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Perspective

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Translating energy equity from a sociological concept to an electric power engineering perspective

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Abstract

The implementation of energy equity is a pivotal goal of the global energy transition, driven by widespread recognition of energy inequities worldwide. Energy equity has been broadly regarded as a sociological concept rather than an engineering one. The absence of technical engineering methods necessitates the development of a justified and sound approach to making energy equity an actionable practice in the broader realms of energy, environment and sustainability. In this Perspective, we propose a generalized definition of energy equity from the engineering perspective of electric power systems. We look at policies for energy equity that have already been introduced in Europe and the USA, noting their limited effectiveness, and provide four categories of classification for current energy-equity research: quantifying energy equity, improving equity in the accessibility of electricity, improving equity in the affordability of electricity, and improving equity in the resilience of power systems. We then set out a roadmap to address ongoing research challenges in energy equity.

Sections

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Key points

• Energy equity means fair and just access to energy for everyone: the challenge of energy inequity worldwide is urgent.

• Energy equity is a sociological concept, and current research often fails to integrate that concept in the engineering perspective of electric power systems.

• Although some policies to tackle energy equity have been enacted, they lack guidelines for actionable engineering solutions.

• Energy equity has been defined in several ways, but here we make a generalized definition based on power system characteristics.

• Our roadmap for achieving energy equity in electric power systems incorporates both technical and application challenges.

Introduction

Equity means achieving equal outcomes for all, even though everyone's circumstances are different, through the appropriate allocation of resources and opportunities[1]. Equity has been studied and applied in various fields, including economics[2], education[3] and public health[4], and is also relevant in the ongoing energy transition, intended to reduce greenhouse-gas emissions in accordance with the 2016 Paris Agreement on climate change. Ideally, communities of different circumstances would all benefit equally from a more sustainable energy system, in terms of economics, environment and reliability, but in reality there are many energy inequities built into the current electrical power system (Fig. 1), and those inequities need to be addressed. Moreover, pollutive power plants are harmful to human health, and their unequal distribution, predominantly in low-income areas, contributes to environmental inequity. Environmental equity emphasizes that every individual has the right to breathe clean air, drink safe water and live in a healthy community: equitable access to clean energy contributes to cleaner air, cleaner water and healthier communities.

Energy inequities can take many forms. For example, according to a 2023 World Bank report[5], the percentage of the population with access to electricity is lower than 100% in many countries or regions of Africa; many people have no access to electricity at all. The same report shows that 100% of the population of the USA has access to electricity (although a 2020 article[6] reported that approximately 60,000 US citizens, particularly in remote areas such as parts of the Navajo Nation, lacked access to electricity).

But in the USA, access to clean energy is inequitable. Peaker plants (which run only when there is high demand for energy) and fossil-fuel-fired power plants with harmful by-products are more likely to be distributed in communities of colour and communities that have relatively high rates of poverty[7–11]. The installed capacity of small-scale distributed generators, which entail many benefits, is disproportionately smaller in disadvantaged households[12], and access to renewable energy or clean energy also differs among communities with different incomes or different ethnicities[13,14]. Low-income households cannot afford to install distributed energy resources (DERs)[15], and renters and households in multifamily residences cannot install rooftop solar panels[16]. In 2018, it was estimated that households with an annual income of more than US$200,000 are about four times more likely to adopt rooftop solar energy than households with an annual income of less than US$50,000 (ref. 17). This unequal distribution of rooftop solar energy has the potential to shift grid costs from high-income households to low-income households, increasing the energy burden of low-income households[18]. Similarly, unequal take-up of electric vehicles is related to income and race: electric-vehicle penetration is higher in high-income and white-majority or Asian-majority zip code areas[19], and one of the reasons for this is the lack of adequate charging stations in low-income areas[20,21], more are located in higher-income neighbourhoods[22].

In the USA, many households are unable to pay their energy bills or sustain adequate heating and cooling indoors, which is a form of energy insecurity. The 2020 Residential Energy Consumption Survey showed that 34 million households (that is, about 27% of the population) experienced energy insecurity[23]. Marginalized groups, individuals needing medical equipment and those living in low-energy-efficiency houses were more likely to experience energy insecurity[24,25]. Low-income households living in low-energy-efficiency houses will spend US$18 more per 100 square feet on utilities than high-income households[26], which indicates an increased energy burden on low-income households. It is estimated that the energy burdens of low-income and high-income households in the USA are about 10% and 3.3%, respectively[26]. Moreover, there is a higher energy burden in disadvantaged counties with larger populations of people who are older, impoverished or disabled, as well as those with limited access to health insurance[27]. To reduce their energy burden, low-income households are more likely to use unsafe alternative energy sources (that is, wood and peat) to save money, which exposes them to indoor air pollution — one of the most critical global public-health threats[28,29]. By contrast, low-income households may also use less energy by sustaining unsafe indoor temperatures in summer and winter[30,31]. Additionally, time-of-use rates and carbon taxes increase the energy bills of households with older and disabled occupants and exacerbate energy inequity[32–35].

When extreme events occur, households with different incomes have different electricity consumption behaviours. Affected by three severe winter storms in 2021, service areas in Texas with more minority populations were four times more likely to lose power than white-majority neighbourhoods[36]; Black, Hispanic and Asian populations made up 72% of carbon-monoxide-poisoning cases owing to people using unconventional heating sources[37]. In California, the energy distribution systems of low-income communities during wildfires are a safety deficit[38]. During the COVID-19 pandemic that began in 2020, more people at home during the day led to increases in household electricity consumption[39], increasing energy burden of low-income households. It was estimated that Hispanic households were 4.7 times more likely than white households to be disconnected from the grid during the early period of the pandemic and 2.4 times more likely to be disconnected after 12 months (ref. 25).

It should be noted that user income of course influences electricity consumption behaviour, and addressing income disparity will contribute to addressing the energy-equity problem. With higher or more equitable incomes, households can afford adequate energy consumption, which improves equity in the affordability of energy. However, this only addresses one aspect of the energy-equity problem (affordability), and not two other key aspects, namely, accessibility and resilience: for a community located along a distribution feeder with inadequate clean-energy infrastructure or a poorly maintained distribution network, an increase in household income alone may not improve access to clean resources or the ability to restore power after

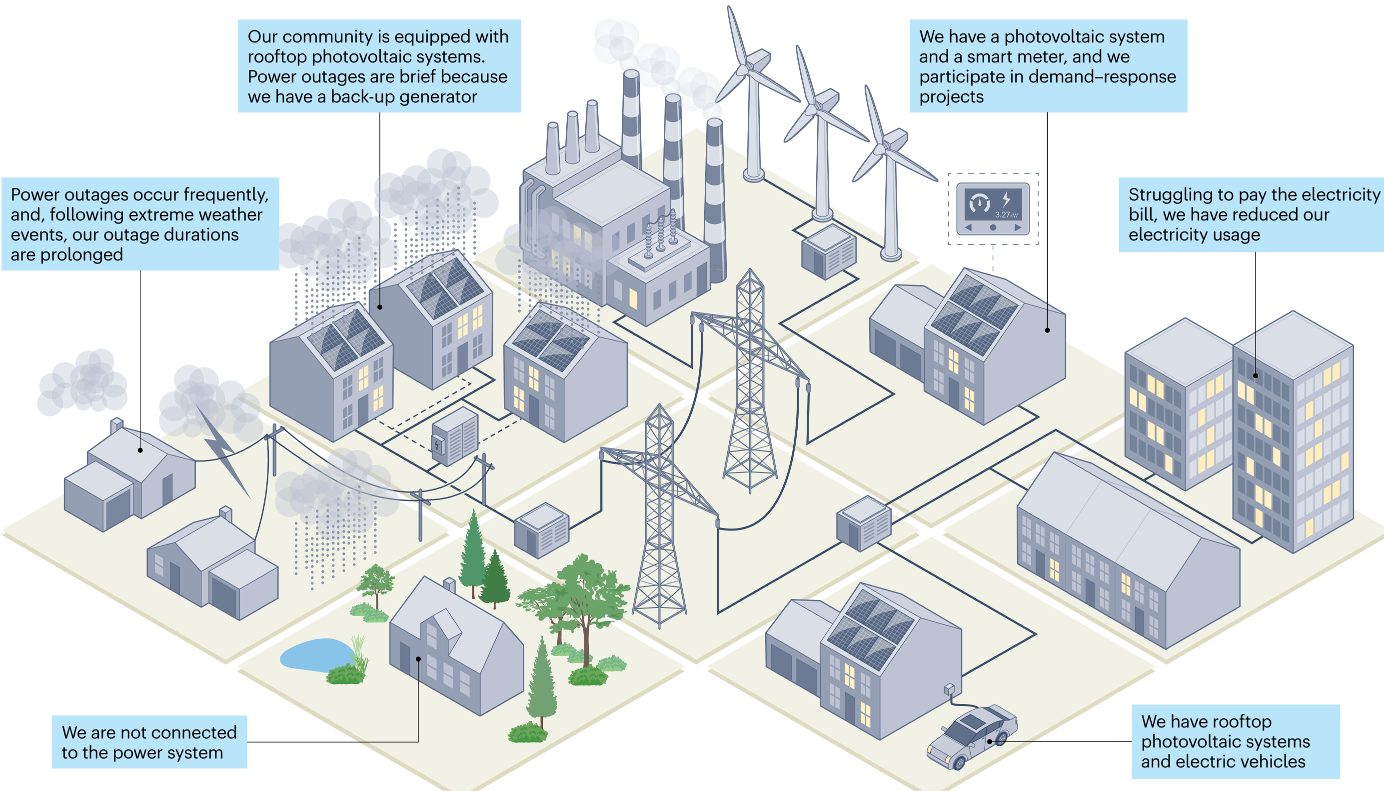

Fig. 1 | Energy inequity in electric power systems. In an electric power system, there may be households in remote areas that are not connected to any power systems. There may also be low-income households that cannot afford their electricity bills, do not have distributed energy resources or frequently lose power after extreme weather. However, the opposite is usually true for high-income households – they might have rooftop photovoltaic systems or electric vehicles, be involved in demand–response projects and have their power supply restored quickly following extreme weather events.

extreme weather events. Addressing income disparity is also a much bigger challenge, and tackling energy inequity concurrently is essential to achieve a swift and effective energy solution.

Although energy inequity in electric power systems is an urgent problem, there is a lack of effective solutions or even comprehensive understanding. In this Perspective, we first analyse the scope of terms related to energy equity and give a generalized definition of energy equity from an engineering perspective. We briefly review present policies to achieve energy equity in Europe and the USA and comment on their drawbacks. Then we discuss existing research on energy equity in electric power systems across four aspects of energy equity: quantitative methods, accessibility, affordability and resilience. Finally, we build a roadmap, setting out the problems to be solved in relation to energy equity.

Definitions

Terms relevant to energy equity include energy justice, energy burden, energy poverty, energy security and energy vulnerability.

Energy justice

The concept of energy justice is based on environmental justice and aims to provide all individuals, across all areas, with safe, affordable and sustainable energy[40,41]. This concept has been refined into three dimensions, namely, distributional justice, procedural justice and recognition justice[41]. Restorative justice has been added as a fourth dimension, which means mitigating the influence of historical energy injustice in energy systems[42].

Energy burden

Energy burden is defined as the percentage of gross household income spent on energy costs, which is calculated by dividing the average energy cost by the average annual income[43]. Here, energy cost is defined as the amount of household expenditure on electricity, natural gas and other fuels (including fuel oil and wood). Energy burden only considers the costs of energy, although other terms (such as energy justice) include multiple aspects.

Energy poverty

Energy poverty is the situation in which households are unable to access sufficient energy services[30]. In addition to a higher energy burden, households experiencing energy poverty tend to lower their household energy consumption[44,45].

Energy security

The International Energy Agency defines energy security as the uninterrupted availability of energy sources at an affordable price[46]. The dimensions included in energy security include the ability of users to pay energy bills[25,47,48], users' energy consumption behaviour[48] and the ability to protect systems from disruption by natural, human or technological phenomena[49].

Energy vulnerability

The World Energy Council defines energy vulnerability as the degree to which energy systems are able to cope with adverse events[50]. This concept encompasses multiple dimensions such as energy access[51,52], energy efficiency[51,52], energy security[52], energy affordability[51,53], energy intensity[50,53,54] and total energy consumption[52,54].

Energy equity

At present, there are many definitions of energy equity[21,55–58], each with a different emphasis, such as sharing the benefits and burdens of the grid, expanding the inclusion and participation of individuals from underserved communities in all of the programmes offered by the US Department of Energy and the private energy sector, or ensuring the affordability of electricity. Although these definitions provide valuable insights, their focus on particular dimensions of energy consumption or energy systems does not fully encompass the broader perspective needed to approach energy equity from an electrical-engineering perspective.

To address this limitation and integrate the engineering perspective of electric power systems with the concept of social justice, in this Perspective we define energy equity as: equal access to energy, equal affordability of energy and equal ability to restore energy supply in the face of extreme events, regardless of the user's race, income or social status.

The logic of this definition is aligned with the engineering process to provide reliable electricity service to consumers. In other words, a consumer needs to have access to energy service first; then, that energy service should be affordable; and finally, the service must be resilient to disturbances or faults to minimize energy-service interruption. It should be noted that equal ability to restore energy supply means ensuring that users with similar criticality levels have equal potential and opportunities for energy-supply restoration after outages: important loads (for example, hospitals, fire departments and police stations) should still have high priority in the restoration list.

Existing policies for energy equity

The United Nations Sustainable Development Goal of affordable and clean energy (SDG 7) calls for the world to 'ensure universal access to affordable, reliable, sustainable and modern energy'. Some countries, particularly those in Europe, and the USA, have enacted a series of energy-equity policies to achieve this goal, but many countries or regions of the world have yet to dedicate major policies or attention to energy equity.

Energy-equity policies in Europe

To achieve the goal of energy equity, the European Commission has created the Just Transition Mechanism, which includes a fund of €19.7 billion, a budgetary guarantee for the region-based Territorial Just Transition Plans within the InvestEU funding programme, and the creation of the Just Transition Platform providing collective technical and financial support. Beyond this European-Union scheme, many countries in Europe are also focusing on national solutions to the energy poverty problem. The UK, for example, uses an energy-burden metric to assess whether households are facing energy poverty and determine the level of support they need[59]. Italy has proposed a metric that compares incomes and expenditures with local averages and considers absolute heating needs, to obtain energy-poverty levels[60], whereas Poland applies a multidimensional index of building quality and ability to pay bills[61].

These policies are useful to some extent, and they address inequity at both macroeconomic and microeconomic levels. However, the expected results may be weakened owing to the lack of technical implementation details and various uncertainties in the process of policy demonstration[57].

Energy-equity policies in the USA

The Climate and Economic Justice Screening Tool was developed within the Justice 40 Initiative of 2023 to identify disadvantaged communities. However, it was found that placing greater emphasis on the 'vulnerability communities' identified by the screening tool is not effective in the context of wildfire resilience investments. Allocating 40% of the total budget or 40% of the total load-shed reduction to these communities failed to reduce power outages and mitigate wildfire risk for Indigenous groups, who experience higher load shedding. This is due to data loss and the lack of context specificity in the generalized vulnerability criteria used by the Climate and Economic Justice Screening Tool[62]. The US Department of Energy runs the Weatherization Assistance Program to increase energy efficiency by improving energy systems in houses. The Low Income Home Energy Assistance Program provides federally funded assistance, which is administrated at the state level, to reduce the costs associated with home energy bills, energy crises, weatherization and minor energy-related home repairs. However, a clear definition of energy poverty is not included in either the Weatherization Assistance Program or the Low Income Home Energy Assistance Program; moreover, households who forgo energy consumption to pay for other necessities are not considered. These two programmes cannot, therefore, assist all low-income households. It is estimated that the Weatherization Assistance Program serves about 100,000 households per year, which is far fewer than the 36 million households eligible nationally[63].

Many cities and states in the USA have also taken measures to reduce the energy burden of households. For example, Minneapolis, Minnesota, created a Climate Equity Plan, which requires the number of households with a high energy burden (more than 4%) to be reduced to zero[64]. In Houston, Texas, a weatherization programme has been promoted to reduce residential energy consumption and the energy burden of low-income households[65]. In Washington state, the Clean Energy Transformation Act adds and expands energy assistance programmes for low-income households[63]. Most of these policies use either income or energy burden, not both, as the criterion for determining eligibility and hence may miss the assistance needs of medium-income or high-income households. For example, medium-income households that have a notable energy cost owing to the use of medical equipment by older residents are not eligible for assistance under income-oriented policies[66]. Also, some low-income households who intentionally limit their use of electricity to reduce energy costs may not be eligible under programmes that are energy-burden-oriented[26,30]. Thus, both income level and energy burden should be considered.

Several cities and states have developed policies that attempt to solve the problem of unequal access to DERs. For example, Washington, DC, launched the Solar for All Program to provide solar electricity to 100,000 low-income households by 2032 (ref. 67). The state of Illinois developed its own Solar for All Program, providing incentives for low-income distributed generation and community solar projects[67]. The Self-Generation Incentive Program enacted by the California Public Utility Commission allocates dedicated funds to increase the adoption of battery storage in lower-income and high-fire-risk

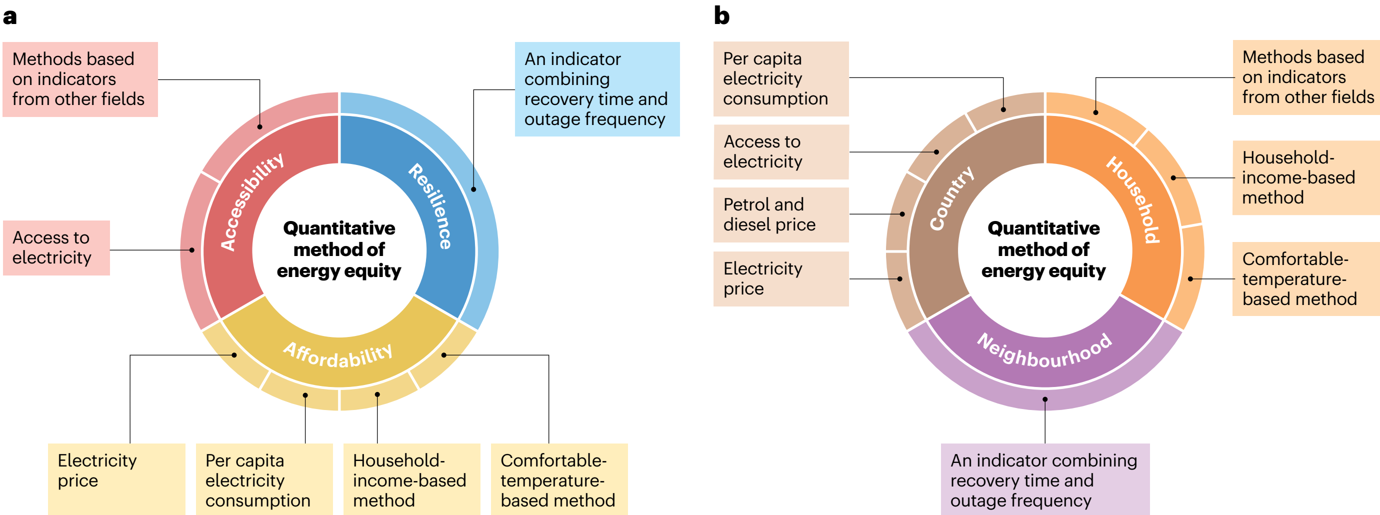

Fig. 2 | Quantitative indices of energy equity. a, Quantitative models for the characteristics of electric power systems can be broken down into a range of indices (outer circle) that relate to the three aspects (inner circle) of our definition of energy equity – accessibility, affordability and resilience. **b**, These quantitative models can also be divided into three levels of social structures – country, neighbourhood and households.

communities[68]. Oregon's Solar + Storage Program provided more rebates for low-income and moderate-income households to improve equity in installing DER[69]. Although these financial incentives have had some success in increasing adoption equity, in general the incentives have declined over time and some have even expired. Indeed, studies now indicate that photovoltaic incentives and energy policies are ineffective at increasing equity of DER adoption[68,70–73].

To ensure equity of resilience after extreme events, many state governments enact emergency policies to protect users during crises – such as banning disconnection from energy supplies or allowing payment extensions and energy-bill reductions[74]. The State of Alaska's COVID-19 policy, for example, disallowed utilities from charging late fees or interest to households experiencing financial hardship during the emergency or from disconnecting their residential utility service owing to non-payment[75]. Although these measures were effective in the short term, in the long run they increase the burden on low-income users: because energy debts are shifted to future bills, once the implementation period is over, low-income users start to incur huge energy bills, which can even lead to bankruptcy[25,36].

Categories of research in energy equity

We categorize the existing efforts to study energy equity in electric power systems into four categories. The categories are: quantitative indices of energy equity, improving equity in the accessibility of electricity, improving equity in the affordability of electricity and improving equity in the resilience of power systems.

Quantitative indices

To analyse the energy-equity problem effectively, it is essential to integrate the sociological concept of energy equity with the engineering characteristics of power systems. A number of different quantitative indices have been developed for such analysis. The classification summary of the quantitative models based on the three aspects of our definition – accessibility, affordability and resilience – is shown in Fig. 2a.

In terms of accessibility, there are two methods: access to electricity[76,77]; and external indicators taken from other fields of study, such as Jain's fairness index[78] and the combined approach of Wilson coefficients and the Gini coefficient[79]. Much existing research has focused on affordability and here multiple quantitative indices have been proposed to quantify energy equity, including electricity price and per capita electricity consumption[76,77], and the household income-based method, focused on concepts such as energy burden[47,48,80–82] and net energy return, which is the ratio of net income (that is, income minus energy expenditure) to energy expenditure[66]. The comfortable-temperature-based method has also been proposed, which refers to the different outdoor temperatures at which households turn their electricity-based cooling and heating units on and off between low-income and high-income households[30,31]. To quantify resilience inequity, an indicator combining the recovery time and outage frequency has been suggested[83].

These quantitative indices can also be categorized based on social structure – country, neighbourhood and households – as shown in Fig. 2b. To quantify the degree of energy equity for a country, the World Energy Council in partnership with the consulting firm Oliver Wyman published three indexes: access to electricity, electricity price and petrol and diesel prices[76]. Indexes for access to electricity and per capita electricity consumption have been developed to analyse energy equity in Bangladesh, India, Nepal, Pakistan and Sri Lanka for the period 2000–2017 (ref. 77). Recovery time and outage frequency have been combined to analyse resilience equity of neighbourhoods[83]. For households, quantitative methods for assessing energy equity can be broadly divided into three categories: the household income-based method[25,47,48,66,80,81], the comfortable-temperature-based method[30,31] and the quantitative method based on indicators from other fields[78,79]. (The details of these three categories are the same as mentioned earlier).

In either approach (Fig. 2a,b), there is at least one quantitative index for evaluating energy equity in each aspect. However, existing quantitative indices do not capture the inequity of access to DERs, give a comprehensive assessment of users' income and electricity consumption or analyse whether users are more vulnerable to power outages. The lack of a comprehensive quantitative system for analysing energy equity in power systems remains a barrier to further research.

Improving equity in accessibility
Existing research on energy accessibility focuses mainly on access to clean energy and consists of two categories of technical problem: the planning problem for electric-vehicle charging stations, and the siting and sizing problem for DERs. An optimization framework considering equitable resilience and resource utilization has been proposed to guide the development of charging infrastructure for electric vehicles across New York City[83]. Energy management of smart parking lots has been developed, considering social equality in access, to optimize the generating and storage schedules of mobile charging stations[20]. To minimize the energy burden of a given population of energy-insecure households, a linear programming model has been used to calculate the optimal portfolio of interventions, including weatherization, rooftop solar energy, community solar energy and community wind energy[48]. Generalized guidelines for installing distributed generators have been proposed to reduce the energy burden of low-income households and achieve energy equity in distribution systems[82].

All the aforementioned studies have considered energy equity during the planning optimization stage, but none has quantified the rates of access to DERs. Therefore, the effectiveness of these models in improving the equity of accessibility remains to be investigated.

Improving equity in affordability
Currently, the research that we classify as improving equity in affordability is focused on the analysis of electricity prices in the distribution market. Time-of-use rates have increased the bills of households that have older and disabled occupants because these populations have a greater reliance on energy for medical equipment and are constrained in load shifting[32]. Policies based on volumetric consumption to recover fixed costs favour affluent income groups[84]: in relation to this problem, a bilevel model considering economic efficiency and energy equity was developed to study the optimal design of retail electricity tariffs; the study concluded that the most efficient policy was to provide financial compensation directly to low-income households[80]. However, in the USA, there is a lack of information exchange between the Federal Internal Revenue Service and utility companies, and the implementation of such income-based compensation policies would require changes in the political and legal landscape[80].

A mechanism to charge users equitably has been proposed, which regularizes the distribution-system operator's social welfare objective function with Jain's index of fairness[78] — however, the charge mechanism emphasizes fairness, rather than improving affordability for low-income households. In the peer-to-peer market, a shareholding-based resource-sharing mechanism was proposed to share distributed-energy-resource assets and to improve individual energy utilization and energy equity[79]. This mechanism assumed that all households have a DER and an energy storage system, but many low-income households have neither. Considering energy equity in the constrained electricity market-clearing model, an energy-equity-driven multiplayer framework has been proposed to establish differentiated pricing for participants based on their income levels[85]: market participants were divided into three layers — high burden, medium burden and low burden. The market-clearing process was conducted sequentially, starting with the high-burden layer and progressing to the low-burden layer, thereby promoting energy equity. However, although this approach addresses energy equity through energy burden, other factors such as variations in energy consumption behaviours need to be included in future studies. In conclusion, current research has not fully solved the problem of affordability equity.

Improving equity in resilience
Resilience refers to the ability to 'keep the lights on' during extreme events such as summer heatwaves, wildfires and polar vortices; reliability pertains to maintaining power during not-so-extreme events, such as equipment failures, owing to ageing or protection-device malfunctions. Both concepts emphasize the capacity to supply electricity after disturbances, but extreme events often lead to more severe and widespread infrastructure damage. If grid resilience is improved, it follows that the grid must also be robust enough to maintain good reliability under less severe conditions. In other words, a power system that provides adequate resilience for all users, including low-income communities, also ensures acceptable reliability. Therefore, in this Perspective we prioritize equity in resilience.

Energy equity related to the resilience of power systems has not been extensively studied. However, unequal resilience is a pressing problem, as low-income households tend to be in areas where distribution facilities are in poorer condition and are thus more vulnerable to power outages. To solve this inequity, a cost allocation scheme with an income threshold has been proposed to improve distribution facilities, and it requires that if a household's income falls below the threshold, the cost is borne by utility-wide ratepayers; otherwise, the cost is borne locally[38]. Considering that electric vehicles can serve as power resources over short time periods, an optimization framework for the allocation of charging stations has been proposed to improve the equitable resilience of power systems and resource utilization[83].

There are three steps for dealing with extreme events and improving the resilience of power systems: planning before events, operation during events and recovery after events. Energy equity should be considered at each step, but research thus far has focused primarily on the stage of planning before events. More research on improving equity of resilience is needed.

Challenges in achieving energy equity
There is still a long way to go to achieve energy equity in electric power systems. We now set out a roadmap (summarized in Fig. 3) to implement energy equity, highlighting both technical and application-related challenges .

Technical challenges
Energy-equity-enabled metrics. Energy equity is a sociological problem. It is generally difficult to solve technical problems in electric power systems while simultaneously considering sociological factors because there is no bridge between the elements of power-system models and the elements of sociological concerns. The energy-equity problem calls for a quantitative set of metrics to create that bridge and cover this gap.

There are economics-oriented and resilience-oriented indices that can be used to characterize power systems — for example, DER access rate, electricity bills and outage duration and frequency, as shown in Fig. 3. A quantitative system of energy equity can be built from the power-system perspective by revising or expanding these existing indices to develop specific new considerations or indices of energy equity. As previously discussed, several quantitative indices developed in research on energy equity are based on existing indices used to characterize power systems. For example, the energy burden obtained based on electricity bills has been used to analyse the energy equity in power systems[43,82], and the indicator combining the recovery time and outage frequency has been applied to analyse the resilience inequity of neighbourhoods[83].

Energy-equity-oriented planning. System investors tend to optimize the operation state of power systems or improve the resilience of power systems by installing distributed generators, energy-storage systems and electric-vehicle charging stations or by upgrading system infrastructure. These problems are formulated as an optimization model, which contains variables and parameters that are based on common measures in electric power systems. Here again, it is difficult to integrate the sociological concept of equity into the original engineering problem. Specifically, in addition to the challenge of developing adaptive quantitative indicators of energy equity, it is also difficult to integrate the indicators into the original optimization model and then solve the model.

A possible approach to deal with the aforementioned difficulties is to create quantitative indicators of energy equity based on measures in electric power systems and then integrate those indicators into the objective function (which defines the goal of the optimization), or model energy-equity requirements based on those indicators as additional constraints in the original optimization model. For example, energy burden can be used to quantify energy equity, then constraints on energy burden can be added to the original model to optimize the strategy for installing distributed generators – the result is greater equity in the affordability of the distribution system[82].

Energy-equity-equipped operation. Economical and stable operations are key for electricity users. At present, the electricity price is determined by minimizing the cost of generation. For low-income areas in a power system, this electricity price may still be too high to maintain a comfortable lifestyle. Additionally, downstream households in the distribution system – often low-income households – will have higher prices owing to voltage limits and power losses if local and distribution market operation is implemented[82]. There is urgent need to improve the equity of affordability by considering energy equity in the electricity pricing mechanism.

In terms of the electricity price in the transmission market, the goal of achieving affordability equity could be regarded as a penalty in the generation cost function. Then, part of the electricity price will be formed from energy inequity. For instance, an additional component has been incorporated into the locational marginal price to reflect power system uncertainties in market clearing[86,87]. The clearing and pricing mechanism in the distribution market is changed by emphasizing energy equity as a goal of energy trading. This shift, which incorporates sociological concerns in the engineering problem and leads to different solutions, has been demonstrated in peer-to-peer energy sharing. It has been observed that consideration of specific users' social attributes (such as income and power usage habits) in peer-to-peer energy sharing leads to different scheduling strategies at the demand side compared with those obtained without considering these factors[88].

Application challenges

Gap between research and practical application. In electric-power-systems research, usually standard test systems or simplified test systems with sufficient measurements are used. However, low-income communities may be served by a small utility that does not have complete measurements and data or the resources for full-scale complex analysis. In this case, generalized guidelines obtained from multiple test systems could be helpful. An example of a generalized guideline given to improve equity in affordability is that it is generally more effective to install distributed generators near low-income communities in the downstream of feeders if there are multiple low-income communities spread throughout a distribution system[82]. Further generalized guidelines should be sought, to improve other aspects of energy equity in low-income communities.

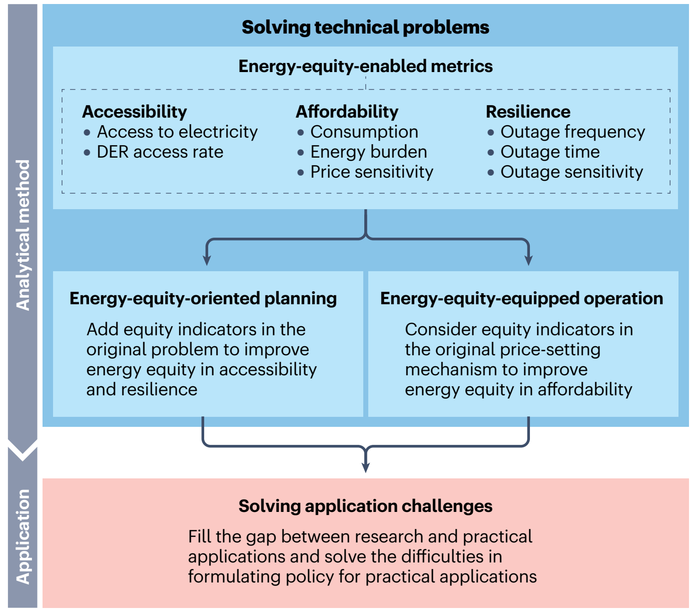

Fig. 3 | A roadmap for implementing energy equity in electric power systems. There are two steps in implementing energy equity in electric power systems: first, the analytical method and then its application. The analytical step involves building a quantitative system of energy equity and solving power-system planning and operation problems with a strong focus on energy equity. In the application step, the challenges are to bridge the gap between research and practical application and to enact useful policies. DER, distributed energy resource.

Difficulty of formulating policy for practical applications. Fundamental transformations of the present power-system scheme are inevitable if the goal of energy equity is to be achieved. An effective policy and its successful implementation rely heavily on consensus and acceptance by a broad group of participants, including low-income and high-income communities. Hence, the reasons for implementing energy-equity policy need to be clearly recognized. Those reasons are: first, that energy inequities among consumers within an electric power system can exacerbate community polarization and cause social and economic challenges; second, that the absence of affordable energy can impede the participation of low-income households in a range of career-development paths and reduce societal productivity; and third, that achieving energy equity ensures low-income households can also meet their individualized essential needs (unlike a flat-rate discount or rebate programme which does not recognize or differentiate households of different income levels).

Energy-equity policies should not only meet the basic needs of low-income communities but also convince other communities, such as high-income communities, that everyone will benefit in the long run.

Previous practice and approaches to equity in education, now accepted by broad communities, might offer some useful insights for implementing energy equity. For instance, communities with high-value properties incur higher property taxes, part of which can be used to fund primary and secondary (K-12) schools that benefit low-income families in the same area[89]; and the provision of free school lunches to students from low-income families is now a broadly accepted approach for achieving educational equity. Similarly with energy, it is necessary to explore broadly acceptable technical approaches for long-term benefits, such as DER planning strategies, variable tariff rates based on income and tariff compensation mechanisms for low-income communities. Sound research studies and subsequent policy implementations have the potential to achieve energy equity in accessibility, affordability and resilience in the future.

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Author contributions

F.L. conceived the idea for the study, revised the manuscript and supervised the project. C.L. conducted the research and led the writing of the initial manuscript. S.J. and J.W. participated in the discussion and commented on the manuscript.

Competing interests

The authors declare no competing interests.

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