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Perspective

Energy justice beyond the wire: Exploring the multidimensional inequities of the electrical power grid in the United States

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ABSTRACT

This Perspective applies a multidimensional, whole-systems energy justice lens to the electrical power grid, conceived of as the national electricity transmission and distribution network in the United States. The electrical power grid exists primarily to provide reliable and safe energy services to anyone and everyone, and at any time of the day. It represents a massive system of physical infrastructure that most scholars treat as agnostic and inherently void of equity dimensions. But underlying the poles and wires are a complicated set of challenges that have equity implications. For example, better power lines are installed in wealthier neighborhoods; lower-income neighborhoods experience blackouts significantly more often than higher-income neighborhoods; and the siting of transmission infrastructure infringes on local communities and ecosystems. In this Perspective, we discuss the philosophical underpinnings of justice and equity, define energy justice, and discuss how the grid can cause and perpetuate four different types of inequity: demographic within social groups and communities, spatial across urban and rural locations, temporal across time, and interspecies in terms of damaging the environment. We chart these four dimensions with twelve distinct examples and provide recommendations to create a more equitable and just future grid.

1. Introduction

The electric grid is expanding, with the total number of power lines worldwide increasing at a rate of 5 % per year, including both transmission lines (generally >69 kV) and power distribution lines (2.4–60 kV) [1]. Yet, in many places around the world, including in the United States, the need for grid expansion and investment far outpaces actual development. Such investment is needed to upgrade existing, outdated transmission and distribution (T&D) infrastructure [2]. Increasingly, investment is also needed to 1) achieve climate change mitigation goals by facilitating expansion of clean energy infrastructure and distributed energy resources, as well as 2) expand climate change adaption protections that enhance grid resilience and reliability under conditions of increasingly virulent weather. These investments will support more high voltage direct current lines, distribution lines, and microgrids, among other electricity infrastructure priorities.

The expansion of the electric grid provides a dual opportunity to pursue decarbonization and energy justice. Expanding energy infrastructure to ensure that such developments do not place undue burdens or disproportionately benefit certain populations requires deliberate intention and action, informed by a well-conceived energy justice framework.

The electrical power grid is not, in and of itself, either just or unjust. After all, the grid is colloquially a bunch of poles and wires, substations and transformers, all facilitating the flow of electrons (current) from one place to another while managing voltage. Albeit an oversimplification, Fig. 1 provides a schematic representation of these elements. The grid is built to provide reliable and safe energy services to everyone at any time of the day or year.

Yet, a careful examination of grid operations reveals a system with inequities spanning from the geographic incidence of blackouts to the toxic release of sulfur hexafluoride, to the disposal of the wires, and to disparities across socioeconomic groups in their risk of grid failure during adverse weather events. In this Perspectives article, we employ a guiding framework previously proposed by Sovacool and colleagues [20] to categorize and synthesize these inequities—which includes

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demographic, spatial, inter-species, and temporal dimensions—then provide several real examples of each. We conclude with preliminary suggestions for addressing several of these challenges.

In doing so, we aim to make multiple contributions to the literature. While a small but growing corpus of studies examines equity and justice impacts of the grid or power lines, they tend to lack a holistic approach, wherein they typically study only one type of justice, or at only one part of the grid, or at only a single community or location. Examples include Bailey et al., who investigate power line proposals, and emphasize community equity concerns in Nailsea, the United Kingdom [4]. Kundson and colleagues examine high voltage transmission lines, and emphasize procedural justice concerns in Norway and the United Kingdom [5]. Komendantova and Battaglini examine social opposition against two electricity transmission pilot projects in Germany [6]. Kazimierczuk and colleagues utilize an equity lens to study electric grid policy, regulation and planning [7]. Other studies have looked at the equity and justice issues over demand response [8], system flexibility [9], or flexibility justice [10]. What is so far missing is a holistic exploration of the equity and justice issues across *multiple dimensions* but also *the whole system* of the electrical power grid with a comparative evidence base across *multiple locations*. We seek to address this gap head on with a multidimensional conception of energy justice coupled with a whole-systems examination based on published literature across the entire United States.

2. Energy justice: philosophical underpinnings and definitions

As a precursor to discussing the definitions of energy justice and equity, we explore the philosophical origins of these concepts as a foundation upon which more commonly identified definitions build. Since the classical philosophers, justice has been considered a fundamental virtue and a framework for the legitimate use of political power. In his *Nicomachean Ethics*, Aristotle viewed justice as the essential virtue that enables citizens to share the benefits and burdens of the city-state cooperatively. He defined two senses of justice: universal and particular.

Aristotle's *universal justice* connotes the "common advantage and happiness of the political community" [11]. Later scholars, including Adam Smith, built on Aristotle—as well as Plato and Zeno—to define *commutative justice* as abstaining from doing positive harm to a person, a person's property, or a person's reputation [12]. Commutative justice forms the foundation of legal codes and the concept of negatively-defined rights embedded within such codes. The related moral standards prescribed by the rule of law, and the notions of equal treatment and equality before the law, reflect the fundamental nature of commutative justice as a virtue. That is, one should strive to do no harm to other entities.

Aristotle's *particular justice* adds the concept of "equity" or "fairness", which have had contested definitions ever since, complicated by the extent to which "fairness" is a highly social and context-specific concept, and is not itself a moral foundation or directive [13]. Particular justice incorporates the idea of desert or deservingness, or, alternatively phrased, of a person receiving their due. It also includes distributive justice, the equitable allocation of resources, including both costs and benefits. More recently developed concepts within particular justice include environmental justice, the equitable treatment of individuals with respect to environmental benefits and burdens, and social justice, "that all people should have the same rights and opportunities and that a country's wealth and resources should benefit everyone in that country" [14].

John Rawls' "justice as fairness" has been an influential concept of justice [15]. Rawls defined two principles of justice: 1) every person has an equal claim to equal liberty, compatible with equal liberty for all; and 2) inequalities of outcomes must satisfy two conditions. These two conditions are equality of opportunity and the difference (or maximin) principle, which states that distributive outcomes should be to the greatest benefit of the least advantaged in society [16].

These various philosophical notions of justice have been contended over centuries, as many people have defined them differently and have conceived of different institutional ways of operationalizing them. One area of disagreement has been whether the notion of equity embedded in the various forms of particular justice are *procedural* or *outcome-based*. Does equity require equal access to institutional processes, or does it

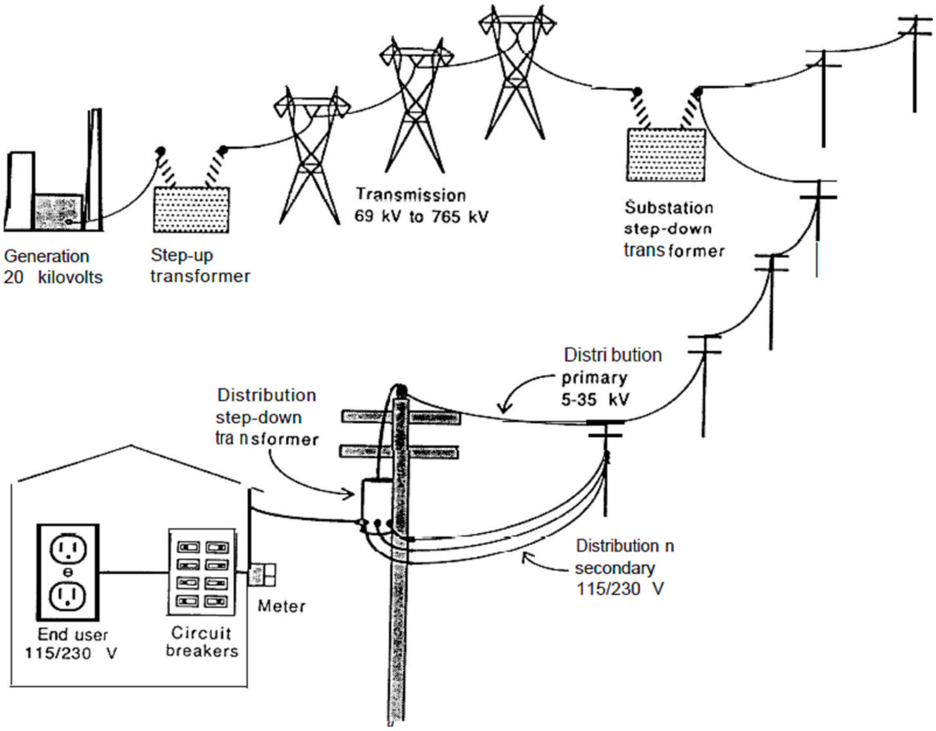

Fig. 1. Schematic representation of the electrical power grid.
Source [3], used with permission.

require particular material outcomes? A procedural conception of distributive justice emphasizes equality of opportunity and access rather than *ex post* redistribution. This distinction, although blurry in certain contexts, lends itself to modern definitions of procedural and distributive justice.

To the extent that distributive justice implementation interacts with economic activity, this distinction between procedural and outcome-based can affect incentives for production and the productivity and wealth of a society— one important dimension of Aristotle's definition of flourishing. If a procedural conception of distributive justice would yield more productive economic activity, that outcome creates more opportunities, while a conception focused on *ex post* redistribution could undermine economic activity. In contrast, arguments for redistribution emphasize reduced productivity arising from situations in which the least advantaged bear disproportionate burdens.

Energy justice, by a modern definition that is a descendent of these philosophical roots, refers to a conceptual approach involving *costs* of energy services, policies, and byproducts of energy systems such as pollution; the fairness (or unfairness) in ownership of, exposure to, and capture of *benefits*; the impartiality, inclusivity, and representativeness of *procedures*; and the *recognition* of vulnerable and traditionally marginalized groups [17]. Energy justice therefore employs elements of distributive, procedural, and recognition justice, a cumulative concern for the wellbeing and lack of harm to all beings, as well as cosmopolitan concerns of human rights, the incidence of global externalities, and recognitional concerns of vulnerable groups, dispossessed minorities, and varying species [18].

To capture an array of justice concerns and dimensions, including these philosophical underpinnings and this modern definition, we apply and extend a multidimensional and whole-systems energy justice framework, combining elements of scale and lifecycle [19,20] with four dimensions of inequity [21]. Energy justice through a "whole systems" lens, which is inclusive of the standard tenets of energy justice as well as a cosmopolitan extension of energy justice, can reveal potential justice impacts across an entire lifecycle supply chain of a given technology or system. A whole-systems approach also suggests the possibility, for any given technology or system, of four different categories of possible energy inequity, all of which deserve concerted consideration:

- Demographic: unfair adoption patterns or impacts within social groups, often categorized by gender, income, age, levels of education, family size, or race and ethnicity;
- Spatial: geographic separation between positive externalities, risks or benefits and negative externalities, risks or benefits;
- Interspecies: destruction of ecosystems, habitats, and the extinction or harm of non-human life;
- Temporal: burdens shifted to future generations or issues of intergenerational equity.

Such an approach situates justice concerns across multiple scales, and multiple dimensions of energy justice, adding a degree of pluralism not often found in the existing literature [22].

3. The multidimensional inequities of the electrical power grid in the United States

This section applies our multidimensional and whole-systems energy justice framework to reveal interlinked and overlapping inequities in the electrical power grid. To summarize how we compiled evidence for this section, having first selected our justice framework, we then searched the published literature, inclusive of academic papers and policy or technical reports, for studies that used words such as "equity," "equality," "vulnerability," "justice" and "injustice" alongside words such as "grid," "transmission," "distribution," and "power network." From these searches, we read all of the collected material (about 100 studies) for examples that fit the framework published over the past 20 years. This makes our approach more deductive rather than inductive. It also means that there are many possible dimensions to inequity that are not covered in the study. Table 1 summarizes twelve distinct examples from the extant literature in the context of the electric grid, three per dimension of equity, yielding an illustrative but not exhaustive list. We provide a brief overview of each in turn.

3.1. Demographic inequity

One form of demographic inequity built into the grid reflects variations in blackout exposure by income or race. Lower income households and neighborhoods are more vulnerable to blackouts, less likely to have backup power (e.g., battery storage), and are less able to recover quickly following blackouts [23]. During the failure of the Texas power grid during a severe winter storm in 2021, which left >4.5 million people without electricity for several days, communities with a higher share of a minority population were four times more likely to have suffered a power outage [24]. In particular: predominantly white areas had an 11 % chance of experiencing an outage compared to a 47 % chance in areas with high shares of communities of color. Fig. 2 shows these trends in Houston, Texas, from February 14–18, 2021. Given that communities of color are surrounded by less critical infrastructure such as hospitals, police stations, and water treatment facilities—a set of inequities in and of themselves—they are prone to earlier and longer periods of blackouts, while system operators protect areas with critical infrastructure first. Numerous studies from other contexts and time periods have also confirmed such social and economic disparities in terms of electricity system restoration, frequency of power outages, and duration of longer power outages, which all affect disadvantaged groups disproportionately. [26–29] Minority groups are also often the last to recover after a natural disaster that affects the power grid such as a Hurricane, are the last to receive emergency services, and in some cases have been scapegoated as causing the blackout [30,31].

Grid siting is necessary for the maintenance and expansion of our energy systems. Disproportionate siting of grid infrastructure such as high-voltage transmission lines—which are always expensive and time-consuming to build—can also occur by income or race, with poor patterns of procedural justice, where residents are often excluded from the planning of infrastructure development. A lack of procedural involvement can lead to the perception among some residents that the grid is a burden on low-income or minority communities [33,34]. Such perceptions are only exacerbated by a general lack of trust among the public of both government and utility companies [35]. In New York state, scholars

Table 1
Summarizing multidimensional inequities with the electrical power grid.

Demographic inequity (between groups)	*Spatial inequity (across geographic scales):*
- Variations in blackouts by minority status - Unfair siting of grid infrastructure by income or race - Concentration of power outage impacts among vulnerable groups and those with medical conditions	- Environmental hazards including health issues and wildfires - Uneven siting of grid infrastructure across rural communities - Concentration of blackout risks to peripheral areas
Interspecies inequity (between humans and non-humans):	*Temporal inequity (across future generations):*
- Emissions and leakage of SF6 - Avian mortality with T&D lines - Land use impacts of T&D corridors (deforestation, clearing land for rights of way)	- Failure to upgrade the grid for wildfires or other climate events - Failure to upgrade the grid, especially transformers and high-voltage sub-stations, against future terrorist attacks - Embedded risk of electronic waste for future generations

Source: Authors.

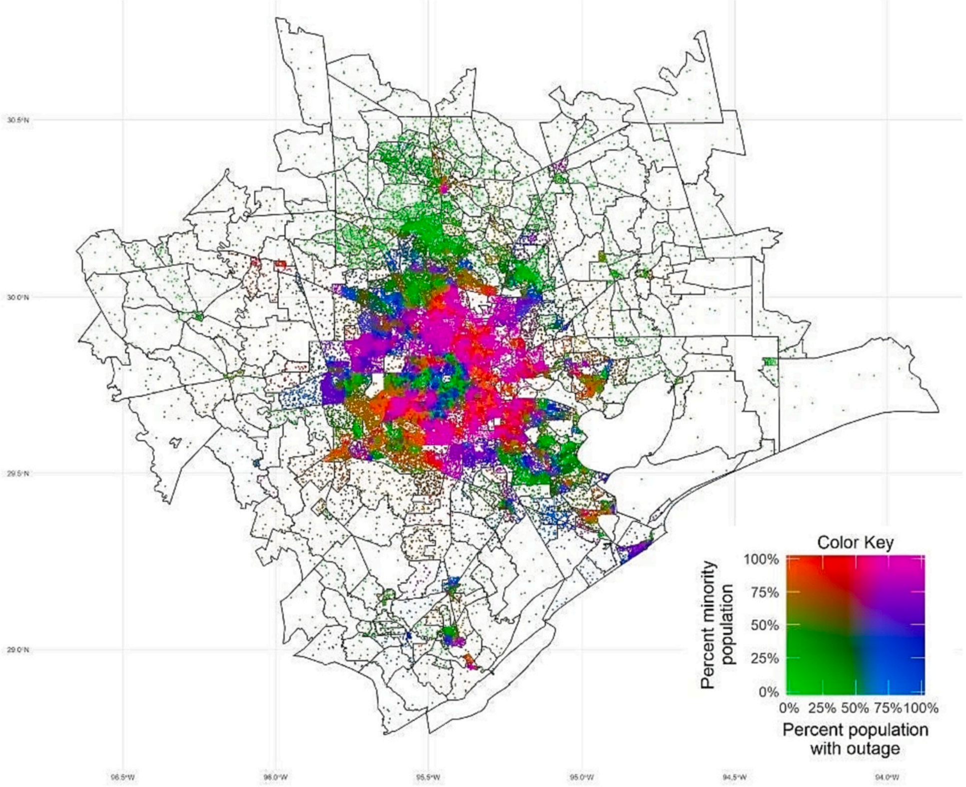

Fig. 2. Map of the Houston, Texas, Metropolitan Statistical Area showing proportions with blackouts and minority populations during the winter storms of February 14–18, 2021.
Source: Each dot represents 100 people.

found the distribution of high-voltage transmission lines to be strongly skewed by race, income, homeownership status, and level of education [36].

A final demographic inequity relates to the concentration of grid outage impacts among vulnerable groups, especially those with medical conditions. Multiple studies have shown that blackouts have potent negative health impacts including poisoning from carbon monoxide and temperature related illnesses, and can even result in death when those with cardiovascular, diabetes, or respiratory diseases cannot rely on electricity-dependent medical devices at home, especially those who need oxygen concentrators [37–39]. Blackouts that occur in conjunction with heatwaves can lead to heat exhaustion and stroke, especially for those living in poor housing stock that depend on air conditioning to keep cool [40]. A secondary concern can be the failure of wastewater treatment plants, telecommunication networks, and transportation hubs in the wake of a blackout, which also tend to be more frequently interrupted, and less resilient, in minority areas.

3.2. Spatial inequity

In terms of spatial inequity, environmental hazards related to T&D construction and operation, including health issues, are concentrated unevenly in rural areas as well as other areas near transmission corridors. Overhead lines in particular can visually intrude into landscapes, generate radio noise, buzzing, or humming, and can negatively affect property values [43]. More seriously, power lines can frequently cause wildfires, which usually occur during periods of elevated fire danger (e.g., heatwaves) and produce even more daunting consequences. Examples include California's deadliest wildfire, the 2018 Camp Fire, which was caused by transmission lines owned and operated by Pacific Gas and Electric Company and induced billions of dollars in damages [44].

Power lines also generate magnetic fields that can be damaging to human health. U.S. Navy studies have concluded that exposure to even low intensity electromagnetic fields is linked to elevated triglyceride levels, stress, and adverse behavioral affects. The National Institute of Environmental Health Sciences has determined a weak link between magnetic fields and cancer, with strong evidence of health among occupationally exposed adults such as electric utility workers, machinists, and welders [46]. More recent epidemiological evidence suggests that residence very close to power lines is associated with greater risk of childhood leukemia [47]. As Table 2 indicates, these spatial burdens can involve not only overhead transmission lines, but also underground cables and even subsea cables.

A second spatial inequity relates to the uneven siting of grid infrastructure across rural areas, in some cases not providing affordable access to electricity for those who host the infrastructure. Rural residents often oppose the construction of extension of transmission lines [49], but have such infrastructure imposed on them regardless, including governments that claim eminent domain or declare rights of way [50]. This pattern holds especially true across federal lands and tribal areas in the United States, and reflects a pattern of pushing necessary but socially unwanted infrastructure out from core, urban regions to the social, political, or spatial periphery, where communities have less power and resources to oppose them [52]. Frustrations by affected residents can be further worsened by the perception of authoritarian or undemocratic planning processes, in which residents may feel that the benefits of grid infrastructure are not shared by the community, who are instead left with "altered landscapes and continued peripherality." [53]

A final spatial inequity is the concentration of blackout risks to peripheral areas. The number of blackouts and brownouts is increasing rapidly; one assessment calculated that blackouts have increased 60 % between 2015 and 2021 [54]. The risk of these outages however is concentrated in particular geographies. Two-thirds of residents from Atlanta, Georgia, Detroit, Michigan, and Phoenix, Arizona would be at

Table 2

The concentrated burdens of electricity transmission infrastructure on nearby communities.

	T&D losses	EMF	Infrastructure	Visual intrusion	Noise	Property values	Interruption of supply	Land use	Ecosystems
Overhead lines									
Construction	−	−	++	++†	++	−	−	++	++
Operation	++	+*	−	++†	+	++	++	+	+
Dismantling	−	−	−	−	+	−	−	−	+
Underground cables									
Construction	−	−	+	++	++	−	−	+	++
Operation	+	−	−	−	−	+	+	+	+
Dismantling	−	−	−	−	−	−	−	−	−
Undersea cables									
Construction	−	−	+	−	−	−	−	−	++
Operation	+	−	−	−	−	−	+	−	+
Dismantling	−	−	−	−	−	−	−	−	−

Source: ++, significant impact, +, moderate impact, −, minor impact. * * Urban/populated area and rural, high-value landscape. † †Urban/populated area. T&D = transmission and distribution. EMF = electromagnetic fields.

risk for heat-related health conditions if a heat wave and a blackout were to occur simultaneously [55]. Another assessment of social vulnerability, medical vulnerability, and electricity outages found the greatest risks are concentrated in Louisiana, Ohio, and West Virginia. Research examining power outages from 2018 to 2020 across 2447 US counties (73.7 % of the US population) and 520 million customer-hours without power annually found that outages took place with greatest prevalence in Northeastern, Southern, and Appalachian counties, and that Arkansas, Louisiana, and Michigan counties experienced a dual burden of frequent 8+ hour outages, highest incidence of social vulnerability, and prevalence of electricity-dependent durable medical equipment use [57]. Rural areas also take longer to recover from blackouts—they have longer durations of an outage and slower and uneven restoration times—compared to urban areas [58]. Fig. 3 plots the location of severe power outages caused by natural disasters on the United States power grid in 2019, and shows a spatial concentration in the mid and south-eastern states.

3.3. Interspecies inequity

Interspecies inequities encompass environmental damages from the grid in the form of greenhouse gas emissions, habitat and species loss, and land use. For instance, the most persistent and potent greenhouse gas, sulfur hexafluoride, or SF6, is used extensively in the electricity supply industry as an arc quenching and insulating gas in electricity transmission and distribution networks [60]. However, a single ton of SF6 is equal to 23,500 tons of carbon dioxide, and it remains in the atmosphere for 3200 years, affecting not just humans but also our interspecies counterparts [61]. SF6's popularity as the "preferred gas" of the transmission industry is attributable to many of its features: it can be used across the medium to high voltage spectrum; its dielectric strength is constant; it has high heat capacity and low viscosity; it is cheap; and it is widely available [62,63]. But it also has serious and long-lasting impacts on climate change. Losses and leaks of SF6 are common and occur during manufacturing, maintenance, and malfunctions, with common annual leakage rates of up to 3 % per year and some of the worst performers at a rate of 10 % per year for those that produce additional leakage during maintenance [64]. 80 % of SF6 emissions come from the electricity transmission and distribution sector, and even though global annual production of SF6 is estimated to be about 8000 tons, it is equivalent to the annual greenhouse gas footprint of *40 million* passenger cars [65,66]. As Fig. 4 indicates, global concentration of SF6 have almost tripled over the past two decades.

Avian mortality with transmission lines is another interspecies impact. Electrocution and collision with power lines and pylons have been long acknowledged as a serious threat to avian wildlife, killing up

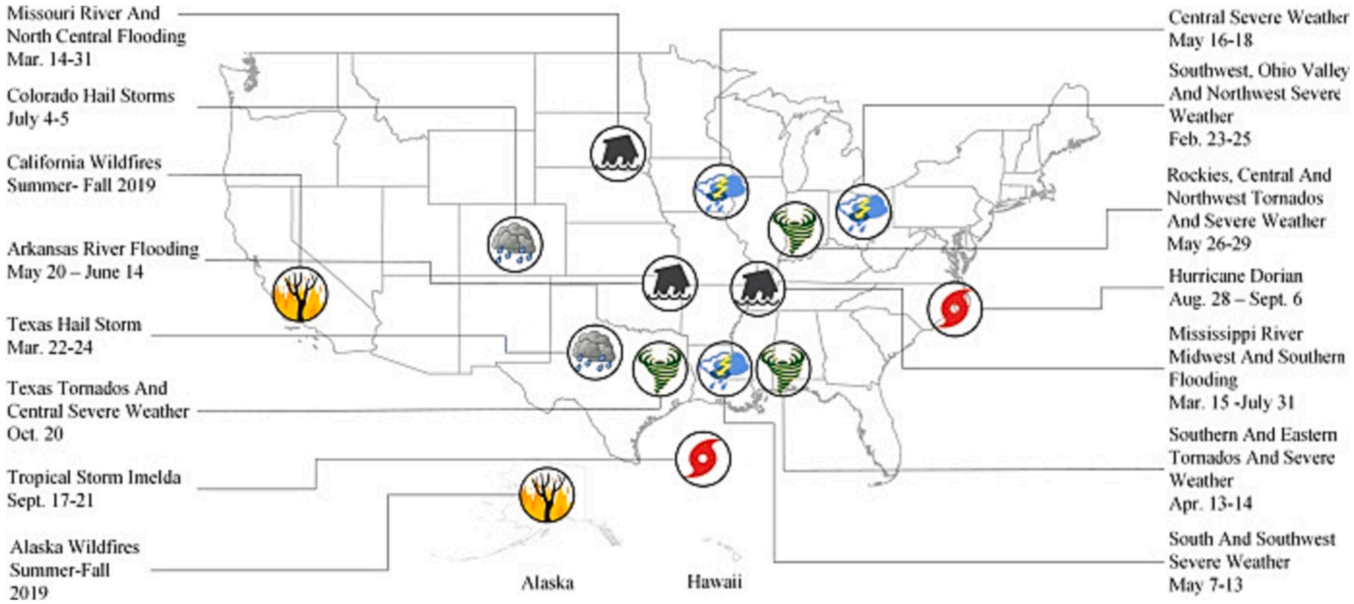

Fig. 3. Severe power outages caused by natural disasters occurring in the United States, 2019.
Source: [59].

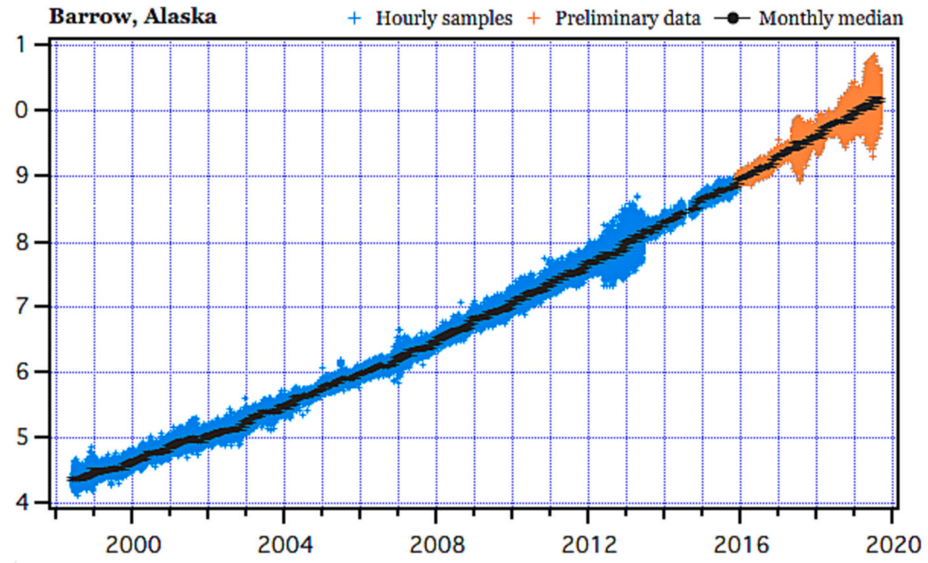

Fig. 4. Concentrations of SF6 in the atmosphere from 2000 to 2020 (in parts per trillion).
Source: National Oceanic and Atmospheric Administration atmospheric monitoring laboratory, showing a chromatographic time analysis of atmospheric SF6 at Barrow, Alaska.

to 64 *million* birds annually in the United States and one *billion* birds globally pear year. These avian deaths can also produce secondary effects such as when bird carcasses serve as hosts for botulism and cause death and disease among scavengers and other wildlife. Poor fliers such as ducks, heavy birds such as swans and cranes, and birds that concentrate in flocks are all at an elevated risk of striking power line infrastructure [68], along with birds that are young, have large bodies, or have low maneuverability [69]. The loss of birds is most significant where power lines cross migratory paths; intersect with feeding, nesting, or roosting sites; or are sited adjacent to major avian use areas. Heightened risk is also present when land topography funnels birds into corridors of power lines, a particular threat to endangered bird species of small populations [70].

A third interspecies inequity is land use impacts of the grid including deforestation and clearing land for rights of way. There are approximately 250,000 km of central grid power lines in the United States [71]. The construction of transformers, substations, pylons, and transmission corridors all requires land, much of it in forests and mountains. Large transformer stations can occupy as much as half a square kilometer of land [72], and higher voltage transmission lines need wider corridors. T&D infrastructure occupies >4 million hectares of land in the United States [73], or an area of land about the size of the country of Japan. Transmission corridors are especially burdensome on big carnivores and reindeer, due primarily to noise during construction and construction traffic on roads. Reindeer have been known to reduce their grazing areas by 50–90 % in areas closer than 4 km to transmission lines. In Arctic areas, big carnivores, such as brown bear and wolf, are negatively affected within 2 km distance from transmission corridors. Researchers have also found that the construction of powerline corridors spread invasive species and facilitate the colonization of non-native plants. Land fragmentation from transmission corridors threaten plant-pollinator networks by isolating populations [77] and fundamentally alter the relationship between predators and prey within an ecosystem.

3.4. *Temporal inequity*

Temporal inequities involve embedded risks of energy systems for future generations. Failure to upgrade the grid for wildfires or other climate events fall into this category. The grid remains at perpetual and growing risk from fires, landslides, and even earthquakes in the Western United States [79]. Global temperature increases arising from climate change will compound these risks, and are making natural disasters such as ice storms, hurricanes, droughts, heatwaves, and wildfires more severe. Changing weather patterns increase future blackout risk factors for future generations by triggering threat multipliers such as [81]:

- Higher temperatures and heat waves limiting the transfer capabilities of transmission lines, which causes line sagging and increases energy losses;
- High winds during storms or hurricanes damaging overhead lines via debris or collapsing pylons and towers;
- Freezing temperatures, ice, and snow damaging insulators or collapsing distribution lines;
- Lightning strikes triggering faults and damaging transformer wings;
- Rain and flooding damaging substation equipment, switchgear, and control cubicles.

Wildfires are another persistent risk, with >200,000 wildfires occurring in the United States from 2017 to 2020, which collectively burned >25 million acres of land. Collectively, such natural disasters and weather-related outages cause up to $70 billion in annual inflation-adjusted damage, costs borne by the public in the form of lost output and wages, spoiled inventory, delayed production, inconvenience, physical damage to the grid, and costs to future generations in the form of exacerbated climate change due to fire emissions and the destruction of emissions sinks [83].

Another inherent temporal risk is failure to upgrade the grid against future terrorist attacks, including cyberattacks. The energy sector is the third most targeted cyberattack sector, after national defense and health. Transmission systems are the most common targets of physical attacks, with 76 % of terrorist attacks focused on substations or transmission lines, rather than generating stations or office buildings and headquarters [85]. In the United States, security analysts have warned that it would take merely a few motivated people with minivans, a limited number of mortars and few dozen standard balloons to strafe substations, disrupt transmission lines and cause a “cascade of power failures across the country,” costing billions of dollars in direct and indirect damage [86]. A deliberate, aggressive, well-coordinated assault on the electric power grid could devastate the electricity sector and leave critical sectors of the economy without reliable sources of energy for decades. Analysts argue that the time needed to replace affected infrastructure would be “on the order of [reconstructing] Iraq,” not “on the order of a lineman putting things up a pole." [87] Widespread consensus also exists among state and federal government officials, utilities, and manufacturers that high-voltage transformers in the United States are vulnerable to terrorist attack, and that such an attack potentially could have catastrophic consequences [88], which both current and future publics would also bear [89].

A third temporal inequity concerns the embedded waste streams in grid equipment. Transformers, cables, wires, switchgear, towers, and substations all need prodigious amounts of metals and minerals, which can both contribute to climate change over time and accumulate into waste burdens. A single line-frequency transformer can generate up to 2.5 tons of waste including copper windings, steel tanks, and iron cores [90]. Even presuming a clean (European) based electricity mix, a transformer rated at 500 MV-amperes could emit as much as 88,000 tons ofCO2-eq during its lifetime [91]. As Table 3 summarizes, other embodied lifecycle impacts to transformers include oil consumption, water pollution, eutrophication, metals contamination, ozone emissions, and acid rain. These impacts have two other temporal aspects: firstly, market actors will need to replace such infrastructure every 30–40 years, which will impose on future generations; secondly, market actors will also need to expand the grid in the future to accommodate distributed forms of power such as renewable energy, which will increase the scale and scope of such risks. Very recent modeling of the global metal demands for the grid based on high penetration of wind and solar energy systems suggests that associated electrical grids will require large additional quantities of metals: 27–81 million tons of copper cumulatively, followed by 20–67 million tons of steel and 11–31 million tons of aluminum [93]. Electrical grids built for solar photovoltaics have the largest metal demand, followed by offshore and onshore wind. Power cables are the most metal-consuming electrical components compared to substations and transformers. All these metals and materials will eventually need proper disposal and recycling.

4. Discussion and conclusion

While the electric grid itself is neither just nor unjust, decisions about grid investment and expansion have procedural and distributional justice implications. The grid can both create or contribute to a range of inequities along demographic, spatial, inter-species, and intergenerational aspects. The inequities, and thus also the challenges, reviewed in this article run the gamut from issues of safety, embodied emissions, siting, environmental degradation, and risks associated with infrastructure failure, among other topics.

The examples presented herein were primarily violations of distributive justice. Yet addressing any of these 12 challenges, as well as others that our short Perspective did not cover, require procedural justice, including engagement with local communities and those who bear the greatest burdens, as well as consistent implementation of commutative or universal justice. When evaluating the grid from a justice perspective, the literature has covered fewer cases of procedural injustices. Thus we do not include a thorough discussion in this paper about the procedure of siting, permitting, and developing electrical infrastructure, and we are mostly discussing physical, operating infrastructure, which rarely involves active decision-making that could be more inclusive. Yet addressing these inequities would undoubtedly demand more than just distributive justice—it would necessitate strong commutative, procedural, recognitional, restorative, and cosmopolitan justice. It would also benefit from more inclusive, reflective frameworks for energy justice rooted in feminism, anti-racism, or anti-colonialism and a more critical interrogation about the role of the state in addressing injustice [96] [97]. It would lastly need to grapple with contested notions of accountability [98], and the path dependence and role of historical institutions and patterns of poor governance [99].

Decarbonization requires infrastructure expansion, which in turn requires effective permitting, siting, and development. Failure to expand will continue to exacerbate inequities on the grid associated with poor infrastructure in certain places that are more prone to blackouts, and also associated with the environmental and social burdens of existing power plants. From both a decarbonization and a just transition perspective, the conundrum is to continue improving while simultaneously expanding T&D, and with a focus on equity and other aspects of justice that go beyond distribution.

Tackling these challenges is far from easy, and tackling the full suite of them introduces myriad tensions. For example, streamlining permitting would help ensure more timely installation of new T&D infrastructure. Such developments will improve grid reliability and enable the expansion of renewable energy, which will in turn facilitate the retirement of older and higher carbon energy infrastructure. Yet speeding up the permitting process may have downsides, namely an incomplete consideration of the land use, environmental, and socioeconomic implications of siting the new infrastructure, and a lack of local community acceptance could lead to longer delays, more protracted legal challenges and major cost burdens to utilities, generators and ultimately the public [100].

Beyond embedding these diverse tenets of justice in markets and regulatory design, other potential solutions are more technological in nature. One approach to grid expansion is to make the greatest possible use of existing rights of way to site higher-capacity lines, including grid-enhancing technologies such as dynamic line rating and more efficient transmission technologies like high voltage direct current (HVDC). Coupling this idea with adaptive reuse of decommissioned coal plants—and their transmission connections—to site renewables, geothermal, and small modular nuclear reactors may minimize the impact of grid expansion as these technologies develop and mature.

Another approach to grid expansion that has both economic and equity benefits, at both the transmission and distribution levels, is to shift the policy focus to capacity utilization. To the extent that existing T&D wires are underutilized currently, dynamic signals like prices can,

Table 3
The negative environmental lifecycle impacts of transformers.

Impact category (unit)	Transformer rating (MVA)								
	0.315	10	16	20	40	50	63	250	500
Climate change (kton CO_2-eq)	0.27	4.61	6.20	8.50	16.22	21.90	23.86	51.62	88.23
Fossil depletion (kton oil-eq)	0.08	1.36	1.84	2.51	4.79	6.46	7.04	15.24	26.03
Freshwater ecotoxicity (kton 1,4-DCB-eq)	<0.01	0.06	0.08	0.11	0.20	0.27	0.30	0.65	1.11
Freshwater eutrofication (ton P-eq)	0.22	3.83	5.16	7.10	13.56	18.37	20.11	43.09	74.08
Human toxicity (kton 1,4-DCB-eq)	0.15	2.61	3.54	4.83	9.14	12.32	13.68	29.01	50.08
Marine eutrophication (ton N-eq)	0.27	4.66	6.26	8.59	16.39	22.16	24.20	52.12	89.34
Metal depletion (ton Fe-eq)	0.01	0.17	0.26	0.27	0.42	0.45	0.61	1.27	2.05
Ozone depletion (kg CFC-11-eq)	0.01	0.23	0.31	0.42	0.80	1.07	1.17	2.55	4.34
Particulate matter formation (ton PM10-eq)	0.36	6.14	8.28	11.21	21.27	28.51	32.10	67.58	117.57
Photochemical oxidant formation (ton NMVOC)	0.59	10.17	13.75	18.54	35.07	46.92	51.91	111.44	190.73
Terrestrial acidification (ton SO_2-eq)	1.09	18.44	24.83	33.93	64.65	87.18	99.36	205.41	362.43
Terrestrial ecotoxicity (ton 1,4-DCB-eq)	0.03	0.52	0.70	0.95	1.79	2.40	2.67	5.70	9.81

for example, lead to greater electric vehicle charging during low utilization hours. Digitization of the grid also makes grid-enhancing technologies possible, including dynamic line rating, advanced power flow control, and topology optimization techniques like the dynamic operating envelopes used in Australia, which can enable better capacity utilization to accompany greater variable resource integration [101].

Other options to make the electricity grid more equitable and just include investing and upgrading and expanding the grid, to help address temporal inequities. Siting concerns can be addressed by working with local communities, building trust, and perhaps deploying community-benefit agreements. Reducing barriers to permitting, while still seeking protection of species and human populations, and prioritizing grid improvements in underserved places first would hedge against demographic, spatial, and interspecies inequities simultaneously. Same with following best practices for siting, land use, and waste flows, coupled with providing emergency shelters during extreme weather events to protect those most likely to experience blackouts.

Yet, this discussion is not to suggest that the pursuit of advanced digitalization, decentralization, and decarbonization is void of injustices and inequities. Indeed, ample examples exist of justice challenges associated with the energy transition that may accompany an upgrading of the electrical grid. For instance, there are a host of possible justice issues in terms of digitalization [102], smart homes [103], local electricity exchange [104], distributed generation [105], and other innovations on the demand-side such as household solar energy [106] or electric vehicles [107]. How these innovations couple with, worsen, or alleviate electrical grid inequities could be explored in future work.

Underlying all these challenges are sets of actors and market institutions that make decisions about infrastructure with consequences for the inequities discussed in this article. Certain actors, for example, decided to locate critical infrastructure in wealthier communities. Other actors have elected to site nuisance facilities in under-served and less advantaged communities. An ongoing complication for the electricity sector is that it is a complex system of systems with so many actors, each operating with its own objectives, and all in absence of any coordinating bodies or institutions to either align objectives or declare certain considerations as fundamental. As such, T&D infrastructure was neither designed nor operated with guiding objectives related to equity. Moving forward, the dilemma will be to determine how, institutionally, to embed equity and justice principles in the combination of regulation and markets that combine with the physical assets to create a cyber-physical-social system.

CRediT authorship contribution statement

Benjamin K. Sovacool: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Sanya Carley:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Lynne Kiesling:** Writing – review & editing, Writing – original draft, Formal analysis.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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