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Sustainable urban transformations based on integrated microgrid designs

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The impacts of natural hazards on infrastructure, enhanced by climate change, are increasingly more severe emphasizing the necessity of resilient energy grids. Microgrids, tailored energy systems for specific neighbourhoods and districts, play a pivotal role in sustaining energy supply during main grid outages. These solutions not only mitigate economic losses and well-being disruptions against escalating hazards but also enhance city resilience in alignment with Sustainable Development Goal (SDG) 11. However, disregarding socioeconomic factors in defining microgrid boundaries risks perpetuating inequalities and impeding progress towards other SDG 11 targets, including fair democratic participation. Our approach integrates social and technical indicators to bolster urban microgrid planning. Through a case study in a US county, we illustrate how integrated microgrid planning effectively intertwines urban resilience, well-being and equity while promoting sustainable development. This study underscores the importance of integrated microgrid planning for sustainable and resilient urban transformation amid environmental and societal challenges.

The global climate crisis, highlighted by critical infrastructure damages and power disruptions from natural hazards[1], has severely impacted the well-being of urban populations worldwide. Power outages pose especially severe consequences, particularly impacting vulnerable populations[2–4] and revealing varying impacts across households[5–9]. Climate change-induced heatwaves and hurricanes underscore the urgency of comprehensive preparedness for cities. Moreover, cities grapple with the complex challenge of achieving economic productivity, social inclusivity and environmental sustainability.

In view of these challenges, in many world regions further aggravated by substantial urban informal settlements[10], a shift towards decentralized renewable energy systems[11] has brought the concept of so-called microgrids to the forefront. Microgrids[12,13] are small, localized energy systems that can generate, store and distribute energy independently or in conjunction with the main energy grid. In this context, community power storage systems are gaining relevance[14] and can serve as nuclei for microgrids in urban areas, offering potential interconnection possibilities[13,15,16].

As a conclusion, microgrids potentially prevent critical service disruptions due to power failures and enhance urban resilience while laying the foundation for local energy communities and innovative energy democracy models[17–19].

However, threat scenarios for urban utilities extend beyond natural hazards and physical damages to include cyber attacks[20,21], illustrating that even microgrids can fail. This is a widely overlooked aspect in microgrid planning, which this study considers. Furthermore,

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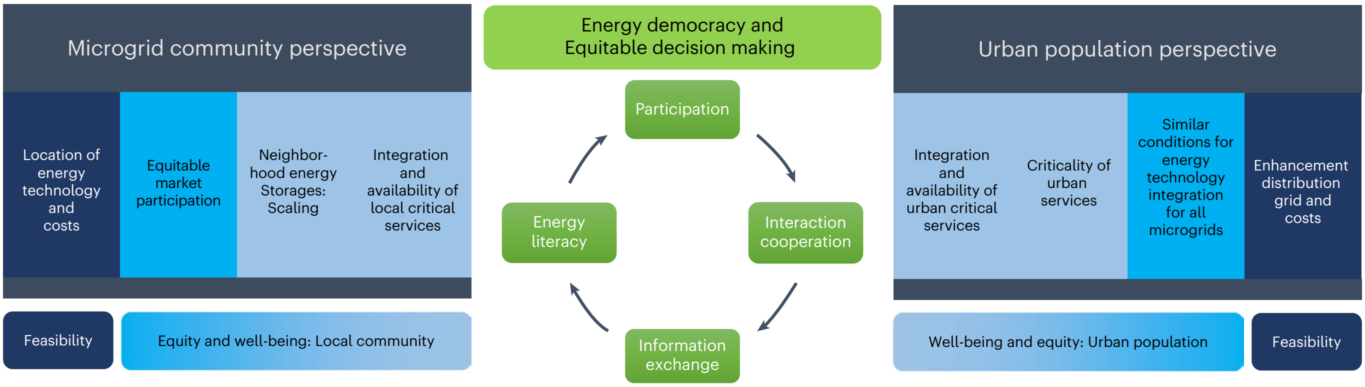

Fig. 1 | Fostering interaction, a cornerstone for inclusive microgrid communities. A participatory approach to enhance microgrid sustainability and well-being involves ongoing community and urban-level assessments. These assessments consider criticality and social vulnerability, culminating in a clear understanding of current needs and technology investments. Fostering interaction among social groups within local communities promotes information exchange, enhances energy literacy and drives increased participation.

most research on microgrids primarily focuses on economic feasibility, market designs[22] or purely technical infrastructure resilience[23,24], neglecting their long-term impact on urban resilience, well-being and equity. Consequently, this study addresses the following fundamental question in the context of planning urban clean energy systems:

How can urban microgrid design consider high levels of urban resilience and well-being with respect to multiple future hazards while considering fair democratic and equity-based decision-making processes?

Strategies recommended for household well-being during outages include addressing sanitation disruptions, prioritizing children's needs and incorporating paediatric mental health services[9]. The literature emphasizes a tailored approach prioritizing essential services to meet household needs[7,25]. Despite the pivotal role of microgrid planning, current approaches often lack an integrative assessment of the social burden related to critical service availability and citizen participation[17,25]. Urban governance, rooted in the Capability Approach pioneered by the Nobel laureate Amartya Sen, emphasizes equity and resilience, especially during disasters[2,26,27].

Furthermore, a major limitation in contemporary microgrid planning is the concentration of numerous critical services within individual microgrids[17]. If these microgrids fail, it would cause considerable burden, contrary to the primary objective of mitigation. Addressing these multifaceted issues from a microgrid planning perspective necessitates a comprehensive and inclusive approach, considering underlying social disparities and vulnerabilities[26]. Our study contributes to the research and policy discourse on sustainable urban transformation, emphasizing the need to account for a range of new hazards, irrespective of their current relevance, and the need for integrated policies to enhance urban resilience and overall well-being.

Building on the imperative of an inclusive approach and the consideration of well-being in urban microgrid planning, it is crucial to underscore the necessity for equitable participation in democratic processes within socioeconomic groups[28]. The concept of 'energy democracy' offers a promising avenue through various participatory mechanisms, allowing local populations the 'right to the city' and involving them in microgrid decision-making. This encompasses economic, societal, technical and legal aspects, emphasizing considerations such as profit optimization versus societal contribution, microgrid financing and energy technology selection[28–31]. Considering the districting of urban microgrids, determining the right number and boundaries of microgrids is crucial for the fair representation of social groups within microgrid communities. However, the literature often overlooks the diverse composition of these groups as a factor for fostering equitable participation. In conclusion, while participatory formats are essential for energy democracy, careful consideration of 'who is in or out' is needed to avoid inequities and the potential risk of 'energy gerrymandering' akin to partisan gerrymandering[32], where votes are lost due to the way constituencies were defined, favouring one political party over others, thereby influencing election outcomes. This highlights the role of informed decisions on microgrid districting to ensure equitable outcomes. Hence, in the pivotal initial phase of urban microgrid districting, we advocate for a collaborative approach involving local governments, city planners, critical service providers and communities[33]. Urban leaders and community representatives can engage in so-called focus groups, fostering discussions with local governments to devise equitable solutions on an urban scale[34]. This collaborative endeavour seeks to enhance socially informed planning and active participation. By doing so, it aims to elevate energy literacy, fostering a deeper understanding of microgrid dynamics and empowering citizens to make well-informed judgements related to energy democracy[35–37].

Our optimization study, conducted for New Hanover County, North Carolina, provides a transferable solution for microgrid districting. We first present a framework that mitigates the risk of 'energy gerrymandering' and promotes the understanding of basic needs of urban populations. By applying socially informed indicators that incorporate the Social Vulnerability Index[38], the criticality of basic services as well as potential locations of energy technologies within microgrids, our study reveals cost-efficient, urban-resilient and equitable microgrid solutions to diverse threats encompassing both natural and man made, including cyber attacks. These solutions contribute simultaneously to clean energy access (SDG 7.1), income growth (SDG 10.1), basic services access (SDG 11.1), reducing the number of affected people due to disasters (SDG 11.5), mitigation, for example to climate change (SDG 11.b), and participatory urban planning (SDG 11.3)[39]. With a focus on these SDG targets, we provide a comprehensive overview of the innovative indicators and optimization approach in the Methods section.

Results

Our study conclusively supports a positive response to our primary research question. Through the specific case of New Hanover County, we demonstrate that participation, integrated decision-making and planning are instrumental in achieving equity-based and urban-resilient solutions.

Equitable participation and decision making

Our main findings rely on the fundamental observation that, very similar to electoral constituencies in politics, there exists a phenomenon,

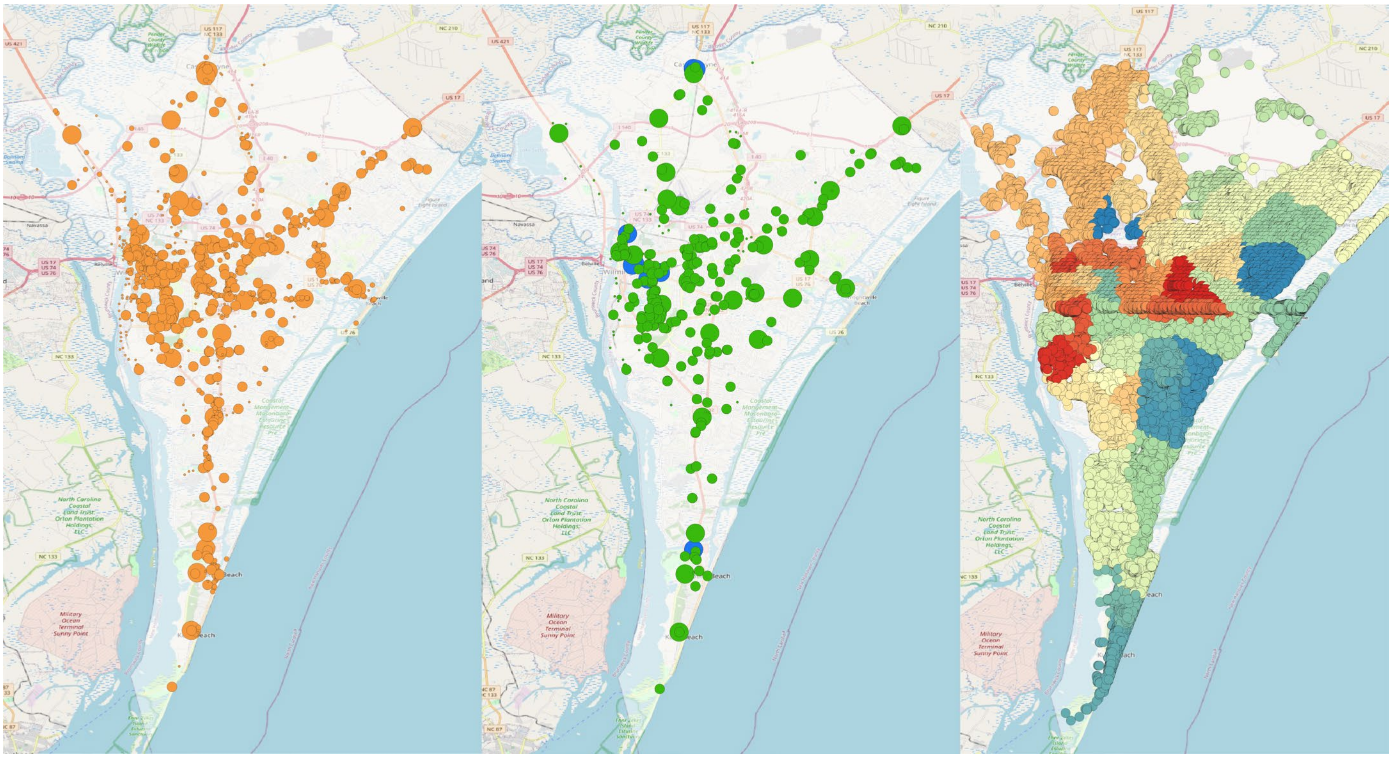

Fig. 2 | Criticalities and social vulnerabilities. Left: criticalities of all critical infrastructures in New Hanover County, assessed via stakeholder survey; the larger the dots, the more critical the infrastructure. Centre: only RHS infrastructure; the blue dots are so-called community lifeline facilities. Right: vulnerabilities of households depending on socioeconomic status and mobility constraints derived from the Social Vulnerability Index, from green (less critical) to red (highly critical).

which we label as 'energy gerrymandering', where voices are systematically lost. In our study, microgrid districting, similar to the delineation of electoral borders, strives to establish fair and balanced 'energy constituencies'[28].

The comprehensive assessment of essential service needs, household criticality and resilience factors largely hinges on the active involvement and contribution of local communities and urban participation (Fig. 1). Planning urban microgrids must consider the possibility of outages affecting critical services at both city and municipal levels, hence decision-making processes in a city must entail assessing social vulnerabilities, household needs and the criticality of critical services (Fig. 2). Practically, community leaders represent communities and relay local needs and views to local government, identifying infrastructure criticalities and vulnerable group needs; ongoing assessments adapt to changing vulnerabilities and needs to strategically place new critical and basic services[2,8,17,40,41], supporting the achievement of SDG target 11.1 (Ensure access to basic services for all) and SDG target 11.5 (Reduce the number of people affected by disasters).

In the long term, promoting equitable participation within microgrid communities enhances energy literacy and ensures fair decision-making, especially benefitting the vulnerable groups[42]. Moreover, fair microgrid districting can safeguard against exclusion, ensuring that all social groups, particularly the vulnerable, can engage in the microgrid development process without large hindrances[42].

Through a 'learning by doing' approach[43], there is huge potential for energy literacy to increase naturally as all social groups engage (Fig. 1). Conversely, if minorities reside within microgrids, their participation and inclusion may be systematically limited. This can occur as coalitions of different social groups may dominate decision-making processes, potentially excluding socially vulnerable minorities, despite democratic principles. Such limitations on participation and inclusion can undermine the fairness of decision making, thereby impacting SDG target 11.3 (Enhance inclusive and sustainable urbanization).

To foster fairness in urban microgrid planning, our proposal involves assessing equity in the spatial layout of microgrids in terms of understanding the representation of socially vulnerable groups by considering specific factors tailored to planned microgrid layouts. Avoiding highly uneven distributions of these groups within microgrid districts mitigates the risk of 'energy gerrymandering'. We use the Social Vulnerability Index[38] from 2018 (Fig. 2, right) in our case study for New Hanover County, providing a positive answer to our research question (Fig. 5).

Inclusive decision-making within local microgrid communities goes beyond assessing criticality, household vulnerability and service needs. It also encompasses critical considerations such as ownership of local solar power systems, optimal locations for neighbourhood energy storage and equitable distribution of emergency energy resources during crises. Discussions should also address equitable surplus energy utilization, whether through market sales or supporting low-income households, and reinvestment of potential local profits into further energy district development. These multifaceted and integrated decisions empower communities to shape resilient and sustainable urban energy systems in the long term, effectively promoting SDG 11.b (Integrated policies and plans for urban resilience).

Sustainable futures based on well-being and resilience

To identify future-proof and resilient urban microgrids, we examine a wide range of potential threats. This encompasses natural disasters affecting physical infrastructure and microgrid failures, such as those induced by cyber attacks. We term this composition of potential future threats as our baseline scenarios.

In our specific case study, the baseline scenarios involve variations in physical damages and resulting power outages, inspired by

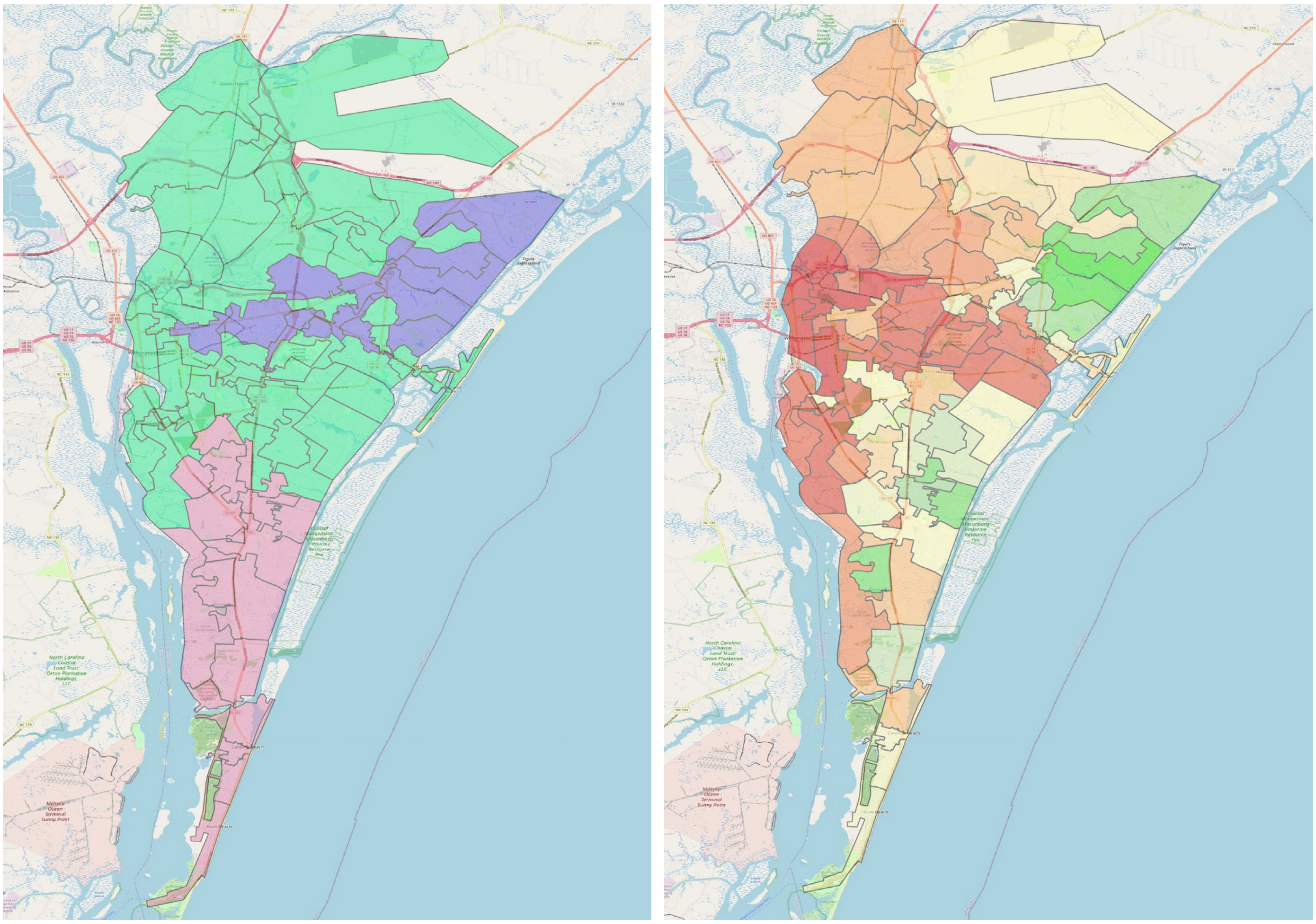

Fig. 3 | Microgrid districting and well-being losses. Left: some microgrid districting with three microgrids. Right: accumulated impact on well-being. Due to power outages, which lasted longer than 8 hours. Here, loss of nutrition and basic services (heat, tap water) that restricted availability of RHS infrastructure in conjunction with low socioeconomic status of households (with respect to the census data of 2018) are considered; darker red indicates higher well-being losses. This was done with a Monte Carlo simulation based on the characteristics of the baseline scenarios including microgrid failures and physical damages.

the impacts of Hurricane Florence. Hurricane Florence was a severe and prolonged hurricane that caused catastrophic damage in the Carolinas in September 2018. In particular, high winds in New Hanover County caused numerous trees and power lines to fall, leaving more than 90% of the county without power[44]. We also account for potential microgrid failures. Given that microgrids rely on existing distribution grids, damages akin to those caused by Hurricane Florence would impact microgrids similarly. This impact results in diverse combinations of damage coupled with microgrid failures, forming the baseline scenarios for our case study.

Similar to the social burden described in refs. 17,40, we relate well-being to socioeconomic status and proximity of functioning immediate post-shock critical services, especially those that are related to relief, health and security (RHS). In finer detail, our concept of well-being establishes a connection between, on the one hand, low socioeconomic status, substandard housing conditions and mobility constraints, as gauged by the Social Vulnerability Index, and, on the other hand, reduced accessibility of currently functioning RHS infrastructure. Evaluation of well-being losses for a given microgrid districting is visualized in Fig. 3. With regard to the baseline scenarios, we say that a particular microgrid districting increases urban resilience more than another if the loss of well-being is relatively lower.

In conclusion, these baseline scenarios establish the foundation for planning resilient urban energy systems within a multiscenario framework. They highlight damages and their immediate effects on the population, thereby specifically addressing SDG target 11.b (Climate change adaptation, disaster resilience) at the local level. As an interim result, the fact that individual microgrids can fail makes it clear that the risk for lack of well-being and urban resilience in a city can be reduced with the use of multiple microgrids instead of one. These points are ultimately confirmed by our study (Fig. 5).

Designing sustainable and integrated urban microgrids

Managing a few neighbourhood energy storages tends to be less vulnerable and more stable than managing a large number of distributed batteries[45,46] in individual households, infrastructure or business corporations. In addition, we operate on the assumption that the majority of RHS infrastructure lacks independent backup power, except for hospitals, which widely corresponds to the current situation. Moreover, it is important to note that numerous households might face financial constraints preventing them from installing personal energy storage. We also explore the potential of urban renewable energy generation, such as utilizing rooftops for solar power[47] (Fig. 4, left). This approach allows solar energy to contribute to filling neighbourhood energy storages or powering critical loads[48] in smart grids.

Thus, methodically incorporating neighbourhood energy storages into the creation of economic, equitable and resilient microgrids within urban or community settings aligns not only with the targets of SDG 11 but also with SDG 7 (Affordable and clean energy), which aims to ensure universal access to sustainable and clean energy for all. These storages

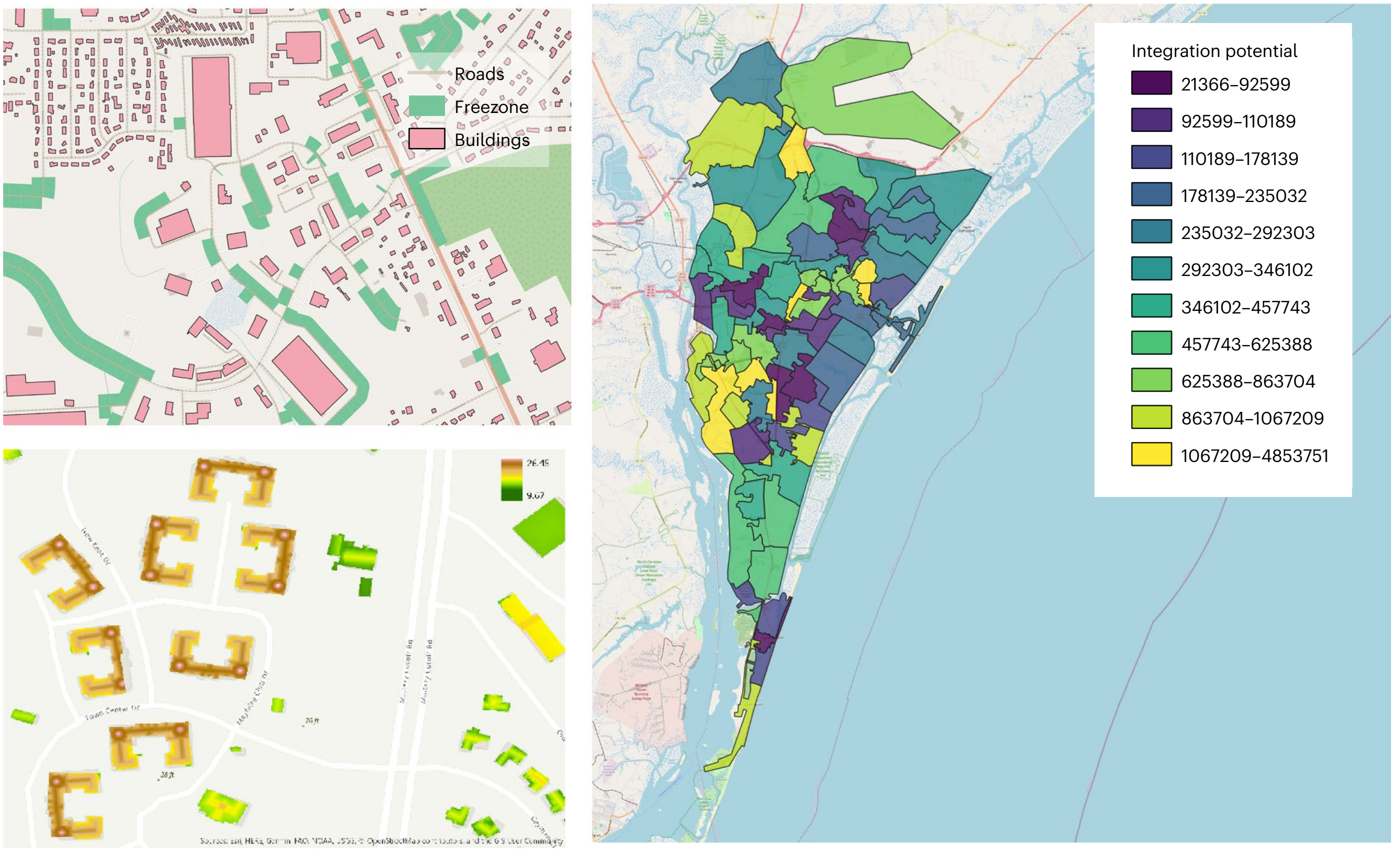

Fig. 4 | Spatial analysis for energy technology integration. Top left: buildings (pink) and empty areas with building permits (green); this is important for questions related to energy storage integration. Bottom left: raster information on the rooftop geometries coming from LiDAR datasets as a base for assessing the potential for photovoltaics installations on roof tops. These data allow identifying azimuth and thus the photovoltaic potential of rooftops. Right: there exist 64 medium voltage circuit boundaries and within each, the potential for integrating neighbourhood energy storages in unbuilt area is displayed in square metres; the same was done for photovoltaics installations on roof tops.

play a pivotal role in achieving practical and dependable microgrid management. A crucial factor for implementing neighbourhood energy storages is the availability of space (Fig. 4, right), contingent on the type and size of the storage. While spatial conditions vary across the built environment, maintaining consistency in the siting potentials and renewable energy capabilities from one microgrid to another is essential when integrating neighbourhood energy storages. This not only ensures practicality but also safeguards urban equity and promotes equal development opportunities within microgrids at the local level, thereby contributing to SDG 10 (Reduce inequality), particularly target 10.1 (Achieve and sustain income growth for the bottom 40 percent of the population). Balancing the integration potential of neighbourhood energy storage and photovoltaics between the microgrids is another aspect that we consider in equity-based microgrid districting (Fig. 5).

In microgrid districting, we estimate costs by assuming that microgrids are technically developed using existing distribution grid structures, inherently a cost-efficient approach. In our case study, beyond the costs for technical equipment of microgrids[17,49], we also consider how medium voltage circuits can be fed from multiple substations and interconnected.

Towards energy resilience and equity

This study links urban resilience with post-catastrophe declines in well-being, with a focus on power outages in cities, within the framework of equity-based and clean energy system planning. Our concept for urban-resilient microgrid districting applies infrastructure and household criticality (Fig. 2, right), depending on socioeconomic status and mobility constraints derived from the Social Vulnerability Index (2018).

A guiding question in our study for urban-resilient microgrid districting concerns the consequences for well-being in the aftermath of a disastrous event or during an energy failure, thereby focusing on the case that single microgrids fail as described in our baseline scenarios. The following basic observations are quite intuitive and form a basis for the assessment of the impact of microgrid districting on urban resilience applied in our optimization study:

1. Concentrating critical infrastructure in single microgrids can lead to simultaneous failures of essential services during microgrid outages, impacting urban well-being substantially more strongly compared with scenarios with lower concentrations of such infrastructure.
2. When many vulnerable households are concentrated in a single microgrid, urban well-being drops considerably if basic services fail during a microgrid outage, especially compared with lower concentration scenarios.
3. Optimally distributing all types of RHS infrastructure across urban microgrids prevents citywide unavailability during a microgrid failure. Districting microgrids in such a way that as many types of RHS services as possible can be found in each microgrid ensures high citywide availability of services even in the event of isolated microgrid failures, thereby increasing well-being.

Addressing (1) and (2), we assess high-criticality and large peak load infrastructure density within microgrids similar to ref. 50. Measuring this assists in identifying microgrid districting with fewer high-criticality infrastructures and large peak loads, facilitating load restoration[51,52] in times of microgrid failure and avoiding concentration

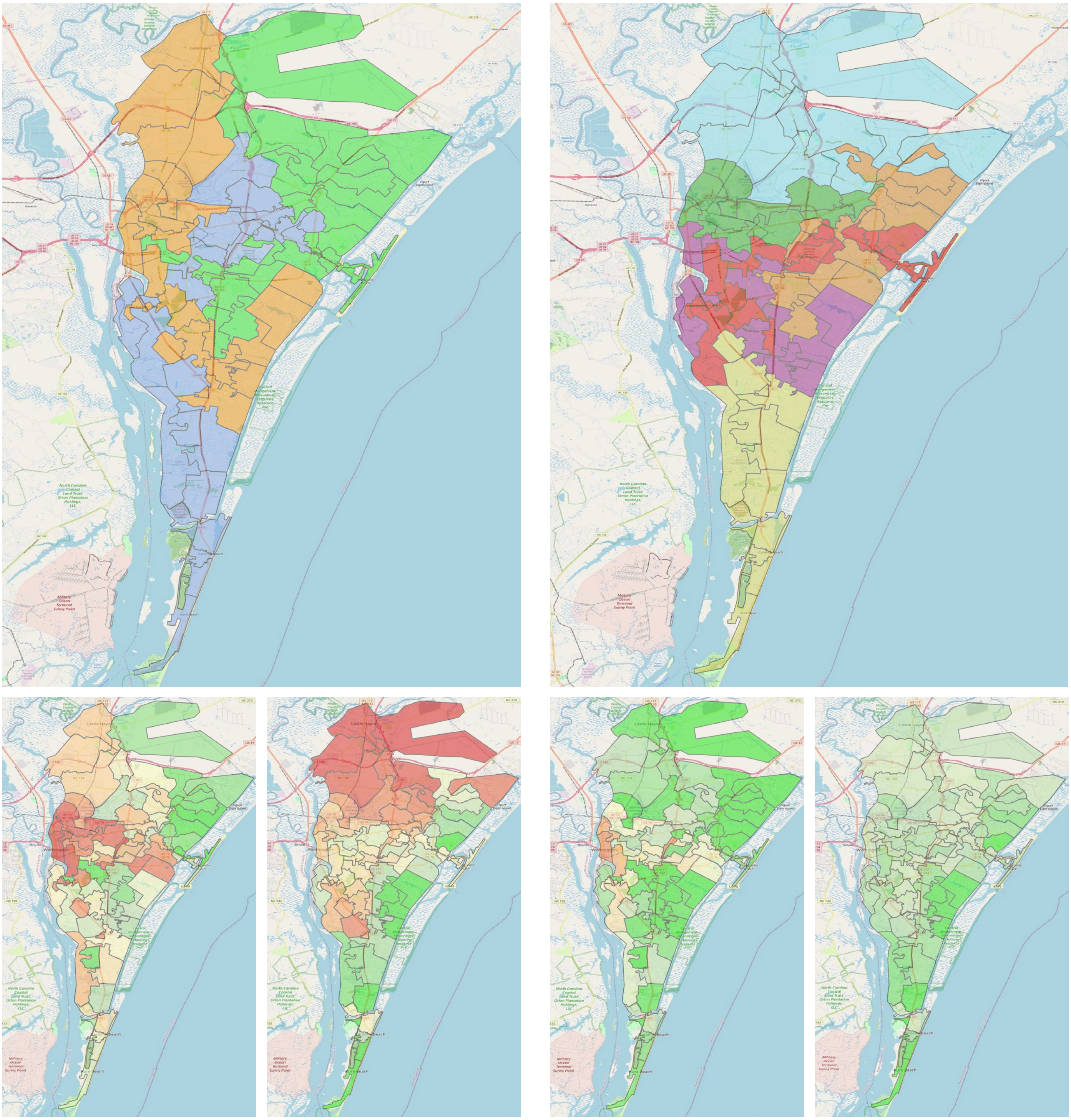

Fig. 5 | Microgrid districting solutions and well-being losses. Top left: example of a microgrid districting, with economic feasibility being prioritized (three microgrids). Top right: microgrid districting solution, where urban resilience, fair democratic participation, equitable distribution of renewable energy and energy storage potentials as well as costs were considered (six microgrids). Bottom: aggregated view of two types of well-being losses (left: referring to socioeconomic status; right: referring to type of housing and transportation) coming from Monte Carlo simulations based on baseline scenarios against the corresponding microgrid districting (top right). Darker red indicates higher well-being losses.

of very critical services in one microgrid. This perspective would favour many microgrids with less critical infrastructure per microgrid to avoid such concentrations.

Referring to (3) and aligning with the 15-minute city concept[53], we argue that each microgrid should ideally host at least one representative for all types of RHS infrastructure. Hence, we measure RHS infrastructure distribution per microgrid. This perspective on microgrid planning would favour larger and thus less microgrids, each accommodating all RHS types, which seems incompatible with the goal of avoiding a lot of very critical services with high peak loads per microgrid, preferring smaller and thus more microgrids, as mentioned above.

Again, based on these considerations and as a quick interim conclusion, an urban-resilient microgrid districting should result in more than one microgrid, because in the case of baseline scenarios with non-functioning microgrids, there is a high probability that residents will be able to access all RHS services despite non-operating microgrids, which would lead to a higher level of well-being.

Our optimization study's key finding involves leveraging the current network structures through the connection or disconnection of medium voltage zones (Fig. 4, right) using switching devices. This process defines microgrid boundaries, emphasizing a cost-effective approach grounded in existing infrastructure.

Considering criticality data and the Social Vulnerability Index, and despite the aforementioned contradictory perspectives, we have identified a microgrid districting solution for New Hanover County answering our research question (Fig. 5). This solution proves to be cost efficient, showcasing minimal well-being losses against baseline scenarios. It also ensures equitable conditions, offering similar potentials for integrating neighbourhood energy storages and rooftop photovoltaics. In addition, it establishes a well-balanced distribution of socially vulnerable groups, mitigating the risk of 'energy gerrymandering'.

In conclusion, our study implies that addressing individual targets in isolation, as infrastructural measures, may inadvertently hinder progress towards other SDG objectives. Nonetheless, we emphasize that there exist urban energy system designs that concurrently promote multiple SDG targets, including clean energy access (SDG 7.1), access to basic services (SDG 11.1), participatory urban planning (SDG 11.3), reducing the number of people affected by disasters (SDG 11.5), promoting mitigation and adaptation to climate change (SDG 11.b), and income growth (SDG 10.1).

Discussion

Microgrids play a pivotal role in enhancing urban resilience; however, their effective implementation involves crucial decisions regarding the number of microgrids to be installed and their districting within urban settlements. If economic considerations are not checked, providers may at early stages of urban microgrid implementation introduce the risk of 'cherry-picking' by prioritizing economically promising urban areas, potentially leading to biased microgrid districting and energy gerrymandering[54,55].

A key implication of our work underscores the necessity for planning based on an integrated analysis, considering the long-term impact of microgrid districting on urban resilience, sustainability and equity. While our case study in New Hanover County provides valuable insights, it is essential to acknowledge that urban situations are highly site specific and often not comparable. In instances where critical infrastructure is dispersed across the city but vulnerable households cluster in peripheral areas, identifying microgrid districts that balance the representation of socially vulnerable groups, prevent energy gerrymandering, and ensure high levels of urban resilience and well-being can be challenging. However, our findings strongly advocate for the integration of sustainable urban development projects with microgrid planning, applicable across diverse contexts, including industrialized countries, emerging economies and developing nations. Even in situations such as those with vulnerable populations in peripheral areas, mentioned above, or with already existing microgrids, our measurements facilitate the identification of optimal locations for integrating new or relocating existing critical services, ultimately enhancing urban resilience and well-being. In developing countries, this can substantially improve access to basic services and thus promote SDG 11.1 in particular.

The varied dataset used in our study was derived from publicly available data on grid infrastructure obtained through a research project in New Hanover County. While this dataset sufficed to illustrate the added value of our integrated approach to microgrid districting, it suggests that, in a planning context involving multiple stakeholders, an improved and more comprehensive database could enhance the accuracy and efficacy of the analysis. Furthermore, advancing the development of inclusive formats that acknowledge diverse needs and cater to varying levels of energy literacy plays a crucial role in fostering more informed democratic decisions within established microgrid communities.

Moreover, there is an urgent need for further exploration and adaptation in characterizing and quantitatively measuring social vulnerability, customizing these approaches to specific local circumstances. Addressing inquiries related to integrating new data sources to assess household vulnerability and refining well-being definitions is crucial for advancing our understanding in this field, as emphasized in previous work[8], which is an integral part of ongoing research.

The growth of energy literacy not only enhances political engagement but also fortifies community and urban resilience[35,36]. In addition, delving into the intricate correlations among Social Vulnerability Index criteria, limitations in adaptive capacity and energy literacy is a focus of current and future studies. This exploration takes into consideration factors outlined in existing research[6,56].

Furthermore, ongoing research is dedicated to refining optimizers capable of efficiently managing heightened complexity, a critical aspect for large-scale urban environments, including big or mega cities. Our proposed approach is universally applicable to the implementation of microgrid projects coupled with sustainable urban development in any city. It facilitates the resilient integration of critical services into existing urban microgrids, emphasizing the importance of thoughtful planning over increased investment in additional technologies.

Methods

The results in this work were developed on the basis of an extensive spatial and infrastructural data, new indicators or metrics that require those data as input, and an evolutionary algorithm for finding optimal clusters. In the following, we describe the data sources, the data used and the metrics for measuring the different aspects and dimensions.

Social Vulnerability Index

The Centers for Disease Control and Prevention Social Vulnerability Index, created by the US Agency of Toxic Substances and Disease Registry's Geospatial Research, Analysis and Services Program, aids public health officials and emergency planners in identifying vulnerable communities during hazardous events[38]. This index assesses the relative vulnerability of US census tracts based on 15 social factors, grouping them into four themes. In this study, we focused on theme 1 (socioeconomic conditions, especially education and income) and theme 4 (housing conditions), crucial for household criticality, using percentiles specific to New Hanover County. The data were derived from the US Department of Energy's project 'Planning an Affordable, Resilient, and Sustainable Grid in North Carolina'[57] focusing on New Hanover County Community and Energy Security, where the University North Carolina at Charlotte (UNCC) is a project partner. This project was extended until the end of 2023. Publications on details will be available in June 2024[58].

Focus groups in New Hanover County

Emergency preparedness in North Carolina involves collaboration between county-level emergency management organizations and the state's Department of Public Safety, specifically the North Carolina Emergency Management agency[59]. The EPIC team from UNCC partnered closely with New Hanover County Emergency Management to enhance resilience following major storms such as Hurricane Florence and Hurricane Dorian in 2020 and 2021[44,60,61]. In the aftermath of Hurricane Florence, which severely impacted the county, an after-action report was prepared by New Hanover County officials in collaboration with focus groups from various Wilmington neighbourhoods[52]. These neighbourhoods, chosen for their high Social Vulnerability households and critical services (Supplementary Material), engaged community leaders to assess past recovery efforts and propose improvements. Focus group discussions focused on sheltering, community feeding, volunteers, fuel and emergency generators, and better inclusion of the faith-based community. The outcome identified potential locations for Community Lifeline Facilities to reduce well-being losses in high Social Vulnerability Index households.

Criticality

Criticality, a relative measure for assessing infrastructure and service provider relevance, ranges from 0 to 1, with a higher value indicating greater criticality[62]. Urban-centric criticality assessments rely on technical analysis methods and stakeholder participation[63]. In New Hanover County, criticalities were identified using focus groups and a direct weighting approach (Supplementary Material).

For household criticality, a range of 0.1 to 0.2 was assigned, with greater social vulnerability impacting preparedness for power outages. Factors in the assessment include socioeconomic status (RPL_THEME1) and housing/mobility (RPL_THEME4), both ranging from 0 to 1 (equation (1)). Original notation from the Social Vulnerability Index (RPL_THEME1 and RPL_THEME4) was retained to avoid misunderstandings.

$$c\,(\text{Household}) := 0.1 + (\text{RPL\_THEME1} + \text{RPL\_THEME4})/20 \tag{1}$$

This equation can use different themes from the Social Vulnerability Index separately, other ways of aggregation or other factors of social vulnerability of households that can be modelled numerically. Also, depending on the relevance of considering household criticality, the interval 0.1 to 0.2 can be adapted.

Since this work was not concerned with the specific technical implementation of microgrids, the potential interconnections among them and energy management issues, but rather with microgrid districting, relative and normalized information on the potential peak load of infrastructure was primarily sufficient (Supplementary Material). We assumed that the relative peak load for households is the same. For all other infrastructure, the information on relative peak load was based on the type and size of the infrastructure, where the information was derived from the NREL GitHub repository[64] containing timeseries on energy consumption (OpenEI Data Lake).

Built environment and photovoltaics potential of roof tops

The analysis utilizes building permits and potential rooftop areas for photovoltaics to assess neighbourhood energy storage and photovoltaics integration per microgrid, addressing an aspect of equity. Building information for 2021, including critical infrastructure, was obtained from cadastral data, along with data on green areas with building permits[60]. Solar panel efficiency is influenced by the North–South orientation (Aspect), with studies suggesting a quantitative estimate of electrical power production based on spatial orientation and vertical angle[65].

Estimates of Aspect classes were derived from the 2014 NCFMP LiDAR dataset, allowing reconstruction of triangle roof structures with precision. A three-dimensional (3D) Digital Elevation Model (DEM) based on LiDAR points and building permits was created, producing an Aspect grid indicating the North–South direction of the 3D surface. This grid was refined to eliminate synthetic DEM data between buildings, providing accurate Aspect information. Each grid cell was multiplied by the corresponding solar power efficiency coefficient, yielding the integral roof solar potential for each Social Vulnerability Index region.

An acknowledged inconsistency arises from the temporal misalignment between LiDAR data and building permits. This issue is expected to be resolved in concrete urban microgrid planning projects with more up-to-date measurements. The methodology contributes to assessing the solar potential of rooftops and neighbourhood energy storage integration, considering equity aspects in microgrid planning[60,65,66].

Customers affected by blackouts induced by Hurricane Florence

Duke Energy, the energy provider in North Carolina, provided power feeder information from 2021, which was used to approximate the medium voltage circuit boundaries. Furthermore, Duke Energy provided timeseries aggregated data on customers per circuit boundary affected by power outages due to Hurricane Florence. From these data, we extracted per circuit boundary CB_x an estimate $P_l^{\text{blackout}}(\text{CB}_x)$ of the maximum share of electricity of customers who were affected by blackouts for at least *l* hours.

Well-being losses

Loss of short-term well-being can be represented in terms of disbursements, such as those made by the government to compensate for food losses due to lack of refrigeration, such as the Supplemental Disaster Nutrition Assistance Program (DSNAP), where households with low income were considered[67]. In addition, the unavailability of critical infrastructure, especially RHS infrastructure, contributes immediately to a worsened situation with respect to critical services. Moreover, the farther away blackout-impacted households with low socioeconomic status or with limited mobility are from functional critical services, and the more affected they are across the city, the greater the loss of well-being at city level. The latter implies the fact that critical services are then prone to congestion and limited operation, which in turn negatively affects well-being[68].

Hence, we applied two types of well-being unitless assessments, which are based on the Social Vulnerability Index data: type 1 applies information on low socioeconomic status, type 2 considers poor housing conditions and mobility constraints.

Let CB_x be a circuit boundary in which $P_l^{\text{blackout}}(\text{CB}_x)$, percentage of households, were affected by a blackout lasting longer than *l* hours. For well-being assessment of type 1, we applied $P_{\text{HH}}^{\text{se}}\,(\text{CB}_x)$ that estimates the relative number of RPL_THEME1 larger than a given threshold within the circuit boundary CB_x. For well-being assessment of type 2, we applied $P_{\text{HH}}^{\text{ph\_mc}}\,(\text{CB}_x)$ that estimates the relative number of households with RPL_THEME4 larger than a given threshold within the circuit boundary CB_x. The threshold value can be adjusted, and we used 0.3.

Further let $P_{l,\text{total}}^{\text{blackout}}$ be the share of all households in New Hanover County affected by blackouts lasting longer than *l* hours, $((c_1, d_1\,(\text{CB}_x)), (c_2, d_2\,(\text{CB}_x)), \ldots, (c_e, d_e(\text{CB}_x)))$ all *e* RHS infrastructure in New Hanover County that are still running with criticality and distance to the affected households in CB_x, *J* the index set of RHS critical infrastructure types (Supplementary Material) having no functional entity in New Hanover County, and $(c_j)_{j\in J}$ their criticalities.

We introduce the following functions:

$$C_J := \prod_{j\in J} 1/(1 + c_j) \tag{2}$$

$$\hat{A}(\text{CB}_x) := \begin{cases} 1, \ \mathit{if}\ e = 0 \\ (a^{\sum_{i=1}^{e} \frac{1}{c_i d_i}})^{C_J}, \ \text{else} \end{cases} \tag{3}$$

where $0 < a < 1$.

$$\hat{B}(\text{CB}_x) := \begin{cases} 0, \ \mathit{if}\, P_{l,\text{total}}^{\text{blackout}} = 0 \\ b^{1/P_{l,\text{total}}^{\text{blackout}}}, \ \text{else} \end{cases} \tag{4}$$

where $0 < b < 1$.

The assessment of the two types of well-being per circuit boundary is given as follows, and for the sake of simplicity, we neglected the argument CB_x in the above-mentioned objects:

$$\text{wl}_{\text{type1}}(\text{CB}_x) := P_l^{\text{blackout}} \times P_{\text{HH}}^{\text{se}} \times \hat{A} \times \hat{B} \tag{5}$$

$$\text{wl}_{\text{type2}}(\text{CB}_x) := P_l^{\text{blackout}} \times P_{\text{HH}}^{\text{ph\_mc}} \times \hat{A} \times \hat{B} \tag{6}$$

For the qualitative behaviour, it does not matter what specific values a and b have as long they are between 0 and 1. For our study, we set a to be 0.5 and b to be 0.9.

The factor $\hat{A}$ is attributed to well-being losses referring to the reachability of still running RHS infrastructure and their criticalities in the aftermath of a shock event; if an RHS critical infrastructure type has no functional entity, well-being decreases since this particular RHS service cannot be provided.

Metrics for assessing microgrids in built environments

Here, urban resilience refers to the functioning of critical services despite power outages due to baseline scenarios.

The following metrics always refer to the evaluation of a microgrid districting solution S. The greater their values, the better the evaluation. I_S is the index set referring to all microgrid boundaries in S. J is the index set referring to all infrastructure, including households, in New Hanover County and $J_A \subset J$ is the index set referring to all infrastructure belonging to a microgrid $A \in I_S$. Railroads, roads and highways were not included because these infrastructures span the entire urban area and microgrids are primarily concerned with serving local infrastructure. Drinking water infrastructure and shelters were also not considered, as there was only one unit for each of these infrastructures. Furthermore, let c_j and p_j be the criticality and the peak load, respectively, of an infrastructure $j \in J$.

Resilience referring to critical infrastructure: In the following, we refer to two metrics addressing the concentration of high-criticality, high peak load infrastructure in a microgrid and the distribution of RHS infrastructure per microgrid.

Equation (7) evaluates the density of high peak load, high-criticality infrastructure[50] in a microgrid A:

$$\mathrm{CD}_A^{x,y} := \sum_{j \in J_A} \left(\frac{c_j}{\sum_{k \in J} c_k} \right)^{1-x} \cdot \left(\frac{p_j}{\sum_{k \in J} p_k} \right)^{1-y} \tag{7}$$

where $0 \le x, y \le 1$ and $x + y = 1$. The coefficients x and y may be adjusted according to how criticality is relatively ranked compared to the peak load. The metric that measures the criticality and peak load density of critical infrastructure for a microgrid solution S is given in equation (8).

$$R_1(S) := \left(\max_{A \in S} \mathrm{CD}_A^{x,y} \right)^{-1} \tag{8}$$

Let J_A^{RHS} be the index set of all RHS infrastructure in A and $\mathrm{RHS}_A(i)$ the number of RHS infrastructure $i \in J_A^{\mathrm{RHS}}$ in A.

Let $R_2^A := \prod_{i \in J_A^{\mathrm{RHS}}} \prod_{j \in J_A^{\mathrm{RHS}} \setminus \{i\}} \frac{\min(\mathrm{RHS}_A(i), \mathrm{RHS}_A(j))}{\max(\mathrm{RHS}_A(i), \mathrm{RHS}_A(j))}$ and $f \in (0,1)$, $\widehat{I_S} := \{A \in I_S : R_2^A = 0\}$ and $n := |\widehat{I_S}|$.

Equation (10) defines the metric that evaluates the homogeneous distribution of RHS infrastructure in S.

$$\overline{R_2}(S) := \begin{cases} 0, \ if \ n = |I_S| \\ f^n \cdot \min_{A \epsilon I_S \setminus \widehat{I_S}} R_2^A, \ \text{else} \end{cases} \tag{9}$$

$$R_2(S) := d^{|\log_{10} \overline{R_2}(S)|} \tag{10}$$

where $0 < d < 1$, and is set to be 0.8 for our optimization studies.

The more microgrids there are that do not have all RHS infrastructure, the lesser $R_2(S)$ gets.

Cost factors for microgrid implementation: Solutions should always be economically feasible. Here we explain the factors of costs associated with microgrid districting that we used to measure cost efficiency of microgrid districting.

In our case study, we used an estimation of existing medium voltage circuit boundaries in New Hanover County. Medium voltage circuits can be fed from more than one substation controlled by switches and tie breakers. To connect two medium voltage circuits that are not fed by one substation would mean expensive infrastructure measures. We can directly infer that if planning is too small scale, that is, a large number of microgrids are to be installed, then correspondingly large investments in microgrid technology, power electronics, information and communication technology infrastructure, and energy management centres must be made[17,49].

Let h be the number of substations that belong to the circuit boundaries that were utilized for defining the boundaries of microgrid A and were not connected with each other in the medium voltage grid. The more substations are involved, the more expensive it gets; this is described with equation (11).

$$F_1(S) := \prod_{A \epsilon I_S} s^{h-1} \tag{11}$$

where $0 < s < 1$.

The more microgrids there are, the more expensive it will be to set them up and equip them with the appropriate management units and the necessary information and communication technology infrastructure, which is evaluated via equation (12).

$$F_2(S) := f^{|I_S|} \tag{12}$$

where $0 < f < 1$.

Implementing microgrids that cover areas that are not geographically connected is a costly endeavour, as they require connecting cables, which is measured with equation (13).

$$F_3(S) := \prod_{A \epsilon I_S} p^{\hat{a}-1} \tag{13}$$

where $\hat{a}$ is the number of path components of A.

Since we were only interested in relative comparison, we did not need explicit cost calculations for microgrids. However, estimated implementation costs as in ref. 17 are implicitly considered in equation (12).

Distribution of potentials for photovoltaics and neighbourhood energy storage location over all microgrids: Equal photovoltaics installation potential and neighbourhood energy storage location potentials were assessed with equations (14) and (15).

$$\mathrm{SST}(S) := \prod_{A \in I_S} \prod_{B \in I_S \setminus \{A\}} \frac{\min(\mathrm{bP}(A), \mathrm{bP}(B))}{\max(\mathrm{bP}(A), \mathrm{bP}(B))} \tag{14}$$

where $\mathrm{bP}(A)$ and $\mathrm{bP}(B)$ is the aggregated area of building permits in microgrid A and B, respectively.

$$\mathrm{SPV}(S) := \prod_{A \in I_S} \prod_{B \in I_S \setminus \{A\}} \frac{\min(\mathrm{pv}(A), pv(B))}{\max(\mathrm{pv}(A), \mathrm{pv}(B))} \tag{15}$$

where $\mathrm{pv}(A)$ and $\mathrm{pv}(B)$ is the aggregated rooftop-photovoltaics potential in microgrid A and B, respectively.

Representation of socially vulnerable groups in a microgrid: Let $0 < s_1 < \ldots < s_p < 1$ define equidistant Social Vulnerability Index-intervals that fully cover [0,1] and which are indexed by $P := \{1, \ldots, p+1\}$ and let $l \in P$.

$$\mathrm{SVI}H_A(l) := \begin{cases} \mathbf{1}, \quad \text{if there are no households with SVI value in the } l\text{th interval} \\ \text{the number of households with SVI value in the } l\text{th interval, else} \end{cases} \tag{16}$$

be the metric that evaluates whether a microgrid contains households belonging to a certain Social Vulnerability Index-interval.

Let

$$\mathrm{FD}_A(S) := \begin{cases} 1, & \text{if } A \text{ contains only households belonging to exactly one SVI interval} \\ \prod_{i\in P}\prod_{j\in P\setminus\{i\}} \frac{\min(\mathrm{SVI}H_A(i),\mathrm{SVI}H_A(j))}{\max(\mathrm{SVI}H_A(i),\mathrm{SVI}H_A(j))}, & \text{else} \end{cases} \tag{17}$$

be the degree of homogeneous distribution of households with respect to their Social Vulnerability Index within microgrid A.

An overall evaluation of solution S referring to the homogeneous distribution of households with respect to their Social Vulnerability Index per microgrid is given by equation (17)

$$\mathrm{FD}(S) := \min_{A\in I_S} \mathrm{FD}_A(S) \tag{18}$$

Pareto optimization and evolutionary algorithm

The metrics R_1, R_2, F_1, F_2, F_3, SST, SPV, FD represent different criteria or objective variables for assessing microgrid districting. A weighted sum of these metrics is the objective function being applied for finding optimal spatio-topological solutions for microgrid planning. To give a positive answer to the research question, we chose the weights in such a way that all criteria were considered (Supplementary Material). Here, finding an optimal solution had a maximized objective function. This is a districting problem with multiple objective variables similar to the districting problem in the context of gerrymandering[32]. This type of optimization problem is considered to be at least non-deterministic polynomial time hard[69]. Underlying this problem are so-called building blocks, in this work, the medium voltage circuits or the geographic extent of the respective service areas associated with them, which cover the city without overlap and combinable metrics that make this problem a Pareto optimization problem. Here, microgrid districting involved assigning building blocks, such as medium voltage circuits, to clusters, forming microgrid boundaries. Solutions ranged from each block in a separate cluster to all blocks in one. Evolutionary algorithms[70] offer feasible solution approaches, with complexity based on block number and a weighted sum fitness function. Realistic constraints limit microgrid numbers, focusing on a fixed upper limit. The solution space reduces to partitions with a maximum number of subsets[71]. This approach ensures practicality in considering mathematically conceivable microgrid numbers in urban planning. In our case, with 64 building blocks, considering only five microgrids would still lead to a very large number of possible solutions—more than 10^{42}.

The implemented evolutionary algorithm was based on the following assumptions:

1. For economic reasons, there is a maximum number of clusters/microgrids specified; this drastically limits the solution space, which can be specified case by case (Supplementary Material).
2. The microgrids are geographically interconnected.

Monte Carlo simulations and baseline scenarios

To assess how urban-resilient microgrid districting is against multiple baseline scenarios, we used Monte Carlo simulations of these scenarios and aggregated well-being losses using equations (5) and (6). The less aggregated well-being losses are, the more urban resilient the microgrid districting is.

Variation of different blackout scenarios based on the power outage data we have for Hurricane Florence: Of interest here is the maximum percentage of affected customers per circuit boundary who were without power from the grid for at least x hours; we chose 8 hours for our calculations. For studies regarding the impact of comparable or larger outages in the distribution grid, higher outage rates, for example, beyond the 95% quantile, were randomly assigned to selected circuit boundaries within defined parameter bounds. Since hybrid hazards were addressed, certain microgrids might suffer a total outage due to cyber attacks. These were randomly selected within appropriate parameter limits that relate to the number of affected microgrids, and the number of affected customers was set to 100%. In addition, the number of affected RHS infrastructure, aligned with the number of affected customers, was also randomly determined. The parameters and their intervals are given as follows:

The number of affected circuit boundaries getting assigned another rate of affected customers:

$\mathrm{cb}_b \in [A_{\mathrm{cb\_min}}, A_{\mathrm{cb\_max}}]$, $a_{r\_\mathrm{hh}} \in [P_{\mathrm{hh\_min}}, P_{\mathrm{hh\_max}}]$ and $a_{r\_cci} \in [P_{cci\_\mathrm{min}}, P_{cci\_\mathrm{max}}]$ for households, commercial customers and critical infrastructure, respectively.

The number of affected RHS infrastructure, depending on the total outage rate in the corresponding circuit boundary:

$$\mathrm{rhs}_r \in [P_{\mathrm{rhs\_min}}, P_{\mathrm{rhs\_max}}]$$

The number of affected microgrids:

$$\mathrm{mg}_b \in [A_{\mathrm{mg\_min}}, A_{\mathrm{mg\_max}}]$$

The selection of each parameter was based on a uniform distribution. For a selected microgrid solution, a Monte Carlo simulation was run and per-run well-being losses for both types (equations (5) and (6)) were calculated per circuit boundary and added to the previous results. The higher the values, the worse the protection of the microgrid against losses of well-being.

For our Monte Carlo simulations (100,000 runs), we applied the following parameter setting:

$A_{\mathrm{cb\_min}} = 2$, $A_{\mathrm{cb\_max}} = 5$, $P_{\mathrm{hh\_min}} = 0.9$, $P_{\mathrm{hh\_max}} = 1$, $P_{cci\_\mathrm{min}} = 0.9$, $P_{cci\_\mathrm{max}} = 1$, $P_{\mathrm{rhs\_min}} = 0.9$, $P_{\mathrm{rhs\_max}} = 1$, $A_{\mathrm{mg\_min}} = 1$, $A_{\mathrm{mg\_max}} = 3$.

Model limitations

Due to the large problem complexity, which is even larger for bigger cities with more medium voltage circuits than in New Hanover County, the evolutionary algorithm implemented here has to be used with additional strategy parameters and on high performance computers. A further complexity aggravation arises if instead of the medium voltage circuits, the low voltage networks are taken as building blocks. This would provide a spatially finer granularity and thus a more accurate (that is, less aggregated) projection of social vulnerability to households. The space of possible solutions would thus be drastically increased, while better solutions would also become possible. Furthermore, enhanced computational efficiency can be achieved through the refinement of equations, particularly those related to FD (equation (18)). In addition, the normalization process can be improved to facilitate a more comprehensive and integrated treatment of the metrics.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data on critical infrastructure and the built environment are from the utility and the cadaster, respectively, and were collected as part of the US Department of Energy project 'Planning an Affordable, Resilient, and Sustainable Grid in North Carolina'[57]. The free NCFMP LiDAR dataset[66] from 2014 was used to reconstruct triangular roof structures and to estimate the rooftop PV potential. Furthermore, the Social Vulnerability Index is publicly available (https://www.atsdr.cdc.gov/placeandhealth/svi/index.html) and has been scoped to New Hanover County, North Carolina. These data were used in preprocessed format for the optimization study and are available in this form via Zenodo at https://zenodo.org/records/11383276 (ref. 72). Power outage data used in this study to assess well-being losses are considered sensitive information and may be provided on a case-by-case basis by the corresponding author. In addition, further details on the data related to the mentioned US Department of Energy project will be available in a final report to be published in June 2024[58] or can be made available through the corresponding author.

Code availability

The code with which the optimization study was carried out is available via Zenodo at https://zenodo.org/records/11383276 (ref. 72). The optimization method is based on an evolutionary algorithm developed specifically for the project. The free geoinformation system QGIS v.3.26.1 was used to visualize the results. The code for conducting the Monte Carlo simulation to assess well-being losses was developed in Python, available in QGIS v.3.26.1 and executed within QGIS v.3.26.1. The results were also visualized using QGIS v.3.26.1. Since the code can be used to draw conclusions about the power outages caused by Hurricane Florence and these data are classified as sensitive information, this code is not publicly available but can be requested from the corresponding author.

References

1. Niggli, L., Huggel, C., Muccione, V., Neukom, R. & Salzmann, N. Towards improved understanding of cascading and interconnected risks from concurrent weather extremes: analysis of historical heat and drought extreme events. *PLOS Clim.* **1**, e0000057 (2022).
2. Keith, M. et al. A new urban narrative for sustainable development. *Nat. Sustain.* **6**, 115–117 (2022).
3. Markhvida, M., Walsh, B., Hallegatte, S. & Baker, J. Quantification of disaster impacts through household well-being losses. *Nat. Sustain.* **3**, 538–547 (2020).
4. Liddiard, R., Gowreesunker, B. L., Spataru, C., Tomei, J. & Huebner, G. The vulnerability of refrigerated food to unstable power supplies. *Energy Procedia* **123**, 196–203 (2017).
5. Casey, J. A., Fukurai, M., Hernández, D., Balsari, S. & Kiang, M. V. Power outages and community health: a narrative review. *Curr. Environ. Health Rep.* **7**, 371–383 (2020).
6. Chatterjee, C. & Mozumder, P. Hurricane Wilma, utility disruption, and household wellbeing. *Int. J. Disaster Risk Reduct.* **14**, 395–402 (2015).
7. Obolensky, M. A. B. et al. *Infrastructure Disruptions: How Instability Breeds Household Vulnerability* (World Bank Group, 2019).
8. Dargin, J. S. & Mostafavi, A. Human-centric infrastructure resilience: uncovering well-being risk disparity due to infrastructure disruptions in disasters. *PLoS ONE* **15**, e0234381 (2020).
9. Clark, S., Peterson, S., Rivera-Gutiérrez, R., Zambrana-Rosario, A. C. & Shelly, M. *Impact of Infrastructure Disruptions on Puerto Rican Household Capabilities, Health, and Well-Being* (Natural Hazards Center, 2022).
10. Sachs, J. D. et al. Six transformations to achieve the sustainable development goals. *Nat. Sustain.* **2**, 805–814 (2019).
11. Bogdanov, D., Gulagi, A., Fasihi, M. & Breyer, C. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination. *Appl. Energy* **283**, 116273 (2021).
12. Bower, W. et al. *The Advanced Microgrid. Integration and Interoperability* (US Department of Energy, 2014).
13. Ajoulabadi, A., Ravadanegh, S. N. & Mohammadi-Ivatloo, B. Flexible scheduling of reconfigurable microgrid-based distribution networks considering demand response program. *Energy* **196**, 117024 (2020).
14. Hadjipaschalis, I., Poullikkas, A. & Efthimiou, V. Overview of current and future energy storage technologies for electric power applications. *Renew. Sustain. Energy Rev.* **13**, 1513–1522 (2009).
15. Yang, W., Sparrow, S. N., Ashtine, M., Wallom, D. C. H. & Morstyn, T. Resilient by design: preventing wildfires and blackouts with microgrids. *Appl. Energy* **313**, 118793 (2022).
16. Cox, W. & Considine, T. Structured energy: microgrids and autonomous transactive operation. In *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)* 1–6 (IEEE, 2013).
17. Jeffers, R. F. et al. *Analysis of Microgrid Locations Benefitting Community Resilience for Puerto Rico* (US Department of Energy, 2018).
18. Hatziargyriou, N. Differences and synergies between local energy communities and microgrids. *Oxford Open Energy* **2**, oiac013 (2022).
19. Warneryd, M. & Karltorp, K. Microgrid communities: disclosing the path to future system-active communities. *Sustain. Futures* **4**, 100079 (2022).
20. Bommareddy, S. et al. Data-centric analysis of compound threats to critical infrastructure control systems. In *2022 52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN-W)* 72–79 (IEEE, 2022).
21. Bhusal, N., Abdelmalak, M., Kamruzzaman, M. & Benidris, M. Power system resilience: current practices, challenges, and future directions. *IEEE Access* **8**, 18064–18086 (2020).
22. Scheller, F. & Bruckner, T. Energy system optimization at the municipal level: an analysis of modeling approaches and challenges. *Renew. Sustain. Energy Rev.* **105**, 444–461 (2019).
23. Panteli, M., Trakas, D. N., Mancarella, P. & Hatziargyriou, N. D. Power systems resilience assessment: hardening and smart operational enhancement strategies. *Proc. IEEE* **105**, 1202–1213 (2017).
24. Dehghanian, P., Aslan, S. & Dehghanian, P. Quantifying power system resiliency improvement using network reconfiguration. In *2017 IEEE 60th International Midwest Symposium on Circuits and Systems (MWSCAS)* 1364–1367 (IEEE, 2017).
25. Clark, S. S., Seager, T. P. & Chester, M. V. A capabilities approach to the prioritization of critical infrastructure. *Environ. Syst. Decis.* **38**, 339–352 (2018).
26. Hick, R. The capability approach: insights for a new poverty focus. *J. Soc. Policy* **41**, 291–308 (2012).
27. Jain, G. & Espey, J. Lessons from nine urban areas using data to drive local sustainable development. *npj Urban Sustain.* **2**, 7 (2022).
28. Wahlund, M. & Palm, J. The role of energy democracy and energy citizenship for participatory energy transitions: a comprehensive review. *Energy Res. Soc. Sci.* **87**, 102482 (2022).
29. Chilvers, J. & Longhurst, N. Participation in transition(s): reconceiving public engagements in energy transitions as co-produced, emergent and diverse. *J. Environ. Plann. Policy Manage.* **18**, 585–607 (2016).
30. Judson, E., Fitch-Roy, O. & Soutar, I. Energy democracy: a digital future? *Energy Res. Soc. Sci.* **91**, 102732 (2022).
31. Becker, S., Angel, J. & Naumann, M. Energy democracy as the right to the city: urban energy struggles in Berlin and London. *Environ. Plan. A* **52**, 1093–1111 (2020).
32. Okamoto, Y. Maximizing gerrymandering through ising model optimization. *Sci. Rep.* **11**, 23703 (2021).
33. Borgström, S. Balancing diversity and connectivity in multi-level governance settings for urban transformative capacity. *Ambio* **48**, 463–477 (2019).
34. Ward, H. D. *From Their Lives: A Manual on How to Conduct Focus Groups of Low-Income Parents* (Institute for Child and Family Policy, University of Southern Maine, 2002).
35. Le, K. & Nguyen, M. Education and political engagement. *Int. J. Educ. Dev.* **85**, 102441 (2021).
36. Persson, M. Education and political participation. *Brit. J. Polit. Sci.* **45**, 689–703 (2015).
37. Adams, J. et al. What is energy literacy? Responding to vulnerability in Philadelphia's energy ecologies. *Energy Res. Soc. Sci.* **91**, 102718 (2022).

38. Flanagan, B. E., Gregory, E. W., Hallisey, E. J., Heitgerd, J. L. & Lewis, B. A social vulnerability index for disaster management. *J. Homel. Secur. Emerg. Manage.* **8**, 0000102202154773551792 (2011).
39. Carpenter, S. et al. General resilience to cope with extreme events. *Sustainability* **4**, 3248–3259 (2012).
40. Clark, S. S., Peterson, S. K. E., Shelly, M. A. & Jeffers, R. F. Developing an equity-focused metric for quantifying the social burden of infrastructure disruptions. *Sustain. Resilient Infrastruct.* **8**, 356–369 (2023).
41. Day, R., Walker, G. & Simcock, N. Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy* **93**, 255–264 (2016).
42. Amann, J. & Sleigh, J. Too Vulnerable to Involve? Challenges of engaging vulnerable groups in the co-production of public services through research. *Int. J. Public Adm.* **44**, 715–727 (2021).
43. Arrow, K. J. The economic implications of learning by doing. *Rev. Econ. Stud.* **29**, 155–173 (1962).
44. *Hurricane Florence: September 14, 2018* (National Weather Service, 2018).
45. Soininen, N. & Huhta, K. in *Sustainable Energy Democracy and the Law* 77–98 (Brill Nijhoff, 2021).
46. Helbing, D. Globally networked risks and how to respond. *Nature* **497**, 51–59 (2013).
47. Bódis, K., Kougias, I., Jäger-Waldau, A., Taylor, N. & Szabó, S. A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union. *Renew. Sustain. Energy Rev.* **114**, 109309 (2019).
48. Petit, F., Vargas, V., Kavicky, J., Kintner-Meyer, M. & Eto, J. *Grid Modernization: Metrics Analysis (GMLC1.1) – Resilience* (US Department of Energy, 2020).
49. Sheikholeslami, M. et al. Sequence of operations for real-time control of microgrids and networked microgrids. *IET Renew. Power Gen.* **16**, 1699–1718 (2022).
50. Ottenburger, S. S., Bai, S. & Raskob, W. MCDA-based genetic algorithms for developing disaster resilient designs of critical supply networks. In *2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)* 1–4 (IEEE, 2019).
51. Sedgh, S. A., Doostizadeh, M., Aminifar, F. & Shahidehpour, M. Resilient-enhancing critical load restoration using mobile power sources with incomplete information. *Sustain. Energy Grids Netw.* **26**, 100418 (2021).
52. Limberger, J. D. & Rigby, J. New Hanover County Hurricane Florence After Action Report - Port City Daily. *SCRIBD* https://de.scribd.com/document/399659667/New-Hanover-County-Hurricane-Florence-After-Action-Report-Port-City-Daily (2019).
53. Moreno, C., Allam, Z., Chabaud, D., Gall, C. & Pratlong, F. Introducing the "15-Minute City": sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities* **4**, 93–111 (2021).
54. Magnusson, D. Who brings the heat? – From municipal to diversified ownership in the Swedish district heating market post-liberalization. *Energy Res. Soc. Sci.* **22**, 198–209 (2016).
55. Vitéz, B. & Lavrijssen, S. The energy transition: democracy, justice and good regulation of the heat market. *Energies* **13**, 1088 (2020).
56. Martins, A., Madaleno, M. & Dias, M. F. Energy literacy: what is out there to know? *Energy Rep.* **6**, 454–459 (2020).
57. NC Clean Energy Technology Center. Planning an Affordable, Resilient, and Sustainable Grid in North Carolina. https://nccleantech.ncsu.edu/2019/12/12/planning-an-affordable-resilient-and-sustainable-grid-in-north-carolina/ (2019).
58. Cox, R. & Chowdhury, B. Planning an Affordable, Resilient, and Sustainable Grid in North Carolina. https://nccleantech.ncsu.edu/our-work/center-projects/planning-an-affordable-resilient-and-sustainable-grid-in-north-carolina/ (2024).
59. North Carolina Department of Public Safety. Emergency Management. https://www.ncdps.gov/our-organization/emergency-management (2022).
60. New Hanover County. Common Maps. https://www.nhcgov.com/886/Common-Maps (2023).
61. *Hurricane Dorian, September 6, 2019* (NOAA National Weather Service, 2019).
62. Münzberg, T., Wiens, M. & Schultmann, F. A spatial-temporal vulnerability assessment to support the building of community resilience against power outage impacts. *Technol. Forecast. Soc. Change* **121**, 99–118 (2017).
63. Katina, P. F. & Hester, P. T. Systemic determination of infrastructure criticality. *IJCIS* **9**, 211–225 (2013).
64. National Renewable Energy Laboratory. NREL/ComStock. *GitHub* https://github.com/NREL/ComStock (2023).
65. Mertens, K. *Photovoltaics: Fundamentals, Technology and Practice* (Wiley, 2014).
66. *2014 NCFMP Lidar: Statewide North Carolina (Phase 2) Point Cloud Files with Orthometric Vertical Datum North American Vertical Datum of 1988 (NAVD88) using GEOID18* (NOAA Office for Coastal Management, 2014).
67. *Disaster Supplemental Nutrition Assistance Program (D-SNAP)* (US Department of Agriculture, 2023).
68. Ottenburger, S. S. & Ufer, U. Smart cities at risk: systemic risk drivers in the blind spot of long-term governance. *Risk Anal.* **43**, 2158–2168 (2023).
69. Lucas, A. Ising formulations of many NP problems. *Front. Phys.* https://doi.org/10.3389/fphy.2014.00005 (2014).
70. Bartz-Beielstein, T., Branke, J., Mehnen, J. & Mersmann, O. Evolutionary algorithms. *WIREs Data Mining Knowl. Discov.* **4**, 178–195 (2014).
71. Mansour, T. & Schork, M. *Commutation Relations, Normal Ordering, and Stirling Numbers* (Chapman and Hall/CRC, 2015).
72. Al Omar, E., Ottenburger, S. S., Müller, T., Deines, E. & Trybushnyi, D. Spatio-topological microgrid planning. *Zenodo* https://zenodo.org/records/12579154 (2024).

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Author contributions

S.S.O. and R.C. contributed to the conceptual work of this study. R.C., B.H.C. and S.A.K. provided essential critical infrastructure data. S.S.O. was responsible for designing the applied metrics and the optimization study. In addition, S.S.O. led the manuscript writing process, gathering various text modules from the co-authors. S.S.O., U.W.U. and W.-R.P. provided insights into sustainability and equity considerations, as well as contributed to the textual content. B.H.C., S.A.K. and W.L. contributed valuable insights regarding technical microgrid implementation and provided textual contributions accordingly. D.T., E.A.O., E.D. and T.O.M. were involved in the processing of geo-referenced data, data preprocessing and the development of optimization software. S.S.O., S.M. and W.R. contributed considerations on resilience and provided corresponding textual contributions.

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Competing interests

The authors declare no competing interests.

Additional information

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Reporting Summary

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☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection
Data analysis	The code with which the optimization study was carried out is available at https://zenodo.org/records/11383276. The optimization method is based on an evolutionary algorithm developed specifically for the project. The free geoinformation system QGIS version 3.26.1 was used to visualize the results. The code for conducting the Monte Carlo simulation to assess well-being losses was developed in Python, available in QGIS 3.26.1, and executed within QGIS 3.26.1. The results were also visualized using QGIS 3.26.1. Since the code can be used to draw conclusions about the power outages caused by Hurricane Florence and this data is classified as sensitive information, this code is not publicly available, but can be requested from the corresponding author.

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data on critical infrastructure and the built environment are from the utility and the cadaster, respectively, and were collected as part of the DOE project 'Planning an Affordable, Resilient, and Sustainable Grid in North Carolina' (https://nccleantech.ncsu.edu/our-work/center-projects/planning-an-affordable-resilient-and-sustainable-grid-in-north-carolina/). The free NCFMP LiDAR dataset (https://noaa-nos-coastal-lidar-pds.s3.amazonaws.com/laz/geoid18/4957/index.html) from 2014 was used to reconstruct triangular roof structures and to estimate the rooftop PV potential. Furthermore, the Social Vulnerability Index is publicly available (https://www.atsdr.cdc.gov/placeandhealth/svi/index.html) and has been scoped to New Hanover County, North Carolina. This data was used in pre-processed format for the optimization study and is available in this form at https://zenodo.org/records/11383276. Power outage data used in this study to assess well-being losses is considered sensitive information and may be provided on a case-by-case basis by the corresponding author. In addition, details of the data related to the DOE project will be available in a final report to be published in June 2024 or available through the corresponding author.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Not applicable since no participants involved
Reporting on race, ethnicity, or other socially relevant groupings	Not applicable since no participants involved
Population characteristics	Not applicable since no participants involved
Recruitment	Not applicable since no participants involved
Ethics oversight	Not applicable since no participants involved

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study is based on mixed qualitative and quantitative methods. The study was conducted for New Hanover County, North Carolina. The study refers to data that were publicly available or obtained through stakeholder engagement (e. g. for criticality assessments). Criticality and vulnerability data and metrics were expressed numerically and unit-free through a mixed qualitative and quantitative method. Loss of well-being for households was accounted for in terms of the forms of availability and accessibility of critical services. No further types of research samples were necessary.
Research sample	The study used different representative data sets for New Hanover County. The data comprises critical infrastructure data, information on the built environment, social vulnerability data, data on power outage due to a hurricane, and representative survey data on criticality of infrastructure allowing this comprehensive study.
Sampling strategy	All data that were available and relevant for the metric-based evaluations were collected or produced
Data collection	Raw data used is largely publicly available; criticality assessments were conducted through stakeholder integration; all this data is without bias and is formula-based and neutral in this sense.
Timing	Data collected and analyzed between 2021 and 2023. Data based on stakeholder integration and survey: starting May, 2021 and ending October, 2022; 2021: start of collection of cadaster, infrastructure data and updates by the end of 2022. December 2022-March 2023 evaluation and use of all available data (as mentioned above) for the study; the LiDAR data is from 2014 since no better

	data source was available: this in connection with OSM data was applied for a first robust assessment of rooftop pv potentials.
Data exclusions	No data was excluded
Non-participation	Not applicable since no participants involved
Randomization	Randomization of the power failure scenarios was used in the Monte Carlo simulation for achieving robust results

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A