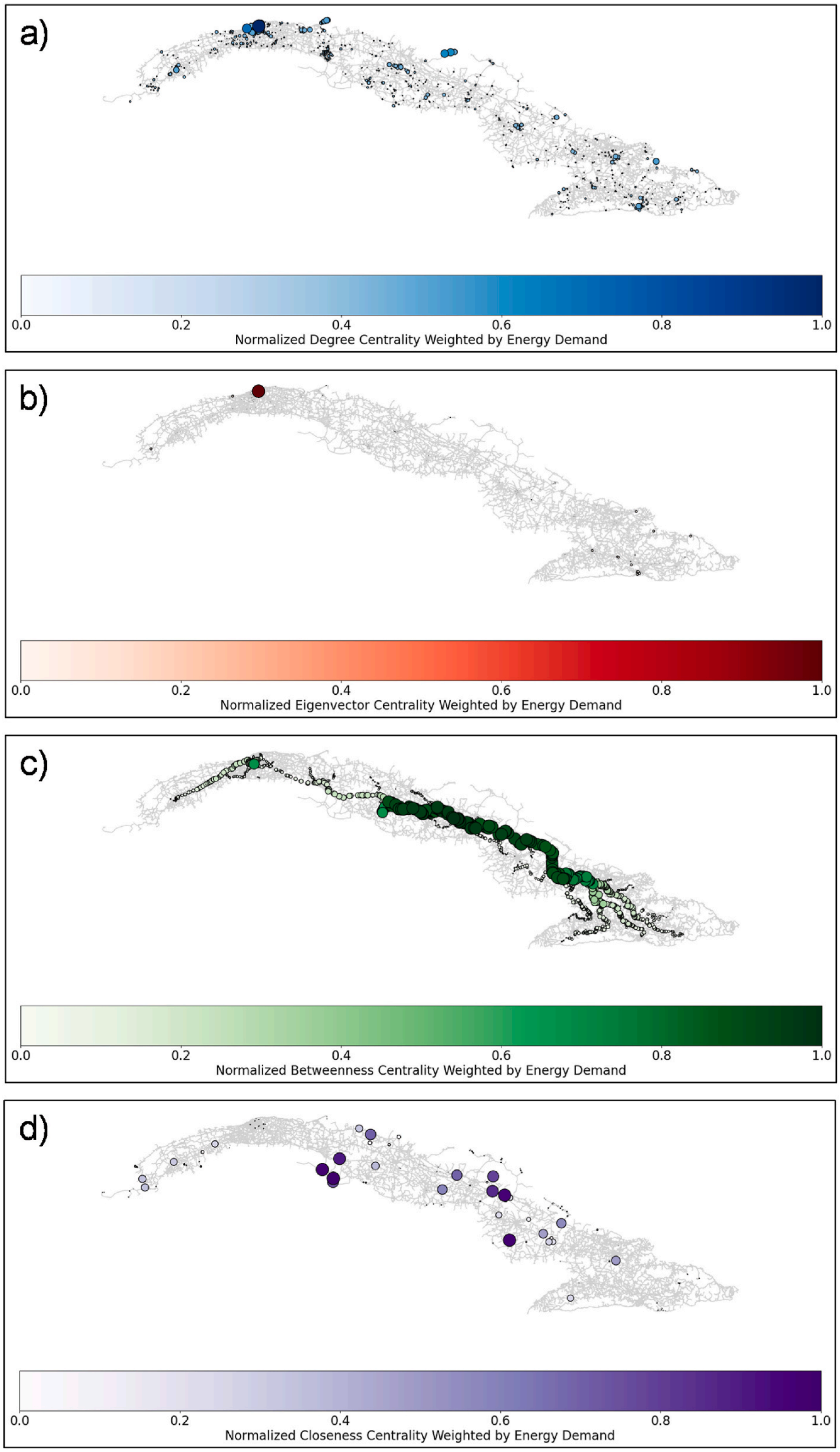

Fig. 6. Normalized centrality metrics weighted by energy demand: a) Degree; b) Eigenvector; c) Betweenness; d) Closeness. Larger node size indicates higher metric value.

also contribute to the broader grid, turning a potential cost into an economic advantage.

The storage capacities, as determined by the requisite installment of 250 kW Li-ion batteries, exhibited varying demands across the analyzed scenarios. Under AS1, a higher demand was observed, requiring 150 units of the 250 kW batteries. The cost optimization results show the AS2 system recorded a slightly reduced requirement, with 138 units of such batteries. Because the capital cost of battery is high and the model minimizes cost instead of investing more in battery storage, the model chose to buy excess electricity from the central grid. That is the reason

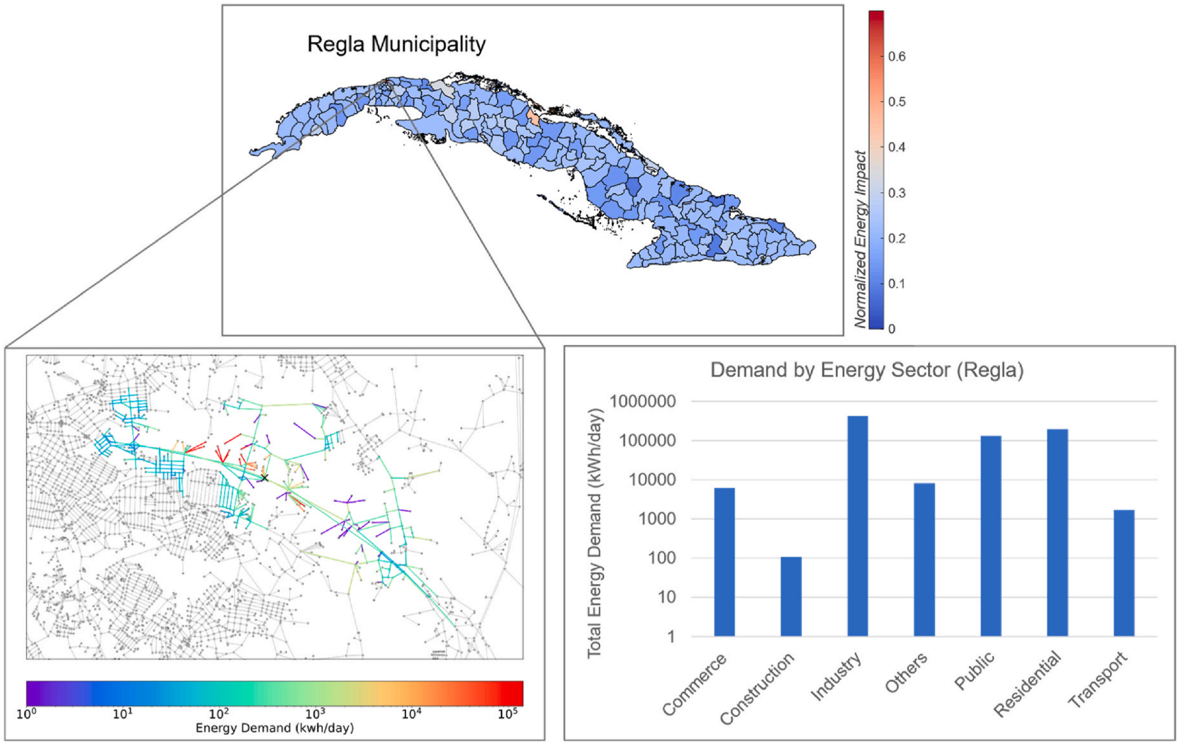

Fig. 7. Selected municipality and corresponding disruption analysis results, highlighting Regla in Havana city. The top figure shows the distribution of normalized disruption impacts per municipality. In the bottom left figure, the most disruptive node is marked with an 'X' and the colors represent neighboring demand links. The distribution of total demand per sector is displayed in the bottom right figure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

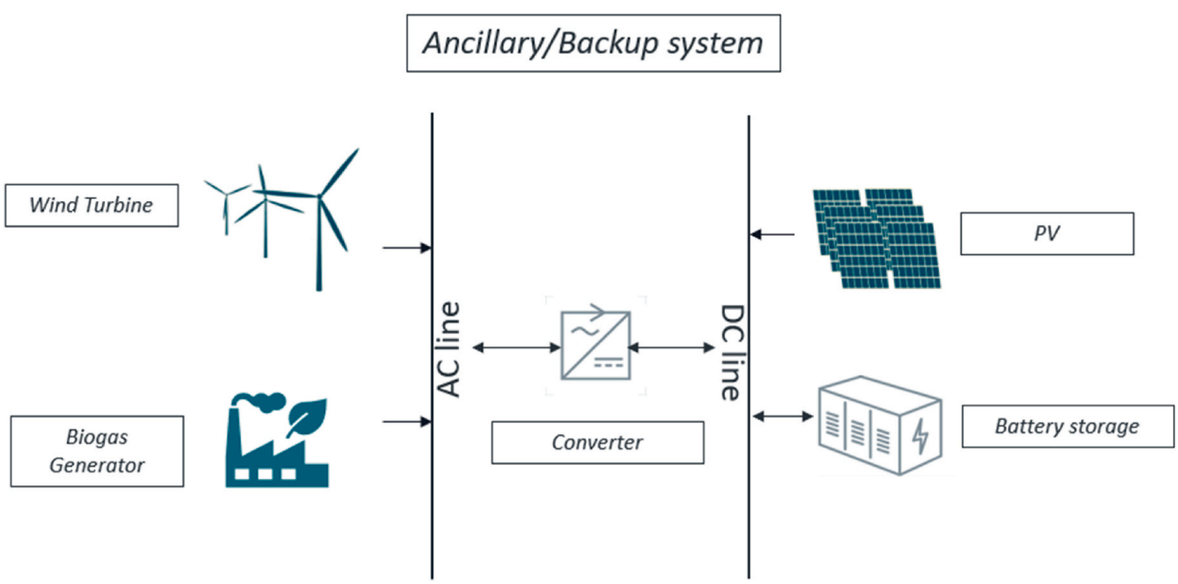

Fig. 8. Energy system architecture.

why AS2 scenario purchased 32 GWh more electricity per year when compared to AS1 to manage the supply side. The model results of BS1 and BS2 scenarios shows that each required for 37 units of the 250 kW batteries. The key takeaway is the importance of balancing initial investment in battery storage against purchasing electricity from the grid. For Regla, the different scenarios offer varying trade-offs between upfront battery costs and ongoing electricity purchases, highlighting the need for strategic planning in energy management.

3.2.2. *Economic requirements*

In assessing the economic feasibility of different energy systems in Cuba, it's crucial to compare the Levelized Cost of Electricity (LCOE) and capital investment costs against a well-established baseline. This baseline is the current average electricity cost in Cuba, providing a clear reference point. For instance, the Cuban-specific models (AS2 and BS2) show higher costs and LCOE compared to the global benchmarks (AS1 and BS1). Specifically, the capital investment required in Cuba is about 25 % higher than the global average. This significant difference becomes

Table 3
Electricity production and capacity for modelled scenario.

Production (GWh/year)	AS1	AS2	BS1	BS2
PV	283	97	38	43
Biomass generator	0.65	0.98	0.59	1
Wind turbine	583	589	42	24
Capacity in MW	**AS1**	**AS2**	**BS1**	**BS2**
PV	156	53	21	24
Biomass generator	1	0.5	1.5	3.5
Wind turbine	147	148.5	10.5	6

more pronounced when considering the LCOE for the BS2 scenario, which substantially exceeds Cuba's current average electricity price of $120/MWh. Such a comparison raises concerns about the economic viability of the BS models in the Cuban context, especially considering the ability of customers to afford these costs. The disparity in LCOE values emphasizes the impact of regional factors and specific configurations on the financial practicality of energy systems. Thus, when analyzing the suitability of these systems for Cuba, the AS model emerges as a more economically sound option, but the upfront cost is the challenge here. LCOE is one of the important parameters for financial evaluation in choosing and integrating energy systems. The study ensures that the systems are technically feasible and suggests a potential for them being financially sustainable. Table 4 presents the capital cost and LCOE from each modelled scenarios for Regla municipality.

3.3. Power system resilience improvements

The power system resilience improvement assessment is performed for all combinations of scenarios and sub scenarios described in section 2.2.2, The decentralized solutions' potential for improving power system resilience is evaluated based on the metrics such as supplied load, unmet load, and number of people affected. The metrics evaluated in the absence of a disruptive event are marked as BAU, and the metrics evaluated in the presence of a disruptive event are marked as DIS. The results of the power system resilience can be seen in Fig. 9.

The decentralized solutions result in higher supplied loads and reduced unmet loads in the BAU cases, for both AS and BS. Notably, they lead to greater improvements of supplied load in the presence of a disruptive event compared to the absence of such an event. The greater improvements correspond to 66 % and 56 % increases in supplied load between DIS and BAU in AS1 and AS2 respectively. For the BS, the improvements in DIS are 12 % and 9 % higher than in BAU in BS1 and BS2 respectively. It should, however, be noted that even with the greater improvements in a disruptive event, loads will remain unmet. This indicates that decentralized solutions can be effective in improving power system resilience for the Regla power system on a BAU-basis, and particularly effective for the purpose of improving power system resilience during disruptive events.

Comparing AS1 and AS2 shows no difference in potential power system resilience improvements in the BAU case. In the presence of a disruptive event, however, the supplied load is lower, and the unmet loads are greater under the influence of the Cuban Average Scenario compared to the Global Average Scenario. An unmet load of 13 MWh/day remains in AS2, compared to an unmet load of 3 MWh/day in AS1. With BS, unmet loads will remain in all cases. In BAU, unmet loads are marginal. In DIS, they however remain at 56 MWh/day in BS1 and 59 MWh/day in BS2. This suggest that the specific conditions of Cuba, modelled as higher average costs of renewable energy technologies in our analysis, might impede the potential for using decentralized solutions to improve power system resilience.

Without decentralized solutions, for both AS and BS, the number of people affected in BAU is zero, whereas DIS would leave 12 664 people without power over a day. Here, adding power supply from decentralized solutions could potentially eliminate the number of people affected. Assuming that the power generated by the solutions is distributed equally among the residents in Regla municipality, a minimum average power supply of 2.29 kWh/day/person could be provided in AS1 and a minimum average of 2.00 kW/day/person in AS2. With BS, a minimum average of 0.69 kWh/day/person could be provided in BS1. The corresponding number for BS2 is 0.58 kWh/day/person. This demonstrates that the systems provide a varying degree of improvements of electricity supplied to residents during a disruption.

Table 4
Economic output for modelled scenarios.

Economic parameters	AS 1	AS 2	BS1	BS2
Capital cost (Million US dollars)	404	426	61	86
LCOE ($/MWh)	9	34	107	155

4. Discussion

Our assessment allowed the identification of Havana city and, more specifically, Regla municipality as the most vulnerable hotspots in case of disruption for energy demand in multiple sectors. Disturbances in this area could potentially cause the largest cascading failures in the electric power system. This is due to predominant demands from commercial and industrial buildings. Prioritizing investments in solutions in this geographical location can lead to significant economic benefits, since it would meet the needs of critical sectors, increase productivity and consumption, and improve infrastructure in a dense urban environment. Even though this applies to the Cuban context, the proposed network-based approach in this study is generalizable to other data-scarce IS, since the required inputs are readily accessible from high-level open source and governmental databases.

The results from the power system resilience assessment indicates that both AS and BS can lead to improvements of power system resilience, considering local socio-economic constraints. In all analyzed combinations of scenarios, AS bring greater improvements in the occurrence of a disruptive event compared to in the absence of one. Such differences in improvements are not as discernible for backup systems. This suggests that ancillary system solutions can be more efficient for the purpose of improving power system resilience against power system disruptions. At the same time, ancillary systems involve greater investment costs, suggesting that trade-offs need to be made when choosing a set-up. The BS scenarios leave more loads unmet compared to the AS scenarios, particularly during disruptive events. This suggest that system dimensioning can be particularly important for backup system set-ups. Most countries, including islands, tend to have more traditional centralized energy systems. However, these centralized systems are nevertheless prone to disruptions from natural disasters. Our analysis overlooks vulnerabilities in AS and BS, assuming they can withstand hazards comparatively. Decentralized systems like AS and BS offer enhanced resilience by distributing power generation, minimizing the impact of any single failure point [56]. Thus, while the assumption neglects vulnerabilities, the decentralized nature of AS and BS help mitigate risks, ensuring a continuous power supply despite potential hazards.

From a discussion with a Cuban expert, it is understood that decisions on renewable energy adoption are dictated by local conditions and the embargo's influence on the available technological choices. Primarily, solar panels emerge as the predominant choice of the Cuban government, due to their economic viability and operational efficiency. Wind energy, while showing potential, is largely localized to the northern coastal regions, attributed to favourable wind patterns. A wide use of wind energy is, however, limited by the technology's high costs and varying effectiveness in different places. At the same time, although studies show that Cuba has great potential for biomass energy, it hasn't become a main energy source yet.

According to the expert, inhibiting factors include not only

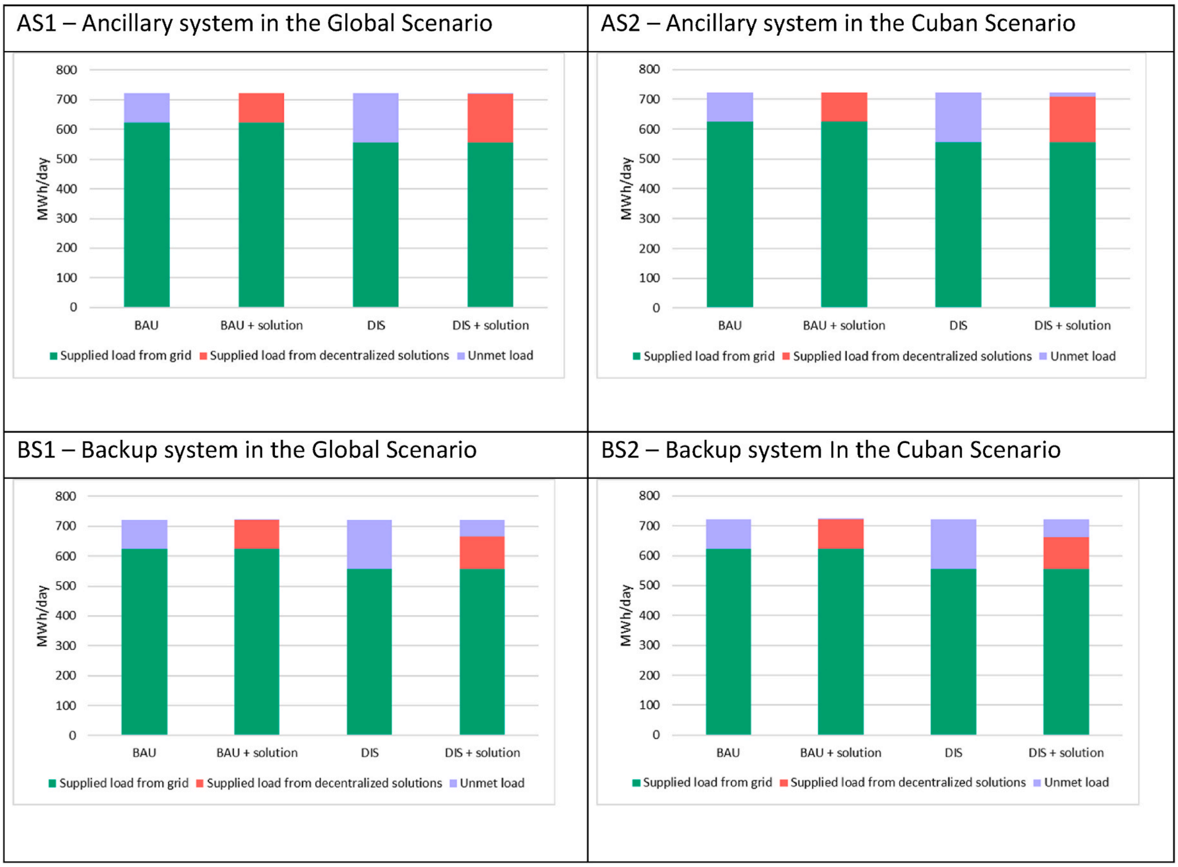

Fig. 9. Evaluated power system resilience metrics in terms of supplied load and unmet load for AS1 (top left), AS2 (top right), BS1 (bottom left) and BS2 (bottom right).

considerable capital and operational expenditures but also specialized labour force needed for this. Some international firms are pioneering research to recalibrate biomass as a cost-competitive renewable alternative for Cuba. Such efforts hold the potential for cost-effective biomass deployment in the future. Currently, biomass represented a very small share of energy production in the modelling results compared to the island's potential.

Expert indicated that energy storage, particularly through battery technologies, is currently in a preliminary phase of evaluation in Cuba and certain regions have initiated pilot tests; however, the associated costs, which are approximately 2–3 times higher than the global average cost, pose significant challenges to their large-scale integration into the Cuban energy infrastructure. In this case, battery energy storage is currently not seen as an option for Cuba's energy system, because of its high investment cost and challenges in importing batteries.

Also, the expert mentioned that the Cuban government is trying to reduce the renewable deployment costs; therefore, they try to find cheap PVs. Currently, China is the main renewable technology supplier of PV and wind turbines to Cuba, as Cuban actors perceive more favourable financial and business terms between the two nations than with other potential partners, including a one-year return period on investments, however, global interest in Cuba's energy sector is intensifying. Ongoing negotiations between the Cuban government and international state and private entities highlight future collaboration. Such collaborations promise not only technological advancement but also the potential for more affordable renewable technologies in future. Moreover, efforts are underway to draft a comprehensive 2050 roadmap aimed at decarbonizing the Cuban electricity sector.

There are nevertheless several limitations with the study. For example, the assessment does not consider hazard occurrence due to the lack of sufficient data. It is implied that every demand node in the simulated electricity grid has the same probability of failure, but our assessment overlook the fact that infrastructure in areas prone to extreme weather events like hurricanes or thunderstorms is more vulnerable to flooding and other disturbances, leading to energy supply outages. Model results do not take into consideration the geopolitical realities of Cuba but optimizes purely based on cost and efficiency metrics. Therefore, the model leans towards wind energy and battery storage. We see this a limitation in our study and the future studies should focus more on considering the geopolitical situation of the nation. The model results, despite their limitations, offer valuable insights for guiding Cuba's energy policy by identifying critical areas for investment and suitable renewable energy sources.

In terms of power system resilience improvements, our modelling framework focuses on the grid's ability to withstand power outages caused by disruptions. Other aspects of power system resilience, such as recovery and restoration, are not addressed in this study. Moreover, due to computational constraints, the network method applied offers vulnerability measures from a topological perspective, without explicit consideration of electricity flows from supply to demand nodes. But research advancements show that flow-based approaches offer more realistic depiction of post disruption scenarios [57]. Also, it is important to note that due to lack of data, we had to make certain assumptions based on expert knowledge and opinions, as well as previous research. The synthetic power network was generated from transportation data and may not accurately represent the actual network. Here, our study's limitations include a small interview sample, with one expert, and limited fieldwork duration, coupled with communication challenges in Cuba, which impeded a more extensive data collection process. Nevertheless, we strived to ensure the accuracy and reliability of our results by cross-referencing data from multiple sources and utilizing established data collection methodologies in the field.

Insights from the expert interview suggest that current energy infrastructure planning approaches tends to prioritize projects that stimulate socio-economic development. Following their approach, Regla municipality would not be deemed as a relevant study area for building out energy infrastructure. This misalignment of approaches and priorities highlights the need to involve energy infrastructure planners in power system modelling for future models to better reflect the reality. At the same time, Regla municipality was identified in this study as the municipality most vulnerable to power system disruptions and cascading effects, that could benefit from decentralized infrastructure reinforcements. This indicates that there is a value for infrastructure planners to include socio-economic development with considering the energy vulnerabilities in the municipality in their planning approaches.

5. Conclusions

The purpose of this study was to introduce a modelling framework for designing cost-efficient decentralized energy solutions to enhance power system resilience in island state settings. To do so, we proposed a framework that integrates a vulnerability assessment, through network analysis, with the design of decentralized energy systems under different scenarios, using HOMER Pro, and an evaluation of the designed system using performance-based power system resilience metrics. This was applied it to a case study for Cuba.

Regla municipality was identified as the most vulnerable geographic area based on multi-sectorial energy demands in Cuba. It was deemed most vulnerable due to its combination of high centrality metrics values and a high concentration of electricity demand affected by cascading failure. However, Regla is not a priority for improving energy infrastructure by local planners.

The designed decentralized energy systems, show that Ancillary system (AS) mainly comprise a mix of solar PV and wind turbine capacity installments, complemented with a minor share of biomass energy capacity. BS mainly rely solar PV capacity installments, with a smaller share of wind, and a higher share of biomass capacity compared to AS. Generally, using Cuban specific technology cost data resulted in a higher reliance on wind capacity in AS and higher reliance in solar PV and biomass capacity in BS, compared to when using global average cost data. A power system resilience assessment of the designed decentralized systems, indicate that both AS and BS can be effective in ensuring an electricity supply with least possible interruptions. In particular, AS demonstrated to be more efficient for improving power system resilience against power system disruptions compared to BS, although trade-offs in terms of investment costs needs to be considered when choosing between the set-ups.

The analysis of the system scenarios with the techno-economic results provides valuable insights into the performance and viability of different energy system configurations. In analyzing the energy system scenarios, it becomes clear that the choice of technology is deeply influenced not just by its potential, but by strategic economic considerations. The longstanding US embargo on Cuba has posed considerable challenges in procuring renewable technologies, leading to increased costs. These heightened expenses, play a pivotal role in shaping scenario projections.

This approach will help ensure a more reliable and sustainable energy supply, mitigating the impact of potential disruptions and external factors that could affect the region's energy security. Ultimately, the integration of renewable energy sources into the decentralized grid system will contribute to Cuba's overall efforts towards a more sustainable and robust energy future. This analysis enables informed decision-making on technically feasible, renewable and cost-effective decentralized grid systems for enhancing energy resilience.

While Cuba has served as an insightful case study, it is crucial to emphasize that the methodology we have developed extends well beyond the boundaries of this island nation. The approach proposed in this study is generalizable to other IS with similar energy challenges tailored to their unique circumstances, as many of the input data case be sourced from open-source and government databases. This adaptable framework provides a path to a sustainable and resilient energy future that transcends geographical constraints. Our study not only addresses a critical research gap but also provides a practical solution to a long-standing issue faced by many island nations. IS often contend with energy insecurity, high costs, and environmental vulnerability due to their isolation and limited resources. Our model bridges the gap by offering a customized approach that takes into account the specific energy demands and conditions of these islands. This customization involves a detailed analysis of factors such as the unique geographical layout, climate conditions, and energy consumption patterns of the islands. While our approach is tailored for island contexts, it also offers valuable insights and methodologies that could be adapted and applied to mainland locations with similar characteristics and challenges.

Future research should explore aspects related to the prevention of energy outages in island settings through climate adaptation measures and reflecting the geopolitical situation. Investigating the application of nature-based solutions in combination with decentralized energy systems can enhance resilience by preventing or mitigating the impacts of natural hazards. Emerging machine learning techniques and remote sensing could be utilized to generate insights about natural hazards, infrastructure degradation and energy outages in Island States, as well as generate insights on what role decentralized solutions can play in terms of recovering from an external shock and restoring a degraded power system.

CRediT authorship contribution statement

Gowtham Muthukumaran: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Marlon Vieira Passos:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Jindan Gong:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Maria Xylia:** Supervision, Conceptualization, Writing – review & editing. **Karina Barquet:** Supervision, Conceptualization, Writing – review & editing, Project management, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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