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Research article

Distributed energy systems: A potential solution for equitable electricity access

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Abstract: Equitable access to electricity is a critical challenge confronting urban communities. We investigated this problem empirically and explored the feasibility of leveraging novel distributed energy systems as a potential solution in three steps. First, using historical data, the associations between citizens' socioeconomic attributes and their access to electricity were statistically analyzed to empirically evaluate whether the existing grid systems serve all citizens fairly. Second, a systematic scoping review was conducted to synthesize and analyze the existing knowledge on the design and development of distributed systems to promote equitable access to electricity. Third, a series of semi-structured interviews was conducted to collect subject-matter experts' insights on potential opportunities and challenges for large-scale implementation of distributed energy systems as a solution to the problem of inequitable access to electricity. Finally, using the outcomes of the statistical analysis, systematic scoping review, and interviews, a set of potential research directions are outlined. We set the groundwork for future research and investigations focused on designing novel solutions to overcome the problem of inequitable access to electricity in urban areas. The outcomes of this study will help decision-makers identify potential opportunities and challenges for implementing distributed solutions to create more equitable electricity infrastructure systems.

Keywords: equitability; distributed energy systems; energy justice; electricity access; microgrids

1. Introduction

Equitable infrastructure development is a cornerstone of any just and sustainable society. It embodies the principle that access to essential resources and services should be available to all, regardless of their socio-economic background, race, or geographical location, according to the United Way of the National Capital Area [1]. By prioritizing equity in infrastructure development, we not only address historical disparities and social injustices but also foster economic growth and resilience [2]. Equitable infrastructure promotes inclusivity, reduces inequalities, and creates a more cohesive and prosperous society where everyone can thrive. It is an essential element in building a fair and sustainable future for all [3].

While all urban infrastructure systems play essential roles in facilitating various aspects of urban life, electricity infrastructure systems provide the lifeblood of modern cities. These systems power homes, hospitals, transportation systems, communication networks, and virtually every facet of urban life. As urbanization continues to grow worldwide, the demand for electricity escalates, underlining the necessity for equitable electricity infrastructure systems. Equitable electricity infrastructure is crucial for ensuring that every individual and community has access to reliable and affordable energy resources. The pivotal role of equitable electricity infrastructures in maintaining the well-being of urban populations is becoming more critical due to climate change. Climate change has led to an unprecedented increase in the frequency and intensity of heat waves worldwide. Excessive heat can lead to life-threatening situations for citizens, especially seniors, children, and people with chronic illnesses. Each year, this extreme event claims lives more than any other natural disaster [4]. Therefore, it is vital that all citizens, especially vulnerable populations, have access to air conditioning or other cooling mechanisms during heat waves. This emphasizes the criticality of electrical infrastructures to save lives during these extreme events. Previous studies, including [5], empirically showed that citizens' exposure to extreme heat is disproportionately linked to their socio-economic background since the temperature that they feel depends on their built environment characteristics, such as green spaces and surface material types of roads and buildings. Although there has been an increasing awareness regarding the criticality of equitable urban infrastructure systems, little is known about the extent of the problem. This lack of knowledge motivated our first objective, which focuses on empirically analyzing the accessibility of citizens with socio-economic backgrounds to electricity.

Solving the problem of equitable access to electricity is a multidimensional challenge that may require reconceptualizing fundamental approaches to city planning, infrastructure design, resource management, and construction methods. While some aspects of this issue, such as energy affordability [6], have been targeted in recent studies, we know little about some other dimensions of a comprehensive solution. One of the potential solutions that has not yet been investigated extensively is related to using decentralized energy infrastructures such as microgrids to maintain reliable and equitable access to electric power among all citizens in an urban environment. Decentralized energy solutions have been extensively investigated from various aspects, such as sustainability and environmental impacts [7], financial benefits [8], electrifying isolated rural areas [9], and resilience [10].

One of the potential opportunities that decentralized and distributed energy systems such as microgrids can offer is to augment centralized grid systems to provide more reliable and equitable access to energy. Such integrated electrical systems can support vulnerable areas that grid systems may fail to serve. However, little is known about envisioning, developing, and evaluating distributed solutions to tackle the energy equity issue. The first step towards developing novel solutions using distributed energy systems to promote equitable access to electricity in urban environments is to analyze the extent of the existing knowledge systematically. This need motivated our second objective, which focuses on conducting a systematic scoping review to synthesize the extent of the existing technical knowledge and identify promising directions for future research and investigations.

In addition, little is known about specific challenges that decision-makers may face in the large-scale implementation of distributed energy systems to overcome the problem of equitable energy access. This lack of knowledge motivated the third objective of this study, which focuses on identifying potential challenges through a series of semi-structured interviews with subject-matter experts.

The remainder of this paper is structured based on the three objectives. First, using historical data collected from New York City (NYC), we empirically examine whether there is a statistically significant relationship between citizens' socioeconomic background and the reliability of their access to electricity. Second, we conduct a systematic scoping review using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for Scoping Review (PRISMA-ScR) to search and synthesize the knowledge on using decentralized and distributed energy systems for promoting equitable access to electricity. Third, we present the outcomes of a semi-structured interview seeking subject-matter experts' opinions regarding the issue of equitable access to electricity and potential challenges in front of large-scale implementations of distributed energy systems to solve this problem. Next, using the outcomes of these investigations, we identify and discuss a set of research directions for future studies. Finally, we summarize the outcomes and contributions of this study to the core body of knowledge in the conclusion section.

2. Materials and methods

2.1. Objective I: Statistical analysis of equitable access to electricity

To address the first objective of this study, we empirically analyzed whether there is a statistically significant association between citizens' socio-economic background and the reliability of their access to electricity. In this empirical and statistical study, we focused on NYC. This major metropolitan area is home to more than 7.9 million people, representing a complex urban environment characterized by extensive and diverse urban infrastructure systems that serve many individuals from diverse socio-economic backgrounds.

Two datasets are used for this analysis. The first one, developed by the United States Census Bureau [11], consists of NYC residents' socio-economic factors at a zip code level of granularity. The socio-economic factors analyzed in this study include the population of people living in the zip code, per capita income, percentage of people with higher education, and percentage of racial minorities. NYC contains 173 zip codes corresponding to different areas of the city. The second dataset provides historical records of power outages in NYC at a zip code level from October 2020 to November 2022 [12].

2.2. Objective II: Synthesizing the existing knowledge on using distributed energy systems to promote equitable electricity access

To identify and analyze the existing technical knowledge on potential applications of distributed energy systems for promoting equitable access to electricity, we conducted a scoping review. A scoping review is a form of systematic literature review that mostly focuses on the breadth of the existing studies [13]. This synthesis method is applicable to analyze the extent of the existing knowledge in an emerging domain and identify research gaps and potential directions for future studies [14]. In this study, we designed and conducted our scoping review based on a protocol proposed by Tricco et al. [15], known as the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Extension for Scoping Review (PRISMA-ScR). The review process consists of five major steps as follows:

1) Determining the eligibility criteria
2) Selecting bibliographic databases
3) Designing search queries
4) Identifying relevant studies
5) Reviewing and analyzing the full manuscripts of the relevant articles

Regarding the eligibility criteria, any technical documents written in English that discuss potential applications of distributed energy systems for improving equitable access to electricity in urban areas are included in the review.

2.3. Objective III: Identifying potential opportunities and challenges

In this part, we aim to address the third objective and understand potential opportunities and challenges in using distributed energy systems to improve the equitability of electrical infrastructure systems through a series of semi-structured interviews with subject-matter experts with different but related backgrounds. Eight experts participated in the interview. Table 1 shows the participants' expertise and level of experience.

Table 1. Expertise and experience level of participants.

Participants	Expertise	Work Experience (Years)
1	Financial Manager in Energy Infrastructure Development Programs	38
2	Director in Sustainable Development Investment Projects	20
3	Project Manager in Energy Infrastructure Projects	7
4	Energy Management Expert in Local Government	6
5	Designer and Engineer of PV Panels	12
6	Climate Change Control Expert in Local Government	4
7	Academic Scholar in Sustainability	30
8	Innovation Manager in the Energy Industry	12

These participants were carefully selected from different groups of experts involved in various aspects of designing and managing electrical infrastructure systems. The diverse backgrounds and expertise of the participants helped this study consider the problem of equitable access to electricity and potential solutions using distributed energy systems from different angles to better understand potential opportunities and challenges.

3. Results

3.1. Objective I: Statistical analysis of equitable access to electricity

Using a set of statistical analyses, we examined whether there is a statistically significant association between the socioeconomic attributes and the historical number of power outages at each NYC zip code. Table 2 shows the Pearson Correlation Coefficients between each socioeconomic attribute for each zip code and the number of days that the corresponding zip code experienced a power outage during the analysis period. The numbers on the upper line show the calculated correlation coefficient, and those on the lower line in parentheses show the calculated p-values. The results indicate that, at a 5% level of significance, there is a statistically significant association between each one of the listed socioeconomic attributes and the number of days in which the corresponding zip code experienced a power outage.

Table 2. Correlation between socioeconomic attributes and power outage.

	Socioeconomic Attributes			
	Population	Per capita income	Percent of highly educated people	Percent of racial minorities
Number of days a zip code experienced power outage	0.50392	−0.36284	−0.36599	0.21490
	(1.8E−12)	(9.89E−07)	(7.83E−07)	(0.004632)

The correlation coefficients for the population and the percentage of racial minority populations are positive. This indicates that in zip codes with higher populations and a greater proportion of racial minorities—often considered racial minorities—the expected number of days experiencing a power outage tends to be higher than zip codes with lower populations and a lower percentage of racial minorities. On the contrary, the correlation coefficients for per capita income and percentage of residents with higher education are negative, indicating in zip codes where per capita income is higher and there is a greater concentration of highly educated individuals, power outages occur less frequently compared to zip codes with lower per capita income and a lower proportion of highly educated residents.

It is important to acknowledge that the socioeconomic factors under analysis might exhibit correlations among themselves. For instance, areas with a greater percentage of highly educated residents tend to also boast a greater per capita income.

To analyze the associations between socioeconomic factors and the probability of power outage more rigorously, a set of four univariate linear regression models were developed. Each regression model explains the variations in the probability of power outage in a zip code based on the variations in one of the socioeconomic attributes. The regression models are as follows:

$$Probability\ of\ power\ outage = 22.148 + 0.00031 \times Population \tag{1}$$

$$Probability\ of\ power\ outage = 44.972 - 0.000196 \times Per\ capita\ income \tag{2}$$

$$Probability\ of\ power\ outage = 47.783 - 27.772 \times Proportion\ of\ educated\ people \tag{3}$$

$$Probability\ of\ power\ outage = 28.334 + 13.346 \times Proportion\ of\ nonwhite\ people \tag{4}$$

In all the regression models, the P-value of the explanatory variable coefficients are smaller than 5%, indicating at a 5% significance level, the explanatory power of the variable is statistically significant. It should be noted that the intercepts of the regression equations do not have a meaningful interpretation in this concept.

Through regression models, one can quantify the sensitivity of expected power outages to changes in socioeconomic attributes. More specifically, the regression model explaining the probability of an outage in a zip code based on its population indicates that for every additional 10,000 people, the likelihood of experiencing an outage in a day increases by 3.14%. Concerning per capita income, the corresponding regression model reveals that for every $10,000 increase in per capita income, the probability of a power outage decreases by 1.96%. Furthermore, for every 10% increase in the population of racial minorities in a zip code, the probability of an outage would increase by 1.33%. Finally, for every 10% increase in the proportion of highly educated individuals in a zip code, the probability of an outage would decrease by 2.77%.

The results of the correlation analysis and regression models strongly indicate that zip codes with lower socioeconomic indicators are more susceptible to power outages. This underscores the inequitable distribution of power infrastructure services and the necessity of designing and developing transformative solutions to improve the accessibility and equitability of electricity infrastructure systems.

3.2. Objective II: Synthesizing the existing knowledge on using distributed energy systems to promote equitable electricity access

Per the suggestions of previous studies evaluating databases for systematic literature review, such as [16], we conducted the scoping review using the Scopus bibliographic database. Next, we designed and used the following search query, which contains two major parts separated by an "AND" Boolean operator. The first part of the query contains various combinations of phrases related to distributed energy systems. The second part of the query includes phrases related to equity and accessibility.

((microgrid OR minigrid OR nanogrid OR "decentralized energy systems" OR "small generating units" OR "virtual power plant" OR "plug-and-play systems" OR "distributed energy resources" OR "distributed generation" OR "renewable energy" OR "PV panel" OR "photovoltaic panel" OR "combined heat and power" OR "wind turbine" OR "solar systems" OR "small-scale generator" OR "small-scale energy generator" OR "small-scale electricity supply" OR chp OR dg OR der OR ess OR "energy storage" OR "energy hub" OR "urban energy systems" OR "power system" OR "power grid" OR " power network" "distribution grid" OR "distribution network" OR "electri grid" OR "electri* network") AND (equit* OR "energy access*" OR "electri* access*" OR inclusiv* OR justice))*

Using the query, we conducted the search on the Scopus database in February 2024. The outcomes of the search included 349 documents. Next, we reviewed the keywords, titles, and abstracts of these documents to identify potentially relevant studies. Ironically, only two studies were identified as relevant to the idea of using distributed energy systems to achieve equitable access to electricity.

Although the other studies that were listed as the outcomes of the search query but were not identified as relevant included phrases related to both distributed energy systems and equitability, they did not directly include maintaining and improving equitable access to electricity in urban environments through distributed systems. Some of these researchers, such as those in [17] and [18], investigated how distributed energy systems, such as microgrids, could provide electricity to remote rural areas that do not have a connection to major grid systems. Some other researchers, such as those in [19], discussed strategies to share the financial benefits of alternative energy sources among people fairly. Some others, such as [20], investigated fair opportunities to adopt solar energy in dense urban areas with limited access to rooftops and open spaces to install photovoltaic (PV) panels. Tarekegne et al. [21] explored fair access to clean air using sustainable energy sources for electricity generation. Another group of researchers, such as [22–24], investigated fair pricing and net metering in novel energy solutions such as distributed systems.

Both identified relevant studies investigated the potential roles of distributed energy systems on the reliability of load supply by maintaining a balance between supply and demand, which ensures reliable access to electricity. The primary objective of the first relevant study [25] is to provide continuous access to electricity by balancing the supply and demand for a residential community during load-shedding periods using a hybrid energy system. This hybrid energy system incorporates solar panels, batteries, and a diesel generator. An energy management scheme is proposed to coordinate the operation of the hybrid energy system based on the grid state. The energy management scheme incorporates three distinct operational modes: (1) The grid mode, which utilizes the main grid for power supply and allows for battery charging; (2) the renewable energy sources mode, activated during load shedding, which uses PV and battery power to meet electricity demand; and (3) the diesel generator mode, activated as a backup if PV and battery capacity fail to meet the demand. The findings highlight the scheme's effectiveness in ensuring uninterrupted electricity access during load shedding using a hybrid energy system while minimizing diesel generator usage.

Other researchers [26] propose a novel approach to maintaining a balance between electrical energy supply and demand using energy storage systems (ESS). They evaluate the applicability of three types of ESS systems based on their ownership: (1) Customer-owned ESS, (2) community-owned ESS, and (3) utility-owned ESS. They investigated how these storage systems improve the balance of energy supply when the centralized grid system is disrupted. The study conducted a series of scenario analyses in a densely populated urban area with 265 electrical demand nodes. The outcomes indicated that each type of ownership brings distinct advantages in the case of power interruptions. Customer-owned ESS systems offer an opportunity for individual households to control their energy supply and let them be responsible for managing their energy system during grid failures and disruptions. This can be a viable solution for customers with lower energy requirements. However, it may impose a financial burden on the citizens. Community-owned ESS systems can serve public spaces and critical facilities, ensuring that essential urban facilities receive reliable backup power. For utility-owned ESS, analyses were conducted at three distinct locations along the electricity distribution line (feeder): Near the substation, at the midpoint, and at the end of the feeder. The findings showed that utility-owned ESS systems provide a lower level of load support compared to other ESS types. Moreover, the ability to supply power is influenced by the location of both the ESS and the occurrence of power outages. These utility-owned systems can create a microgrid around their location, offering power supply only to nearby areas. While both studies mention the potential advantages of employing distributed energy systems to offer citizens more reliable access to energy, they do not propose a direct solution to address equity issues or discuss potential challenges that such solutions may face. This essential knowledge gap motivated our third research objective in this paper.

3.3. *Objective III: Identifying potential opportunities and challenges*

The semi-structured interview consisted of 20 questions. The experts participated in the interview individually. Depending on the responses from each expert, follow-up questions were asked for further clarification. In each question, the experts were asked to share the extent to which they agree or disagree with a statement using a five-level Likert scale (i.e., strongly disagree, disagree, neutral, agree, and strongly agree) and provide further explanations to support their responses. Figure 1 summarizes the outcomes of the semi-structured interview.

Figure 1. Summary of the interview outcomes.

In the remainder of this section, each question and the experts' responses are discussed.

Q1. To what extent do you agree or disagree with the following statement:

"Equitable access to electricity is a challenge in urban environments that is not currently addressed properly."

All the participants either agreed or strongly agreed with the statement and emphasized that based on their observations and experience, the existing electrical infrastructure systems in most urban environments do not equitably serve all residents. They also stressed that, currently, decision-makers are not addressing this issue effectively. Some experts mentioned that despite recent increasing awareness among experts, planners do not perceive equity in access to electricity as a pressing concern and it is not regarded as a priority in urban planning and infrastructure development projects. Without recognizing the lack of equitable electrical infrastructure systems as a vital concern, there may be a lack of initiative to address this issue.

Q2. To what extent do you agree or disagree with the following statement:

"There are clear and well-defined metrics and criteria to measure and assess equitable access to electricity."

All participants strongly disagreed with this statement, indicating that the consensus among participants is that there are no clear and well-defined metrics and criteria to measure and assess equitable access to electricity. Defining proper assessment criteria for equitable access to electrical infrastructures can be considered as the first step in understanding the problem.

Q3. To what extent do you agree or disagree with the following statement:

"Distributed energy systems, such as microgrids, can be an effective solution for addressing energy equity issues, particularly in terms of access to electricity."

Every participant agreed or strongly agreed with the statement. One participant noted that addressing social justice issues in terms of access to electricity can be a function for distributed energy systems in addition to their typical roles in promoting resilience and sustainability. However, their large-scale implementation may not be without challenges. One respondent emphasized the importance of acknowledging potential limitations on the electricity generation capacity of these systems. Another expert mentioned that managing the balance between supply and demand might be more complicated when many distributed systems are linked to the grid. This may lead to an extra electricity generation problem that imposes too much stress on distribution and transmission lines (i.e., grid congestion). The participants also mentioned that adopting such solutions may involve various technical and practical challenges that were reflected in their responses to other questions in the semi-structured interviews.

Q4. To what extent do you agree or disagree with the following statement:

"Developing adequate local and federal policies that accept and promote the large-scale implementation of distributed and decentralized electricity systems such as microgrids is currently a critical challenge."

All participants either agreed or strongly agreed with the statement. One expert mentioned that, currently, utility agencies in 32 states in the U.S., including Washington, North Carolina, and Florida, operate in regulated energy markets that do not let customers choose their energy providers. Energy generation is a monopoly in those states, and distributed energy generation and some of its components, such as the transition of customers to prosumers, can be very complicated. Such policies prevent large-scale implementation of distributed energy systems. Another participant noted that developing policies to streamline adopting alternative energy sources, such as distributed energy systems, would provide a structured framework that fosters a shared understanding and collaboration between various entities such as government, utility companies, and customers. Another participant stressed that many politicians look at distributed energy systems as part of the transition to green energy and fighting against fossil fuel, which has been politicized in recent years in many countries, such as the U.S. This perspective makes the adoption of distributed energy systems more complicated across the country and calls for policy changes. Another expert also mentioned that to ensure the widespread adoption of decentralized energy systems among underserved communities, the responsibility likely falls on state-level initiatives rather than the federal government. He emphasized that policy changes should also include new tax regulations that offer incentives for adopting distributed energy systems to support underserved communities.

Q5. To what extent do you agree or disagree with the following statement:

"The lack of knowledge and understanding of the potential benefits offered by distributed and decentralized energy systems by the political leadership is a critical challenge for the large-scale implementation of these systems."

All the participants either agreed or strongly agreed with the statement. They emphasized that without a thorough understanding of the potential advantages of distributed systems, including facilitating equitable access to energy, the widespread integration of these systems is expected to face substantial challenges. One of the participants stated that there is a recognized lack of comprehensive technical understanding among political leadership regarding these systems, which can be a roadblock in front of policy changes.

Q6. To what extent do you agree or disagree with the following statement:

"Resistance by electricity companies that own centralized grid systems to change to distributed systems is a critical challenge for the large-scale implementation of decentralized energy solutions, such as microgrids."

Participants agreed or strongly agreed that the resistance from utility companies is a significant hurdle to the extensive adoption of distributed energy systems. One respondent mentioned that although utilities comply with regulatory obligations, their proactive engagement in the transition to distributed energy systems depends on a clear and compelling financial incentive. One other respondent emphasized that there is a misalignment between the urban development goals and the profit-oriented approach of utilities. Achieving a balance between urban planning goals and utilities' objectives is a challenge in current urban development efforts.

One respondent mentioned that one significant challenge in this transition lies in determining the ownership of distributed energy systems. The respondent argued that resistance from electricity companies owning centralized grid systems may not be an obstacle if the utility holds the ownership of the distributed energy systems and considers that as a viable investment.

Q7. To what extent do you agree or disagree with the following statement:

"Potential employment disruption for workforces of electricity companies that currently own and/or operate centralized grid systems is a critical challenge for the large-scale implementation of distributed and decentralized energy systems such as microgrids."

Experts who participated in this study had different opinions about this question. Two participants agreed, and three strongly agreed that large-scale implementation of distributed energy systems may lead to downsizing utility companies, which might lead to employment disruptions. However, the other participants who disagreed with this argument noted that managing and maintaining distributed systems offer new employment opportunities for those workforces and also it is likely that utility companies are directly engaged in developing and operating these novel infrastructures which would reduce the chance for extreme employment interferences.

Q8. To what extent do you agree or disagree with the following statement:

"The lack of social acceptance due to the public's perception that decentralized electricity generation systems such as microgrids are not reliable is a critical challenge for the large-scale implementation of these systems."

All the participants either agreed or strongly agreed with the statement. One participant noted that not all citizens have enough understanding of how these systems work and benefit their communities. This may lead to a lack of demand and expectation for investment in these solutions and policy changes by the government and other decision-makers. In addition, considering the intermittent characteristics of renewable energy sources such as solar, which are typically used in distributed energy systems, some citizens may question their reliability. Another expert mentioned that people with a more profound familiarity with alternative energy systems are more inclined to support investments in distributed energy systems. Sustainability consciousness and concerns related to global warming may also motivate people to support these technologies. However, different groups of people with various political and social backgrounds may have fundamentally distinct opinions on this matter. Effective communication, public outreach, and educational initiatives can play a pivotal role in increasing awareness about the significance of equitable access to urban infrastructures and potential solutions to address them.

Q9. To what extent do you agree or disagree with the following statement:

"Designing and implementing incentive programs to promote decentralized energy systems among citizens is a critical strategy for the large-scale implementation of distributed electricity systems such as microgrids."

All experts agreed or strongly agreed with the statement regarding incentive programs to promote distributed energy systems. Some experts mentioned that considering the required initial investments for distributed energy systems and the lack of knowledge about their potential benefits among some groups of citizens, financial incentive programs in various forms, such as tax credits, may play an important role. However, one respondent emphasized that the design of an incentive program depends on the location and environmental factors. He noted that residents in areas such as southern California may be more likely to adopt these alternatives due to local factors such as ample sunlight, high energy costs, and potential substantial paybacks. However, in regions like Mississippi, where energy costs are lower and paybacks take longer, incentive programs may play a more critical role. Another expert also highlighted that designing and implementing incentive programs are local issues that require constant evaluation and updating to reflect the evolving needs of the energy market and urbanization.

Q10. To what extent do you agree or disagree with the following statement:

“The variability in the daily amount of electricity generated by distributed systems, such as microgrids, due to their dependency on intermittent energy sources (e.g., solar for PV panels) is a critical challenge for the large-scale adoption and implementation of these systems.”

Experts who participated in this study expressed varying opinions on this question. Three participants agreed, and three strongly agreed, that the daily variability in electricity generation in distributed energy systems relying on renewable sources presents a significant obstacle to their large-scale adoption. One noted that the extensive utilization of distributed and decentralized solutions depends on technological advancements in high-capacity batteries. However, other experts who disagreed with the statement argued that distributed energy systems are not poised to replace centralized grid systems completely. Instead, they will play a complementary role and be integrated with the grid system to augment and support it during high demand and failure. Within this collaborative framework between centralized grid systems and distributed energy installations, the variability in energy generation of distributed systems is manageable with existing technologies.

Q11. To what extent do you agree or disagree with the following statement:

“The technology is currently not mature enough for the large-scale implementation of distributed energy systems such as microgrids.”

All participants, except one, either strongly disagreed or disagreed with the statement. The exception noted that current technology falls short of providing distributed energy systems that meet all energy needs independently of grid support. Additionally, he emphasized that photovoltaic (PV) panels, the predominant component in distributed energy systems, suffer from relatively low efficiency. He added that essential improvements are required in electricity storage technologies to actualize distributed energy systems. Finally, he emphasized that the critical need for technological advancements in this area extends beyond the functionality and efficiency of distributed systems and their components. New technologies are necessary to render these solutions more cost-effective and accessible to a broader range of communities.

While other experts participating in this study acknowledged that technology in this domain has room for improvement, they believed it is mature enough to serve as a reliable addition, augmenting the grid systems. They envision a hybrid infrastructure system capable of offering adaptability and agility during unprecedented situations to maintain fair access to electricity among various groups of citizens.

Q12. To what extent do you agree or disagree with the following statement:

“The short life cycle and solid waste management of PV panels pose critical challenges for the large-scale implementation of distributed and decentralized electricity systems.”

All the participants either disagreed or strongly disagreed with the statement. All experts are optimistic that the growing implementation of distributed energy systems will prompt the establishment of recycling companies dedicated to managing the waste from these technologies. Moreover, one respondent noted that the recycling process for PV panels is not more complicated than recycling many typical household items such as refrigerators. Another expert emphasized that newer PV panel types, currently dominant in the market, do not contain toxic materials. He added that while there might be some concerns regarding lithium batteries used in certain types of distributed systems, there are already well-established procedures in place to manage their waste, and this concern is not considered a deal-breaker. Two experts also noted that expected technological advancements will lead to more efficient systems with longer lifespans and reduced waste generation in the near future.

Q13. To what extent do you agree or disagree with the following statement:

"Distributed and decentralized electricity systems that let citizens sell their extra electricity to the grid or other consumers will lead to energy consumption reduction."

All participants either strongly agreed or agreed with the statement, except for two experts who remained neutral. Those who believed in the motivating potential of selling extra electricity to reduce energy consumption noted that distributed energy systems would introduce a new energy market paradigm. Here, consumers who transition into "prosumers" have a tangible incentive to profit from conserving their electricity. One expert highlighted that financial considerations often drive individual choices, emphasizing that the opportunity for financial gain through selling excess energy to the grid or other households is likely to encourage people to consider reducing their electricity consumption. On the other hand, two participants argued that user energy consumption is inherently complex, and many factors may affect it. One of the experts who was neutral added that general public often lacks the knowledge to interpret complex electricity bills and plan to profit from energy trading. Therefore, there is a considerable chance that they do not change their consumption behavior.

Q14. To what extent do you agree or disagree with the following statement:

"Developing systematic mechanisms for real-time electricity pricing for peer-to-peer or prosumer-to-grid electricity trading is a vital challenge for the large-scale implementation of distributed electricity systems such as microgrids."

All participants unanimously agreed with this statement and stressed the importance of developing systematic mechanisms for real-time electricity pricing. They highlighted that peer-to-peer and prosumer-to-grid electricity trading would be integral components of the large-scale implementation of distributed energy systems. One expert noted that extensive research and scientific investigation have been conducted on designing and governing real-time energy trading in recent years; however, further investigations are needed to develop practical methods suitable for real-world conditions.

Q15. To what extent do you agree or disagree with the following statement:

"Cybersecurity for peer-to-peer electricity trading in distributed and decentralized systems such as microgrids is a critical challenge for the large-scale implementation of these solutions."

Participants either disagreed or strongly disagreed with the statement. None of them questioned the importance of cybersecurity in managing distributed energy systems. However, they noted that the complexity of the cybersecurity management in these systems and their associated operations, such as decentralized electricity trading, will not be more complicated than cybersecurity issues in many other aspects of modern life, such as electronic banking. Therefore, considering rapid advancements in cybersecurity solutions, this concern does not pose a significant challenge for adopting distributed energy systems.

Q16. To what extent do you agree or disagree with the following statement:

"Big data management for peer-to-peer electricity trading in distributed and decentralized systems, such as microgrids, is a critical challenge for the large-scale implementation of these solutions."

All participants strongly disagreed with this statement. Their reasoning echoed their response to the previous question regarding cybersecurity issues in distributed energy management systems. They pointed out that while distributed energy systems and decentralized electricity trading may generate a substantial amount of data, analyzing such big data is not a unique challenge that would hinder the adoption of distributed energy systems.

Q17. To what extent do you agree or disagree with the following statement:

"Lack of space in dense urban areas is a critical challenge for the large-scale implementation of distributed electricity systems such as microgrids."

All experts, except one, concurred with the statement. Those who consider the scarcity of space in urban areas a significant obstacle to the widespread adoption of distributed energy systems stressed that despite recent efforts to allocate more space in public areas and atop buildings for PV panels, typical dense urban environments lack the capacity necessary for large-scale implementation of such systems reliant on sustainable energy sources like solar power. One expert pointed out that the challenge of limited space prompts the development of large solar farms outside cities to harness sunlight for electricity generation and subsequent transmission to urban centers. While this approach, if carefully executed, may foster sustainable development, it fundamentally contradicts the core principles of distributed energy systems and perpetuates a centralized hierarchy. Another expert added that contrary to popular belief regarding technological advancements in PV panels leading to smaller and more efficient panels, newer PV panels are increasing in size to optimize the installation process for greater cost-effectiveness.

The expert who disagreed with the significance of this challenge noted two reasons. First, he emphasized that distributed energy systems will play a complementary role in enhancing the coverage and performance of grid systems. Therefore, the existing open spaces in cities are sufficient to install the required distributed energy systems. Second, he pointed out that the technology of PV panels is advancing rapidly towards maintaining a higher level of efficiency, which alleviates the need for large amounts of space to some extent.

Q18. To what extent do you agree or disagree with the following statement:

"The high initial cost of implementing distributed electricity systems such as microgrids is a critical challenge for large-scale implementation of these systems."

All participants agreed or strongly agreed on the significance of the challenge due to the high initial costs, except for one expert. Those who agreed or strongly agreed highlighted that the large-scale implementation of distributed energy systems requires considerable financial investments, which may burden citizens, utility companies, and governments. One expert noted that without well-designed financial incentive programs, extensive implementation of these systems is not realistic. Additionally, he suggested that new forms of taxing fossil fuels could be a source to secure resources for such incentives. Another participant noted that access to affordable financial mechanisms and debt for alternative energy sources has diminished in recent years due to inflation and higher interest rates.

The expert who disagreed with the statement pointed out that technology in this domain is advancing rapidly and will significantly decrease the cost of distributed energy systems. He added that centralized grid systems also incur significant costs for expansion, modernization, and maintenance. Designing and developing hybrid and semi-centralized systems that integrate distributed energy systems can redirect the capital invested in traditional grid networks toward innovative solutions such as microgrids.

Q19. To what extent do you agree or disagree with the following statement:

"The high cost of maintenance is a critical challenge for the large-scale adoption and implementation of distributed electricity systems such as microgrids."

All participants agreed or strongly agreed with the statement, except for two experts who disagreed. Those who agreed highlighted that novel technologies involve more expensive components and devices, complex maintenance processes, and require more advanced training procedures for maintenance professionals. The other two experts, who disagreed with considering maintenance costs as a critical challenge for the large-scale adoption of distributed energy systems, noted that emerging technological advancements in that area would lead to developing more cost-effective systems with longer life expectancy and lower maintenance requirements. They also pointed out that existing grid systems also incur significant maintenance costs; therefore, the maintenance cost of distributed systems is not a formidable and unique challenge for these systems.

Q20. To what extent do you agree or disagree with the following statement:

"Augmenting existing centralized grid systems with distributed microgrids located in vulnerable areas can improve the reliability and equitability of electricity infrastructure systems."

All participants either agreed or strongly agreed with the statement. Despite the expected challenges reflected and discussed in the previous questions, all experts believed that integrating distributed energy systems with centralized grid networks is a viable solution to address equitable access issues in electricity infrastructures. They unanimously agreed that if equitable access to electricity and social justice factors are incorporated into determining the size and location of distributed energy systems, they can augment and support the grid system to maintain reliable access to electricity for all citizens, regardless of their socio-economic backgrounds. Meanwhile, they stressed that developing systematic solutions to address the identified challenges is of paramount importance for the large-scale implementation of equitable energy systems.

4. Conclusions and discussion

Equitable access to urban infrastructure systems is a cornerstone of sustainable development that promotes social justice and fairness. This study investigated the problem of equitable access to electrical infrastructures in urban environments and explored the feasibility of leveraging novel distributed energy systems as a potential solution. More specifically, the primary contributions of this study to the core body of knowledge are three-fold. First, this study empirically examined the extent of the problem using historical outage data and socioeconomic attributes of the areas that experienced outage. The outcomes indicated statistically significant associations between the number and probability of power outages and some socioeconomic attributes such as per capita income, population, proportion of racial minorities, and percentage of highly educated residents. Second, the study conducted a systematic scoping review using the PRISMA-ScR method to synthesize and analyze the extent of the existing technical knowledge on using distributed energy systems for equitable access to electricity. The outcomes indicated that, despite the importance of the topic, fundamental knowledge gaps exist in the literature regarding designing and implementing systematic methods to develop equitable electrical infrastructures. Third, we identified and analyzed potential opportunities and challenges for adopting distributed energy systems as a solution for the problem of inequitable access to electricity in urban areas through a semi-structured interview with a group of experts with different backgrounds. All experts unanimously agreed that equitable access to electricity is a pressing need in modern urbanization developments, and distributed energy systems can be a viable solution to address this old but persistent issue. Their inputs and discussions revealed potential challenges in front of large-scale implementation of these systems that can be a basis for future studies. Some of the challenges that most experts found critical are (1) lack of well-defined criteria to measure electricity equitability, (2) lack of technical knowledge among some decision-makers, (3) lack of local and federal policies to promote and facilitate distributed energy generation, (4) lack of practical methods for real-time electricity pricing, (5) lack of well-designed and innovative financial incentive programs, (6) the need to accelerate technological advancement in distributed energy systems and their components such PV panels and storage systems to overcome issues such as efficiency, lack of space in dense urban environments, and cost, and (7) the need to increase awareness among citizens regarding potential benefits of these systems.

Addressing these challenges can be a basis for future research directions. In addition, developing conceptual and mathematical models to find optimal locations for a limited number of small energy installations such as microgrid or electricity storage to augment the grid systems and improve equitable access to electricity is another topic for future investigations.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

N.T. Data Collection and Curation, Formal Analysis, Investigation, Visualization, Writing-Original Draft Preparation.

M.I. Conceptualization, Methodology, Supervision, Project administration, Writing-Review and Editing.

G.K. Conceptualization, Methodology, Writing-Review and Editing.
M.P. Conceptualization, Methodology, Validation.

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