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Implications of Green Technologies for Environmental Justice

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Abstract

There are large disparities in access to green technologies between countries and among different demographic groups within countries. Unless carefully managed, the energy transition risks exacerbating some of these inequalities, for example, by burdening those who are excluded from efficient new technologies with the costs of maintaining legacy infrastructure. The energy transition will create new interdependencies between sectors—for example, between buildings, the power sector, and transportation—requiring integrated design of policies and infrastructure in different sectors. The equitable adoption of new technologies is contingent on broadening access to enabling technologies such as the Internet and payment systems. Decision-makers must focus on new technologies that remove disparities in access to services but do not replicate current inefficiencies in providing those services (e.g., equitable access to mobility—not only to motorized personal vehicles). Data at higher resolutions and with broader coverage are needed to design equitable technology deployment strategies and evaluate their success.

Contents

1. INTRODUCTION AND SCOPE

The U.S. Environmental Protection Agency (EPA) provides the following definition of environmental justice:

> Environmental justice is the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This goal will be achieved when everyone enjoys:
>
> - The same degree of protection from environmental and health hazards, and
> - Equal access to the decision-making process to have a healthy environment in which to live, learn, and work. (1)

The EPA's goals lead to three broad categories of outcomes. The first category involves the elimination of differences in access to green energy technologies essential for healthy living. These differences may be due to affordability [e.g., the high upfront costs of efficient technologies (2, 3)] or to the effects of place [e.g., poor design of low-income public housing (4)]. Green technologies have also expanded access to energy services [e.g., light-emitting diode (LED) lighting in the Global South (5)].

The second category focuses on reducing the extent to which exposure to environmental harms varies for different groups. This has been the historic focus of environmental justice studies (6). Differences in exposure might stem from decisions about siting of energy infrastructure (7, 8), where waste or pollution is dumped (9), and the unequal distribution of occupational risks (10). The exposure may not occur where the technology is deployed. Supply chains of technologies used mostly by the rich (e.g., the mining of metals used to produce batteries or motors) may expose the world's poorest people to conflicts or occupational hazards (11, 12).

Green technologies: technology and science geared toward reducing human impacts on the environment

The third category entails technologies that not only produce just outcomes but also are governed fairly. Ottinger (13) describes the characteristics of technologies that are compatible with fair governance. These include simplicity to enable the wide understanding of the technology; the absence of strong economies of scale, permitting local governance and ownership; and transparency in operations and decision-making. Researchers have argued that certain green technologies are inherently antithetical to democratic governance (14, 15). However, this may be the case even for distributed technologies if supply chains are centralized [e.g., rare earths (see 16)] or if there are strong incentives to connect and centrally control them [e.g., centralized dispatch of distributed energy (17)].

Environmental justice outcomes: broad categories that focus on (*a*) elimination of differences in access to green energy technologies essential for healthy living, (*b*) reducing the extent to which exposure to environmental harms varies for different groups, and (*c*) technologies that produce just outcomes and are fairly governed

This review focuses on the first of these outcomes: the degree to which access to green technologies is equitable. Of the three dimensions of a just transition—distributional, procedural, and restorative (18)—the review focuses directly on distribution, although giving currently underserved populations access to, and ownership of, efficient new technologies also delivers restorative justice.

The review expands EPA's definition in two ways. First, it takes a broader view of the dimensions of individuals' identities. It accounts for gender and disability, income, race, and place. Although EPA's focus is domestic (i.e., the United States), this review surveys the literature on the different effects of green technologies on the Global North and the Global South. Globally, the consumption of energy is highly unequal, with an overall Gini coefficient of 0.52. The coefficient is 0.45 for food-related energy use, 0.45 for heat and electricity, 0.56 for health-related energy consumption, and 0.6 for transportation-related energy use (19). The highest decile of income consumes 39% of total final energy, and the bottom decile consumes 2% (19). The review highlights the findings of the literature that is cognizant of intersectionality (20) and of the particularly daunting barriers to accessing green technologies that certain combinations of identity (e.g., women in the Global South) may suffer. Second, the review's unit of analysis is the technologies that the laws, regulations, and policies mentioned in the EPA's definition seek to govern. The review highlights work that recognizes that policies and infrastructure mediate the effect of technology on distributional outcomes.

The review uses as its starting point the 46 key technologies that are part of the International Energy Agency's Tracking Clean Energy Progress effort (left-hand side of **Figure 1**; see also 21). The review focuses on individuals' access to green technologies. This precludes centralized technologies such as large power plants, industry, and agriculture, although global disparities in the availability of green technologies in these sectors have consequences for both mitigation of and adaptation to climate change (22, 23). Organizing the review around a few dozen individual technologies is unwieldy. Therefore, the review is organized along sectors and highlights the interdependencies between sectors and between individual technologies. For example, the environmental justice outcomes of a shift to biofuels in transportation depend on how the concomitant changes in agriculture are managed (24).

The review highlights that infrastructure and policies mediate the effect of technologies on environmental justice outcomes. For example, the benefits of smart technologies may be unavailable to those who have poor Internet access (25). Providing building occupants access to smart technologies will produce only a limited benefit if the electricity infrastructure is not appropriately configured or if suitable policies are not in place. An example of such a policy is a tariff structure that either fails to incentivize off-peak electricity use or is punitive for vulnerable occupants who have a limited ability to shift demand (e.g., the sick or the elderly) (26). It also highlight findings about the distributive effects of policies designed to promote the adoption of green technologies [e.g., subsidies that flow disproportionately to the rich (27) or regressive green taxes (28)].

Figure 1 summarizes the scope and organizing principles of the study. The rest of the review is organized by sector. Section 2 is focused on buildings, Section 3 on the power sector, and Section 4 on transportation. Section 5 concludes.

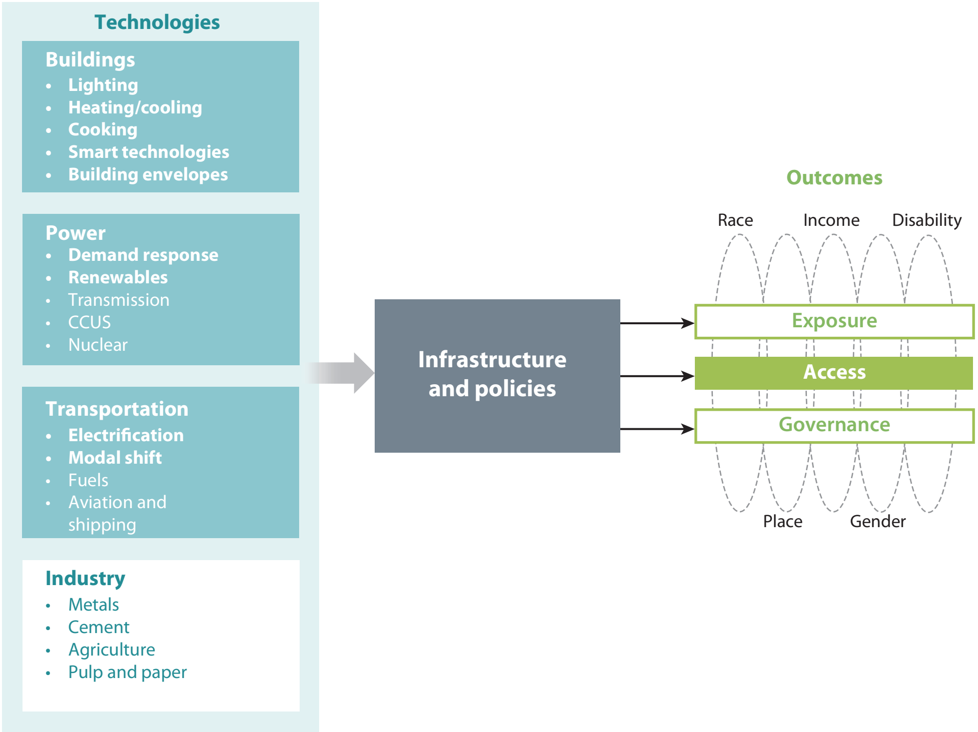


Figure 1

Review scope and organizing principle. The review assesses how technologies deemed critical to decarbonization, mediated by infrastructure and policies, will affect disparities in access to green technologies. The dimensions of exposure and governance are not in the scope of this review. The study excludes technologies in sectors such as industry, or technologies that can be deployed only on an industrial scale (e.g., fuels, aviation, and shipping), where individuals' access to the technology is less relevant. The studies focus on disparities in access along the dimensions of race, place, location, income, gender, and disability. Colored solid boxes and bold text indicate sectors, technologies, and outcomes that are within the scope of the study. Abbreviations: CCUS, carbon capture, utilization and storage.

2. BUILDINGS

Building operations produced 10 gigatons of CO_2 in 2021. Therefore, buildings were responsible for 27% of global energy-related CO_2 emissions: 8% from the direct use of fossil fuels in buildings and 19% from the generation of heat and electricity for buildings. A further 6% of global CO_2 emissions were attributed to material production for building construction CO_2 (29). The focus of this section, illustrated in **Figure 2**, is on the stark inequalities in access to the services that buildings must provide and in access to technologies that reduce the greenhouse gas emissions associated with the provision of those services.

2.1. Disparities in Access to Efficient Technologies

The vast majority of the studies that focus on disparities in access to technologies within a country (rather than between the Global North and Global South) focus on the United States. Therefore, this section draws on empirical studies of disparities in access in the United States. Sections 2.2 and 2.3 focus on global disparities.

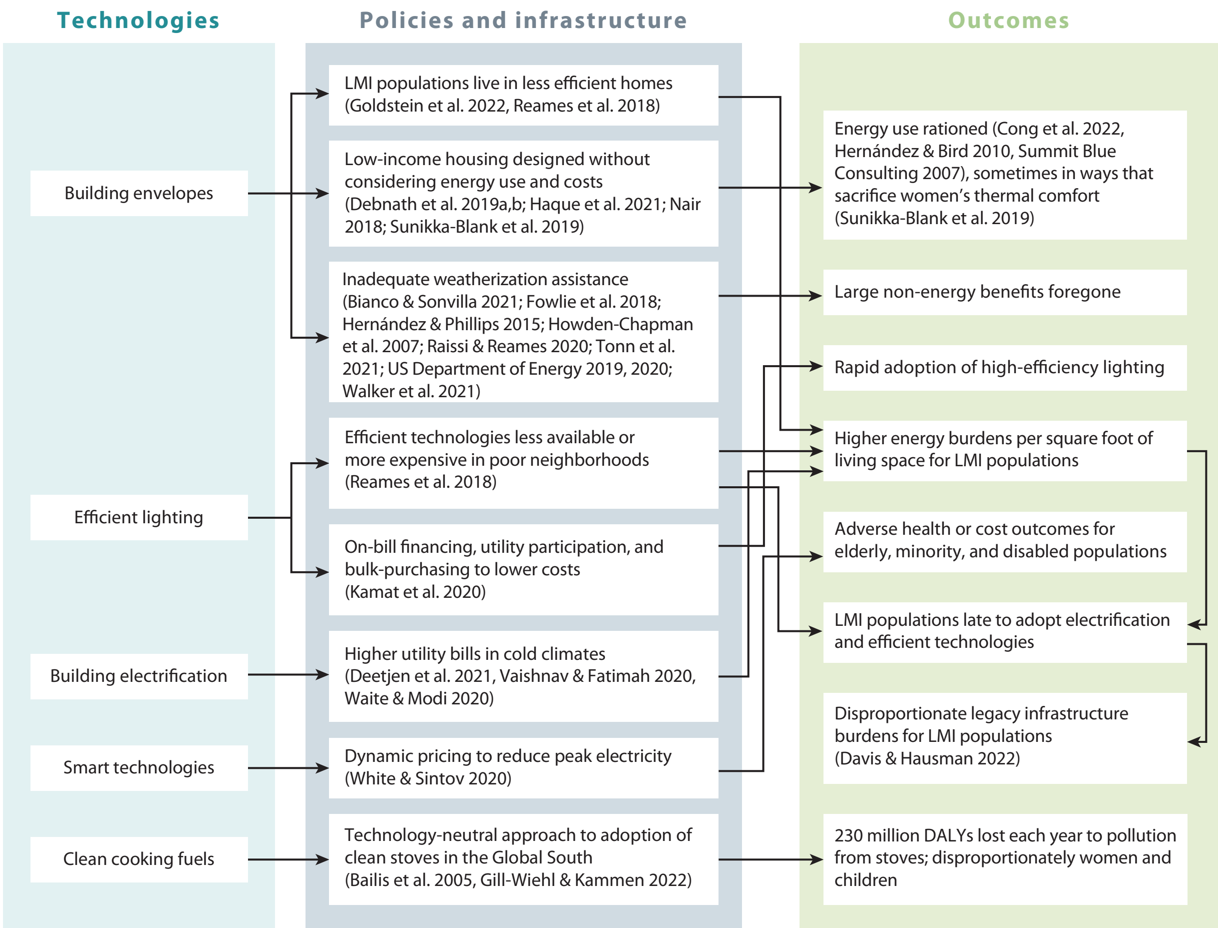


Figure 2

Policies and infrastructure mediate outcomes related to access to technologies in the buildings sector. Policies and infrastructure as well as outcomes data are per References 2 (Reames et al. 2018), 26 (White & Sintov 2020), 30 (Goldstein et al. 2022), 31 (Kamat et al. 2020), 37 (Deetjen et al. 2021), 38 (Vaishnav & Fatimah 2020), 41 (Waite & Modi 2020), 43 (Cong et al. 2022), 44 (Hernández & Bird 2010), 45 (Summit Blue Consulting 2007), 46 (Fowlie et al. 2018), 47 (Raissi & Reames 2020), 48 (US Department of Energy 2019), 49 (Hernández & Phillips 2015), 50 (Howden-Chapman et al. 2007), 51 (Tonn et al. 2021), 52 (Walker et al. 2021), 53 (US Department of Energy 2020), 54 (Bianco & Sonvilla 2021), 55 (Davis & Hausman 2022), 62 (Debnath et al. 2019b), 63 (Debnath et al. 2019a), 64 (Nair 2018), 65 (Sunikka-Blank et al. 2019), 66 (Haque et al. 2021), 68 (Gill-Wiehl & Kammen 2022), 70 (Bailis et al. 2005). Abbreviations: DALY, disability-adjusted life years; LMI, low- and moderate-income.

2.1.1. Low-income and minority-identifying populations live in less efficient homes.

Using a combination of Residential Energy Consumption Survey data and tax-assessor records of the US housing stock, Goldstein et al. (30) show that although homes in postal codes with large Caucasian populations consume more energy, corresponding to higher CO_2 emissions, energy use and emissions intensity per square foot of living space is higher for postal codes with a majority of Black-identifying households. This suggests that minority-identifying populations in the United States live in less efficient homes and that their access to energy-efficient technologies is limited. Surveying availability and price in 130 stores in Wayne County, Michigan, Reames et al. (2) show that LED light bulbs are harder to find and—when they are available—more expensive in areas of high poverty. Solutions to disparities in access have been demonstrated. In India, the government leveraged power distribution companies to reach end users and to provide on-bill financing, increasing LED adoption from 0.3% of sales in 2014 to 46% of sales in 2018. It used its purchasing power to aggressively reduce prices (31).

2.1.2. Electrification alone will likely exacerbate inequalities.

In the Global North, a transition to electric heating using heat pumps is seen as an essential component of the strategy to decarbonize (32–35). For homes that use fuel oil, propane, or resistive electric heating, a switch to air source heat pumps is likely to reduce energy costs (36, 37). However, except in mild climates, the shift from natural gas furnaces to heat pumps is likely to raise households' utility costs (37, 38). Approximately one-fifth of low-income households in the United States already spend such large fractions of their incomes on energy that they are forced to forego other necessities like food or medicine; one in three experience some form of energy insecurity (39, 40). Therefore, given their lower efficiency, the increase in energy bills associated with a switch to electric heat pumps is likely to exacerbate existing inequalities.

In addition, electric heating in cold climates is likely to sharply increase household peak electricity loads, stressing the power distribution system (37, 38, 41). Utilities may use strategies such as time of use (TOU) pricing to shift demand and therefore reduce its peak (42). When applied to air conditioning, which in most places in the United States is the largest residential electric load, TOU prices were shown to increase bills for elderly and disabled occupants, who are more constrained in their ability to shift or reduce cooling demand. Nonetheless, facing higher prices, these vulnerable populations attempted to reduce demand by accepting lower thermal comfort. As a consequence, TOU pricing was shown to lead to worse health outcomes for households with disabled and ethnic minority occupants (26). This is consistent with studies that have found evidence that low-income households wait for it to get warmer outside before switching on air conditioning (43) and evidence from pilot programs that lower-income households are more responsive to price signals than higher-income ones (44, 45). Whether this pattern of vulnerable households accepting uncomfortable or unhealthy temperatures to reduce energy use in the summer also holds for electrified heating in the winter is an open question and a subject of active research.

2.1.3. More and better targeted resources for building improvement must accompany electrification.

Weatherization is a potential solution to the increase in both bills and peak electricity demand associated with heating electrification in cold climates. The US Weatherization Assistance Program (WAP) pays for home weatherization for low-income households. Analyses of the WAP have shown that it produces lower energy savings than initially forecast and has a long payback time (46). Its lack of flexibility (e.g., the funds are not available for homes that need certain kinds of repair) may exclude the neediest households (47, 48). WAP also suffers from split incentive problems; for example, in rental accommodation, the program requires that benefits accrue to tenants, even though only landlords have the authority to initiate and approve participation (44). Nonetheless, analyses of the WAP and other energy assistance programs have shown considerable non-energy benefits, which economic analyses of the program typically exclude (49–51). Data on the cost of unsubsidized retrofits across the United States also suggest that the mean cost of deep retrofits across the country is $20,000 (52), several times more than the $7,700 that the WAP spends per household, on average (53). Overall, these results suggest that broadening access to sustainable residential buildings requires an expansion of weatherization assistance, coordinating efficiency and housing subsidy programs, and a more complete accounting of the benefits when making investment decisions. Assistance can be expanded through direct finance or through mechanisms such as on-bill financing (54), "concierge" services that provide and implement comprehensive weatherization solutions, efficiency requirements for low-income leases or federally guaranteed mortgages, and more stringent building codes.

2.1.4. Inequalities in access to new technologies could produce inequalities in legacy cost burdens. Ensuring broad access to sustainable technologies like electric heat pumps or electric vehicles (EVs) will ensure that low-income and other currently underserved populations are not burdened with the cost of maintaining legacy networks (e.g., natural gas or fuel distribution) as those costs are spread over shrinking sales. Davis & Hausman (55) show that cities in which utilities lost the greatest number of customers had lower incomes and a larger proportion of Black residents, who saw disproportionately large increases in prices.

2.2. Providing Decent Living Conditions in the Global South

Significant proportions of the population in the Global South do not have access to the conditions necessary for decent living (56); for example, 20% of the population of India lacks access to decent housing, 80% lacks access to adequate indoor thermal comfort, and approximately 70% lacks access to sufficient mobility (57).

2.2.1. Sufficiency requires the widespread deployment of efficient technologies. With the deployment of efficient technologies, decent living conditions can be provided to these populations, while keeping energy use projections consistent with scenarios that limit warming to 2°C (57). Globally, sufficiency can be provided while lowering final energy consumption by approximately 40–60% from current levels (58, 59). Sufficiency studies are bounding exercises, since their results assume a politically infeasible reduction in consumption in the Global North as well as for a significant minority in the Global South, whose consumption exceeds what is sufficient (59, 60). However, sufficiency studies play two key roles. First, they describe what services are needed for sufficiency [e.g., in Millward-Hopkins et al. (59), 50 liters of clean water per person per day, 15 liters of water at bathing temperature, 15 square meters of living space, 5,000–15,000 kilometers per person per year of travel] and quantify the distance between the status quo and sufficiency (56). Second, they describe the nature of technologies that are needed and the scale and pace of their development (58, 61).

2.2.2. Thinking of housing and energy needs as separate produces unintended consequences. In practice, attempts to provide sufficiency on one dimension (e.g., housing) can have unintended consequences for another (e.g., energy use). Studies of slum rehabilitation schemes, in which residents were moved from horizontal makeshift slums to modern high-rise apartments, showed that poor design of the new buildings increased the need for mechanical cooling in the form of air conditioning or fans (62). Horizontal slums afforded some protection from intense heat since their density provided shaded communal areas. In high-rise buildings, such communal areas were either absent or dark and there were no shaded communal areas between buildings (63). The corresponding rise in energy bills often played a role in driving occupants back to horizontal slums. There are indications that up to 40% of the occupants move back, even though the rehabilitation housing offers almost three times as much living space as the horizontal slums (62, 64). Those who decide to stay ration their energy use so that mechanical cooling is only used when men and children are at home in the evenings, and not during the warmest parts of the day when only women are at home (65). In some cases, the higher energy costs associated with high-rise housing are mitigated by installing roof-top solar photovoltaic (PV) panels, which eliminate the costs that each household bears for the building's shared electricity use (typically for elevators, lighting, and water pumps). These costs—which do not include the households' own energy use—are 4–8% of average income. To be able to afford rooftop PV panels, residents formed a cooperative organization and partnered with local NGOs (63, 66).

2.2.3. Clean cooking fuels are a public health imperative. In the Global South, indoor air pollution from cooking is responsible for 230 million disability-adjusted life years (DALYs) lost each year, a toll that falls disproportionately on women and children (67). Gill-Wiehl & Kammen (68) recommend that multilateral institutions abandon a technology-neutral approach to promoting the adoption of clean cooking stoves and focus instead on technologies that minimize damage to health. These include liquified petroleum gas, ethanol, biogas, natural gas, electricity, and biomass pellets in clean gasifiers. A diversity of technologies is needed to ensure widespread penetration of clean cooking, because no one technology is capable of being scaled up universally and with sufficient speed. Numerous studies have shown that a transition to clean cooking, even if it is effected using carbon-containing fuels, would reduce net greenhouse gas emissions (69–72) and would in any case contribute ~2% to global CO_2 emissions (73). By mid-century, zero-emissions options can and should be rolled out, including clean electrification and cooking gas obtained from the gasification of municipal solid waste (74).

2.3. Meeting the (Increasing) Need for Cooling in the Global South

Even under the current climate, 1.8–4 billion people—primarily in India, Southeast Asia, and sub-Saharan Africa—need air conditioning to avoid heat-related stresses; meeting this need will increase global electricity demand by 14% (75). A warming climate will expose populations to warmer temperatures, requiring adaptation or triggering immigration (76). Khosla et al. (77) review options for providing sustainable cooling. Options that do not require additional energy use include leveraging traditional materials and building practices in a way that incorporates passive cooling into the building structure, use of green roofs and reflective surfaces, adapting clothing and diet to a warming climate, and recognizing that thermal comfort is a social construct and that humans can acclimatize physiologically to a wide range of temperatures. Khosla et al. (77) also argue that technological alternatives exist to vapor-compression cycle cooling and could potentially reduce energy use and expand access, if investments are made to improve their technological readiness level.

3. ELECTRICITY

In 2021, the power sector produced 14 gigatons of CO_2 emissions, or nearly 40% of global energy-related CO_2 emissions. Expanding and decarbonizing electricity generation is central to decarbonizing buildings, transportation, and industry. Section 2 discusses the electrification of buildings, and Section 4 explores access to charging infrastructure for transportation. Given this review's focus on individuals' access to green technologies, this section addresses two areas: first, recent work on strategies to sustainably extend access to electricity to the 10% of the global population that did not have it as of 2021 and, second, efforts in the Global North to extend access to distributed generation to lower household energy costs, make the electrification of buildings and transportation easier (78), and improve resilience.

3.1. Grid Extension and Distributed Generation in the Global South

Approximately 750 million people, mostly in sub-Saharan Africa, do not have access to electricity (79). There is an extensive literature, which has been the focus of other reviews, on strategies to provide universal access to electricity (80). Historically, low electrification rates in the Global

South have caused scholars to speculate that distributed forms of energy, including small rooftop solar systems and communal microgrids, might allow parts of the Global South to "leapfrog" to clean, distributed sources of electricity (81, 82). However, Aklin & Urpelainen (83) use survey data from India to show that the rapid expansion of admittedly unreliable grid electricity (on average, 15 hours of supply per day) has hurt the popularity of microgrids (84). While kerosene lanterns remain the most common secondary source of energy services in rural areas where the grid is unreliable, solar lanterns and small-scale rooftop solar systems have grown in popularity. Unlike centralized grids, which are often state-financed, privately financed microgrids can have high costs of capital—from 16% to 32% for microgrids in sub-Saharan Africa, according to recent work by Agutu et al. (85). When these higher capital costs are accounted for, the cost-optimal share of standalone systems and grid extension may be higher relative to microgrids than is usually assumed. Sustained declines in battery, solar PV, and wind costs, accompanied by low-cost financing, are needed to replace dispatchable coal power in the electric grid in India with zero-emissions substitutes, and thus make grid extension green. Assuming a social cost of carbon dioxide of $185 per ton (86) and a cost of capital of 5%, hybrid solar PV, wind, and battery plants are cheaper than coal in India today (87).

3.2. Disparities in Access to Distributed Generation in the Global North

In the Global North, access to distributed power generation technologies (e.g., rooftop PV), which can reduce the cost of electrification, can also reduce the burden of electrification for low-income communities (see, e.g., 88). Once again, the majority of studies about within-country disparities in access to distributed energy focused on the United States, as does this section. These studies have consistently shown that residential rooftop solar PV installations have disproportionately occurred in locations with high median incomes, which meant that the subsidies provided to support the diffusion of rooftop PV have also flowed disproportionately to those communities (27, 89). Lukanov & Krieger (89) also show that, in California at the census tract level, housing burden (proportion of income spent on housing), linguistic isolation, and low education levels are all negatively correlated with solar PV penetration. Borenstein (90) showed that in California solar PV had been adopted disproportionately by wealthy households and that the concomitant benefits—including direct subsidies and favorable rate structures—had accrued to these households. These studies found that PV adoption was becoming more equal over time. Barbose et al. (91) showed that rooftop PV adopters were wealthier than nonadopters. Reames (92) showed that rooftop PV penetration in Washington, DC, and Chicago was lower in census tracts with higher LMI populations, even though these census tracts had the same solar potential, as defined by the proportion of rooftops that are solar-suitable (93, 94). Darghouth et al. (95) show that disparities between the incomes of those who own rooftop PV systems in the United States and those who do not are not uniform at the census tract levels. Disparities are higher when owner occupancy is low and in urban areas where mixed multi- and single-family housing coexists. A less robust result suggests that the presence of installers who develop a specialized ability to cater to low-income customers is an important driver of low-income adoption.

Weak power grid infrastructure may restrict access to distributed energy generation and to sustainable technologies such as electric heat pumps or EVs. Brockway et al. (96) found that more than half of the households in the service territories of two large California utilities, Southern California Edison and Pacific Gas & Electric (PG&E), would not be able to deploy sufficient rooftop PV to offset their annual energy consumption. In PG&E's service territory, approximately 40% would not have the capacity to adopt heat pumps or Level 1 (~1.8 kW) EV charging, and nearly two-thirds would not be able to adopt Level 2 (~10 kW) charging. Hosting capacity is lower for households in Black-identifying and disadvantaged communities.

Disadvantaged communities can also gain access to the benefits of sustainable distributed energy resources through community-scale and utility-scale resources. In community ownership models, most common in solar PV, individuals "subscribe" to an asset that is either owned and operated by a third party or that individuals collectively own. This model can replace a high upfront cost with a monthly fee, expanding access. Some portion of the financial return from the installation is then distributed to subscribers. The subscription can be structured so that generation from the asset offsets some portion of subscribers' utility bills. Barriers include long interconnection queues and capacity caps. Low- and moderate-income (LMI) households may still be excluded due to factors such as low credit scores (97). A combination of mandates, incentives, voluntary programs, and creative strategies (e.g., expanding underwriting criteria to include factors such as good bill payment history) have been used to expand community solar access to LMI communities (98).

For utility-scale resources, one mechanism is to site green energy projects in disadvantaged communities and compensate communities through credits on their utility bills. For example, the New York Public Service Commission requires that utility-scale solar projects pay \$500 per megawatt (MW) of installed capacity for 10 years and that utilities disburse the funds to local rate payers (99). Heeter & Reames (100) argue that while such measures address distributive justice, restorative justice would be better served if ownership structures were reformed to include and indeed prioritize low-income and minority-identifying populations. They argue that such shifts in ownership could be engineered by private and federal power purchase agreements that mandate that some or all of the purchased power be provided by minority-owned business enterprises (MBEs); for example, Microsoft recently purchased 250 MW of solar power from the MBE Volt Energy (101).

4. TRANSPORTATION

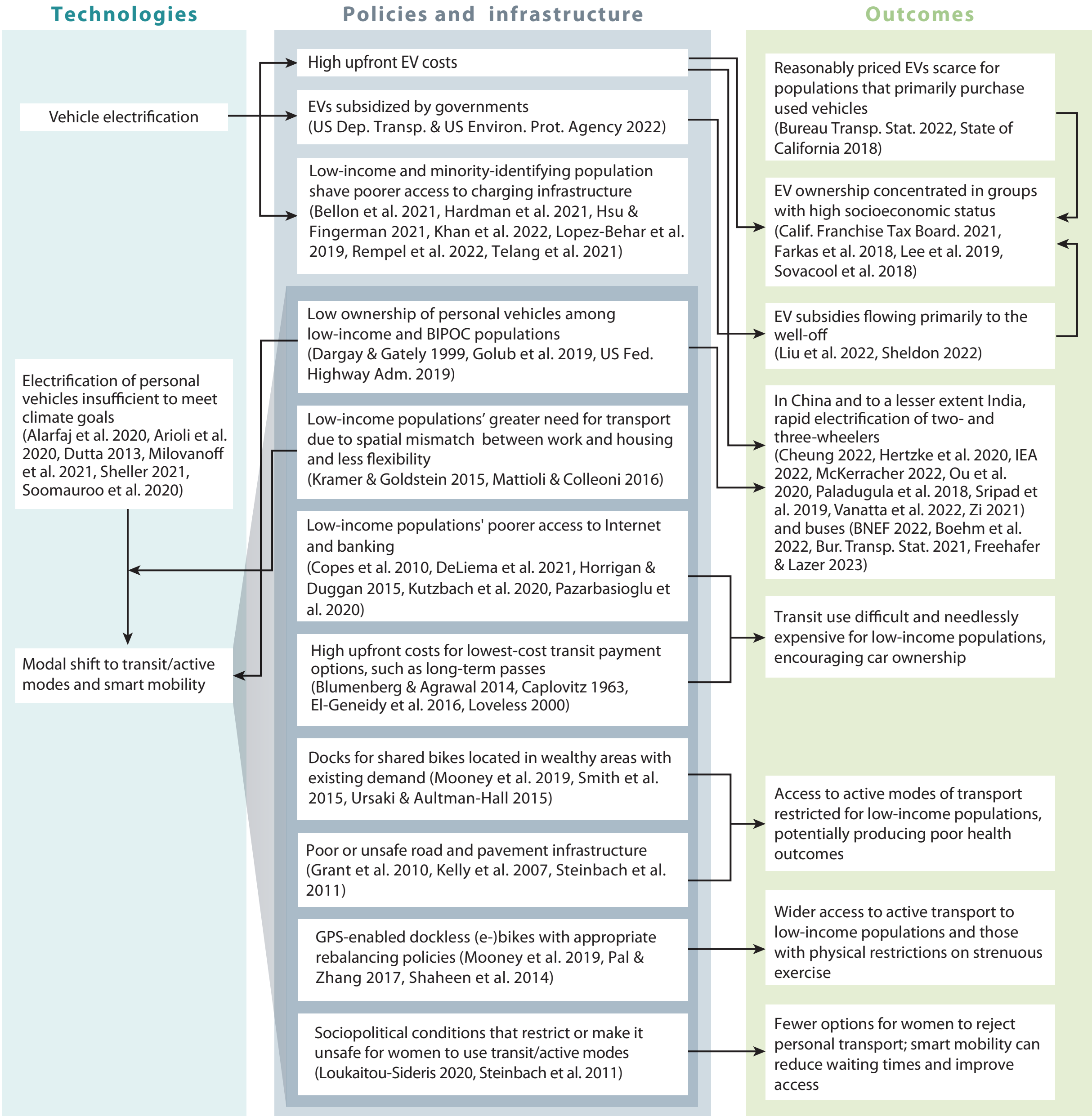
Transportation was responsible for 7.7 gigatons of CO_2 emissions in 2021, or approximately 20% of global energy-related and industrial CO_2 emissions in that year (102). Differences in access to transportation are associated with differences in wealth, access to education, and access to health care. Weiss et al. (103) calculate the travel time from each point on the globe to the nearest city, defined as a contiguous area with a population density of >1,500 per square kilometer or >50% built-up land cover, coincident with a population of >50,000. They find that wealth, educational attainment, and the proportion of fevers that are treated in children are all negatively correlated with the time it takes to travel to the nearest city. There is a strong correlation between the population, economic size, and transportation consumption (104–106) of countries. The causal direction of this relationship is unclear: It may be that transportation contributes to economic growth and is not merely a consequence of it (107). Applying these past correlations to the Shared Socioeconomic Pathways (SSPs), Nkiriki et al. (108) project that the demand for passenger and freight land-based transportation is projected to grow in all regions of the world in all SSPs. As summarized in **Figure 3**, in this section, we review the consequences for equity of two broad findings in the literature. The first finding is that widespread electrification of passenger transport is an essential green technology. The second is that electrification of personal passenger transport alone is not enough to meet climate goals: It must be accompanied by a shift to transit and active modes of transport.

4.1. Electrification of Passenger Transport

For passenger transport, many analysts view EVs, energized by zero-emissions electricity, as key to decarbonization (33, 109). Studies of within-country disparities in access to electric passenger car ownership and charging predominantly focus on the United States. The Global South—led by

China—has seen broad deployment of electric two- and three-wheelers and electric buses. Studies of systematic disparities in access to electric passenger cars in the Global South are rarer.

4.1.1. Disparities in electric vehicle ownership mean electric vehicle subsidies have flowed to the wealthy. EVs can have lower operating costs and in many cases lower lifetime costs (110), suggesting that they would disproportionately benefit low-income populations. In practice,



(Caption appears on following page)

Figure 3 (*Figure appears on preceding page*)

Policies and infrastructure mediate outcomes related to access to technologies in the transportation sector. Policies and infrastructure as well as outcomes data are per References 111 (Calif. Franchise Tax Board 2021), 112 (Lee et al. 2019), 113 (Farkas et al. 2018), 114 (Sovacool et al. 2018), 115 (Bureau Transp. Stat. 2022), 116 (State of California 2018), 117 (US Dep. Transp. & US Environ. Prot. Agency 2022), 118 (Sheldon 2022), 119 (Liu et al. 2022), 122 (Hardman et al. 2021), 123 (Lopez-Behar et al. 2019), 124 (Bellon et al. 2021), 125 (Telang et al. 2021), 126 (Hsu & Fingerman 2021), 127 (Khan et al. 2022), 128 (Rempel et al. 2022), 130 (Cheung 2022), 131 (Zi 2021), 132 (Ou et al. 2020), 133 (McKerracher 2022), 134 (Hertzke et al. 2020), 135 (IEA 2022), 136 (Paladugula et al. 2018), 137 (Sripad et al. 2019), 138 (Vanatta et al. 2022), 139 (BNEF 2022), 140 (Boehm et al. 2022), 141 (Freehafer & Lazer 2023), 142 (Bur. Transp. Stat. 2021), 143 (Alarfaj et al. 2020), 144 (Milovanoff et al. 2021), 145 (Sheller 2021), 146 (Arioli et al. 2020), 147 (Dutta 2013), 148 (Soomauroo et al. 2020), 151 (Golub et al. 2019), 152 (US Fed. Highway Adm. 2019), 153 (Dargay & Gately 1999), 154 (Mattioli & Colleoni 2016), 155 (Kramer & Goldstein 2015), 157 (Kutzbach et al. 2020), 158 (Horrigan & Duggan 2015), 159 (Pazarbasioglu et al. 2020), 160 (Copes et al. 2010), 161 (DeLiema et al. 2021), 162 (Blumenberg & Agrawal 2014), 163 (El-Geneidy et al. 2016), 164 (Loveless 2000), 165 (Caplovitz 1963), 169 (Mooney et al. 2019), 170 (Smith et al. 2015), 171 (Ursaki & Aultman-Hall 2015), 172 (Pal & Zhang 2017), 173 (Shaheen et al. 2014), 177 (Loukaitou-Sideris 2020), 178 (Steinbach et al. 2011), 179 (Kelly et al. 2007), and 180 (Grant et al. 2010). Abbreviations: BIPOC, Black, Indigenous, and people of color; EV, electric vehicle; GPS, global positioning system.

vehicles have been adopted by the well-off. In California, the median EV purchaser earns $190,000 [greater than two times the state household median income of $86,000 (111)]; 55% of EV buyers are white, compared to 41% of conventional car buyers; and only 5% of EV buyers are middle-income renters (112). In Maryland, 30% of the state population, but only 4% of EV buyers, are Black (113). A survey of 5,000 respondents in Denmark, Finland, Iceland, Norway, and Sweden found that men with high levels of education and in full-time secure employment were the most likely to buy EVs, followed by high-income women and retirees (114).

Apart from the higher upfront cost of EVs, a key driver of this disparity is that—in the United States—sales of used vehicles exceed the sales of new vehicles by a factor of more than two (115). The penetration of affordable EVs is currently low, limiting access to low-income buyers, who are more likely to buy used vehicles. The risk of battery failure (real or perceived) in used EVs compounds this problem. California has sought to address this second problem by offering rebates for battery replacement (116). Policymakers have addressed the problem of higher upfront costs by providing rebates for EV purchases (117). For the most part, these have flowed to the well-off (118). In many cases, such incentives take the form of tax credits, which recipients can only fully use if they have substantial tax burdens, and correspondingly large incomes. For example, 62% of the households in the Atlanta metro area would not qualify for the full federal tax credit (119). A solution is to offer the credits upfront at the point of purchase, as several jurisdictions around the world do (120). An evaluation of the US Car Allowance Rebate System ("cash-for-clunkers"), which also aimed to encourage adoption of efficient vehicles, showed that when the program's rebate could be applied to the down payment uptake was higher (121), presumably due to the reduced need for upfront liquidity.

4.1.2. Disparities in ownership are compounded by disparities in charging access. Hardman et al. (122) note that in the United States, low-income residents, including those who live in multi-family housing, face significant barriers to access home charging (123). This not only deters EV adoption but also means that members of these groups would have to rely on public charging options, which in the United States can cost two to three times as much as home charging (124, 125). This dilutes and may even eliminate a key benefit of EV adoption: EVs' lower operating cost relative to gasoline vehicles (110). In addition, access to public charging is uneven: Hsu & Fingerman (126) find that, in California, "compared to Black and Hispanic majority CBGs [Census block groups], White majority CBGs have 1.5 times the odds of having access to public chargers when incomes, highway or freeway distances, and MUD [multi-unit dwelling] housing unit rates are controlled for" (p. 64).

Studying the distribution of EV charging stations in New York City, Khan et al. (127) found that postal codes that had EV charging stations had a higher median income, a higher proportion of white-identifying residents, and a lower proportion of Black-identifying residents than those postal codes that did not have EV charging stations. For postal codes where the median annual income was greater than $64,000 (the area median income at the time), there was a negative correlation between the percentage of the population identifying as nonwhite and the number of EV charging stations. Conversely, there was a positive correlation between the proportion of a postal code's population that identified as white and the number of charging stations present. For incomes lower than $64,000, the correlation between the proportion of zip code residents identifying as white or nonwhite and the number of charging stations was either nonexistent or weak. Low-income postal codes all have poor access to charging; higher-income with large Black-identifying populations have worse access to charging.

Studies have found that failures in payment systems—which often require contactless payment or the use of a mobile phone app—were responsible for approximately one-fifth of failed attempts to charge EVs in San Francisco (128). Given that low-income and minority-identifying populations are disproportionately unbanked, justice advocates have argued that charging stations must be required to accept ordinary chip cards, that states provide EV owners with payment cards at no cost, or that EV charging stations partner with merchants to accept cash payments (129).

Globally, there are wide disparities in the availability of public EV connectors. In 2021, the Netherlands and South Korea had one connector for every 5 EVs; India had one for every 10 EVs; and the United States had one for every 20 EVs (130). In China, as of 2020, there were 4 million pure EVs (131) and—as of 2019—810,000 charging outlets, of which 330,000 were public and the rest were private (132), which means that in China there is one public charging station for 12 EVs.

4.1.3. Two-wheelers, three-wheelers, and buses are crucial for decarbonization in the Global South. In China, a quarter of new car sales are EVs, with EVs commanding a large share of small vehicles (>40% of sales) and large luxury vehicles (~30% of sales) (133). More than 80% of two-wheelers sold in China are electric, and 50% of electric two-wheelers are in China (134). In China, India, and Vietnam, two wheelers account for approximately 50% of gasoline demand for transportation (135), and two- and three-wheelers are responsible for the lion's share of the oil consumption displaced by the switch to EVs (130). While electric cars remain too expensive to constitute more than 0.5% of light vehicle sales in India (135), electric two-wheelers [two-wheelers are 70% of the on-road fleet in India (136)] offer the potential to electrify personal vehicles, reduce greenhouse gas emissions, and potentially improve urban air quality. However, at current prices, electric two-wheelers remain somewhat more expensive than their gasoline counterparts. Achieving cost parity will require reductions in battery cost, as well as improvements in the rest of the vehicle to bring costs down. Access to charging is another potential barrier. Although swappable batteries may be considered for light vehicles with limited range, for a two-wheeler with 100 km of range, the battery pack would weigh 12–30 kg, making swapping difficult for users (137). In areas of the Global South where coal or oil is burned, without pollution controls, to produce electricity, careful analysis is needed to assess the trade-off between reducing CO_2 emissions and potentially increasing the emissions of short-lived pollutants. For example, Vanatta et al. (138) show that electrifying motorcycle taxis in Kampala, Uganda, would reduce emissions of CO_2 and of oxides of nitrogen (NO_x), but increase emissions of fine particulate matter ($PM_{2.5}$) and sulfur dioxide (SO_2).

4.1.4. Electrifying transit would expand access to the benefits of electric vehicles. Switching public transit to zero-emission alternative fuel vehicles would expand access of these technologies and reduce exposure to vehicular air pollution, which disproportionately affects the poor. In 2021, 44% of the buses sold globally were electric, up from 2% in 2013 (139). This transition has been catalyzed by China, where 94% of total EV bus sales have occurred (140). In the United States, efforts by Federal, state, and local governments to expand the use of electric school buses were expected to put 13,000 electric school buses on the road as of 2022 (141). More than 90% of school buses in the United States run on diesel. Children from low-income families are disproportionately exposed to pollution from these buses, since >70% of children from low-income families take the bus to school, while <50% of children from high-income families do so (142).

4.2. Modal Shift: Access to Transit and Active Transportation

In mature markets such as the United States, the electrification of light transport by itself is unlikely to reduce greenhouse gas emissions rapidly enough to reach climate goals (143–145). In the Global South, where the greatest increases in both passenger and freight demand for land transport are forecast to occur, the imperative is to avoid heavy dependence on motorized personal transport. These countries must plan their urban and transportation systems to leverage transit and active modes, including walking or cycling (146–148). The Global North must switch to these modes.

4.2.1. Smart mobility can flatten existing disparities in access to transportation. The strategic deployment of information technology can lower the barriers to accessing existing transit options, while also erecting new barriers (149). While the term smart mobility has many aspects, a common theme is the application of information technology to the provision of transportation services (150). By allowing the supply of transportation services to match the needs of individual travelers more closely, smart mobility can reduce the need for vehicle ownership, while still giving people access to adequate transportations services. Eliminating the need for a personal vehicle disproportionately benefits low-income populations, who may not be able to afford safe personal vehicles, as well as historically disadvantaged communities (151). In the United States, for example, a smaller proportion of low-income and BIPOC (Black, Indigenous, and people of color) households have access to a personal vehicle than do more affluent or white households (152). Globally, there is a strong correlation between vehicle ownership levels and per capita income (153). At the same time, low-income communities may have a greater need for transport due to a spatial mismatch between workplaces and housing (154), and less flexible work schedules (155). Therefore, better access to transit, which smart mobility can enable, can be especially beneficial. Smart mobility and transit can eliminate the need for licensing, which can restrict access to mobility for both low-income and undocumented populations (151, table 2; 156).

4.2.2. Smart transit requires access to enabling technologies including Internet and banking. Smart mobility technologies can improve access to transit by giving users access to real-time information about the timing and crowding levels of transit services (151, table 7). However, access to the Internet and electronic (or indeed any) banking are often essential for smart mobility services. This access is not uniformly distributed. In the United States, low-income households may have unreliable access to the Internet at home or work (151, tables 4 and 5; 157, tables B.13–B.15). Any access they have may be unpredictably curtailed as they reach the limits of data plans. Indeed, a survey found that low-income travelers would like transit agencies to provide wireless Internet access in vehicles and at transit locations (158). Many smart mobility services cannot easily be purchased using cash and may therefore require online banking or credit cards. Many populations, including those in the Global South, may not have access to these services (159). In some cases, low-income and minority-identifying populations may be more concerned about online security because identity theft may be catastrophic for them (160, 161).

A potential inequity in transit access is that long-term passes are often cheaper per ride than individual tickets (162–164). However, purchasing these passes requires access to sufficient funds at one time, which may be difficult for those with low or uncertain incomes. This is reflective of a broader observation: Unable to take advantage of wholesale discounts, the poor often pay more per unit of goods or services consumed than the better off (165). Solutions might include giving those who fall below certain income thresholds free or highly subsidized access to transit or capping daily fares so that paying as you go never costs more than passes.

Other solutions include widespread wireless public Internet access and designing fare payment systems that allow travelers to easily and flexibly use cash to store value. Some transit agencies in the United States have experimented with developing open-loop transit cards that allowed users to use the value stored on the card to pay for other goods and services, effectively providing a form of banking (166). Recent surveys have shown that unbanked transit users would prefer to use government- or privately issued prepaid debit cards, like the ones used to issue benefits and stimulus payments, to pay for transit, just as they can for other goods and services (167).

4.2.3. Active transportation is synergistic with transit but poses additional barriers to equitable access. Bikesharing services are an alternative to personal vehicles and complement transit (168). Electric bikesharing broadens access to those who may find the exertion of riding bikes excessive. Shared bicycles may be docked, which means that they are available from and must be returned to docking stations. The locations of these docking stations can become a self-reinforcing source of inequality: To maximize utilization, they may be located to ensure easy access for the relatively wealthy who are more likely to bike. In turn, this reduces their availability and usefulness to new low-income users (169–171).

Global Positioning System technology allows the deployment of dockless bicycles, whose availability does not depend on the location of docks, since they can be picked up and deposited anywhere (172). Given the comparatively high cost of docking stations (173), dockless systems also allow wider access by allowing more bikes to be purchased with the same resources. However, operators must frequently redistribute bicycles, due to asymmetries in origins and destinations (e.g., commuters may be willing to ride them one way but not the other due to differences in gradient, and the time or purpose of commute). Such rebalancing, which is correlated with patterns of existing use (169), risks entrenching current inequalities. Nonetheless, dockless bikes can allow operators to ensure that all communities, including those that currently are not big users, have some access to them.

Clearly, bikesharing systems suffer from the same limitations associated with uneven access to virtual banking and Internet that transit does, and some of the same solutions apply. Indeed, where these bikesharing services and transit services are operated by either the same entities or by entities who are willing to act collaboratively, as in The Netherlands, a single payment fare and payment system may work across both modes of transport, improving accessibility (174). Bikesharing fees or deposits can, regardless of access to the mode of payment, be a barrier to active transportation (175). Transit and other rail networks become less dense in suburban and rural areas; active transportation can play a role in extending transportation access to such populations and is therefore synergistic with transit (176).

4.2.4. Barriers to transit and active transportation are gendered. In some regions, women may face different cultural, economic, physical, and psychological barriers to access transit and active transportation, limiting women's representation in public spaces (177). For example, some cultures may place restrictions on women's mobility. Women traveling alone may also fear and face physical threats (178). Smart mobility may partially mitigate this situation by allowing better planning of trips in order to, for example, minimize waiting time at transit facilities.

4.2.5. Disparities in access to and quality of physical infrastructure. The ability to use active transportation, including biking, or transit presupposes access to this infrastructure. There are disparities in such access (178); for example, Kelly et al. (179) found that in St. Louis, Missouri, predominantly Black neighborhoods were more likely to have uneven and obstructed sidewalks. This reduced walkability, resulted in poorer health outcomes, and reduced access to transport. Work in Ottawa, Canada, has shown that lower socioeconomic status neighborhoods have less access to active transport and that such access is perceived as more hazardous where it is available (180).

5. CONCLUSIONS

5.1. Disparities in Access to Green Technologies Exist at Different Scales

There are disparities between the Global North and the Global South in individual access to green technologies. These disparities must be addressed in a way that gives currently underserved populations access to energy services without necessarily deploying inefficient technologies that are entrenched in the Global North. For example, reliance on personal transport—even if it is electrified—must be seen as a historic mistake in the Global North, which must not be repeated in the Global South (181). Social norms—including clothing, food, mobility, and comfort—that allow for human flourishing without creating large energy burdens must be preserved and, where appropriate, codified. An example is the Cool Biz campaign in Japan, which sets the standard summer air conditioning temperature in office buildings to 28°C and encourages workers to wear clothing that is comfortable at that temperature (182, 183). In the Global North, where disparities in access to energy services exist, policymakers must incentivize and support the deployment of efficient technologies (e.g., building electrification and weatherization) rather than expanding conditions that encourage profligate energy use.

5.2. Deploying Green Technologies Requires Integrating Currently Separate Infrastructures

No infrastructure or policy should be designed without considering the implications for sustainable, equitable access to energy services. For example, choices made to enhance equitable access to housing must not produce inequitable access to energy services. Architecture and building construction practices must seek to reduce operational energy use and cost. Electrification underpins green technologies in the building and transport sectors. Access to green technologies in electricity, building, and transport sectors can no longer be thought of separately: Each sector must catalyze green technology in others. An example of an effort to do this is the U.S. Department of Energy's Grid-Interactive Efficient Buildings program (184). Equitable access to green energy technologies is conditional on access to technologies that are not usually thought of as energy-related (e.g., Internet and banking).

5.3. Higher Resolution Data are Needed to Design and Evaluate Equity in Energy Access

Equity analyses at different scales often produce different results [the so-called modifiable areal unit problem described by Fotheringham & Wong (185)]; for example, analyses based on geographically coarse data underestimate disparities in pollution exposure (186). Policymakers should employ strategies that make detailed data available in ways that balance commercial and privacy concerns with the need to provide a sound basis for decision-making (169). In the United States, an effort by the Biden-Harris Administration to ensure that 40% of the benefits of Federal investments in climate and energy flow to currently disadvantaged communities has catalyzed the development and curation of tools and datasets to permit the assessment of the distributional consequences of policies (187, 188). With few exceptions [e.g., the National Sample Survey in India (189)], there is a paucity of data on disparities in access to green energy technologies within the Global South. Indeed, reliable time series data about national-level income inequality are not universally available: At the time of writing (October 2022), of the 217 economies for which the World Bank lists economic data, 64 have not reported a Gini Index in the ten years from 2011 to 2020, only 69 report a Gini Index for more than five of those years, and only 5 countries report it for all 10 years (190). Recent work (191, 192) indicates that within-country inequalities explain a greater share of the global inequality in carbon footprints, although the data used to draw this conclusion (e.g., national household consumption surveys and input-output tables) are described as "highly perfectible" (193). Ensuring more equitable access to green technologies must begin with a better understanding of where current inequalities lie.

SUMMARY POINTS

1. Deploying new technologies in an environmentally just way requires that all people have equal access to them, equal protection from exposure to the harms they produce, and equal say in their governance. A transition to new technologies must serve distributional and procedural justice, as well as deliver restorative justice (i.e., mitigate the harms of past injustices).
2. This review focuses on disparities in access to green energy technologies. These disparities exist at different scales: between nations and between different groups within a nation. The data needed to measure these disparities, and indeed detailed knowledge of their existence and nature, are themselves unevenly distributed. There are numerous and detailed studies of within-country disparities in the Global North and, in particular, the United States. There are also numerous studies of disparities between countries in access to energy services such as clean electricity and clean cooking. However, there are few studies of systematic disparities in access to energy services within the countries of the Global South. This is a gap that future work must address.
3. Within the United States, disparities in access to green technologies exist along multiple dimensions (e.g., race, gender, and income). Disparities are sometimes accentuated at the intersections of these dimensions (e.g., women with low incomes may face particularly steep barriers to mobility).
4. Enabling infrastructure—including access to wireless Internet, access to online and physical banking, access to public safety—plays a critical role in providing broad access to green technologies.
5. It is possible to provide broad access to adequate energy services (e.g., lighting, mobility, heating, and cooling) in a way that does not replicate the profligate use of energy in the Global North. For example, mobility may be sustainably provided by favoring transit and active modes of transportation over individual passenger vehicles. While much of the literature on vehicle electrification in the United States focuses on cars, countries in the Global South (notably China) have seen widespread electrification of two- and three-wheelers and buses.
6. A just energy transition requires the codesign of infrastructures that have been treated as separate; for example, cities must be planned to allow convenient use of transit and buildings must be designed to couple with the electric grid.

FUTURE ISSUES

1. Analyses of technological interventions, including those used to justify or evaluate developmental programs, should include consideration of who is likely to benefit from access to the technology and who might bear the costs.
2. Metrics should be developed that allow analysts and decisionmakers to progress from qualitative consideration of distributional effects to quantification. Projects and initiatives must track and report on these metrics when they deploy new technologies.
3. Assessments of the effect of a technology focused on one sector, outcome, or energy service must account for effects on related sectors, outcomes, or services. What to include in such analyses is a subjective choice and decisionmakers must make these choices in an inclusive manner.
4. Equality in access is partly the result of decisions about governance. Similarly, equal access to technologies in the future may not adequately redress past inequities. Although the focus of this review was on distributional justice as it pertains to access, this form of justice is inseparable from participatory and restorative justice.

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