nature human behaviour

REVIEW ARTICLE
https://doi.org/10.1038/s41562-021-01257-8

Check for updates

Equity, technological innovation and sustainable behaviour in a low-carbon future

Benjamin K. Sovacool[1]✉, Peter Newell[2], Sanya Carley[3] and Jessica Fanzo[4]

The world must ambitiously curtail greenhouse gas emissions to achieve climate stability. The literature often supposes that a low-carbon future will depend on a mix of technological innovation—improving the performance of new technologies and systems—as well as more sustainable behaviours such as travelling less or reducing waste. To what extent are low-carbon technologies, and their associated behaviours, currently equitable, and what are potential policy and research implications moving forward? In this Review, we examine how four innovations in technology and behaviour—improved cookstoves and heating, battery electric vehicles, household solar panels and food-sharing—create complications and force trade-offs on different equity dimensions. We draw from these cases to discuss a typology of inequity cutting across demographic (for example, gender, race and class), spatial (for example, urban and rural divides), interspecies (for example, human and non-human) and temporal (for example, future generations) vulnerabilities. Ultimately, the risk of inequity abounds in decarbonization pathways. Moreover, low-carbon innovations are not automatically just, equitable or even green. We show how such technologies and behaviours can both introduce new inequalities and reaffirm existing ones. We then discuss potential policy insights and leverage points to make future interventions more equitable and propose an integrated research agenda to supplement these policy efforts.

Achieving a low-carbon society will require potentially transformative changes in both behaviour (the embedded practices of institutions and individuals) and technology (further improvements in the performance or cost of technologies). For example, as much as 72% of global greenhouse gas emissions can be ascribed to household behaviour and the collective consumptive actions of individuals[1]. A key pathway towards decarbonization therefore involves demand-side reductions, altering cultures of consumption and supporting low-carbon lifestyles[2,3]. However, technologies will also have a key role in the successful transition of the energy system in reaching carbon neutrality by 2050 and beyond. The International Energy Agency underscored this point when it noted that technologies at prototype or demonstration stage in 2020 are expected to contribute almost 35% of emissions reductions up to the year 2070; they also noted a further 40% would come from technologies at the earliest stages of adoption[4].

In short, sweeping changes in both technology and behaviour are needed to achieve a 'net-zero' or 'zero emissions' society[5], and coupling technical and behavioural change is critical to this endeavour[6]. Many countries, accordingly, have established robust goals to decarbonize their national energy systems through a mix of supply-side and demand-side options[7]. To achieve these goals, many researchers are coming to recognize that changes in both technology and human behaviour are dually critical[8–14].

However, these transitions in technology and behaviour occur within—and at times reinforce—entrenched patterns of inequity. Average per capita emissions are not equal across income groups; the combined emissions of the wealthiest 1% of the global population account for more than the poorest 50%[15]. Simply put, global consumers will need to reduce their footprint by a factor of 30 to stay in line with Paris Agreement targets[16]. It therefore follows that behaviours such as taking flights often, heating and cooling multiple large homes and driving large cars must cease, given their disproportionate impacts on the environment and climate.

But what will such a transition entail in terms of equity? Here, we review how four particular technological innovations that also have deep behavioural implications create complications and force trade-offs on different equity concerns and criteria. We draw from these cases to discuss a typology of inequity dimensions and discuss policy and research insights.

Equity, technology and behaviour across four innovations

The central concern of this Review is equity, a term that we conceptualize as the quality of being fair or just. Such a definition admittedly cuts across different dimensions and closely related terms, including equality of access, equality of resources, fairness and justice. Inequity, therefore, is meant to capture patterns of unfairness or unjustness, intersecting with inequality (disparities in equal opportunity or access), injustice (lack of fairness of process, outcomes or recognition) and vulnerability (exposure to the possibility of being harmed).

Equity and fairness represent not only ethical imperatives but also serve as instrumental enablers of more rapid and socially acceptable pathways for climate stability[17,18]. One of the most important of these dimensions is the distributional consequences of particular climate or energy policies[19], as well as a range of equity considerations arising from the uncertainty in net benefits and from the distribution of costs and benefits among winners and losers[20,21].

Although there is an extensive and growing body of literature on the allocation of a global carbon budget among countries based on quantified equity frameworks[22,23], less explored are the possible inequities that result from new low-carbon technological innovations, including a deep examination of the social practices and behaviours that can lock-in or perpetuate injustices[24].

This lacuna is unfortunate given that innovations in technology and behaviour, even those geared towards sustainability,

[1]University of Sussex Business School, Brighton, UK. [2]Department of International Relations, University of Sussex, Brighton, UK. [3]Paul H. O'Neill School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA. [4]School of Advanced International Studies, Johns Hopkins University, Washington, DC, USA. ✉e-mail: b.sovacool@sussex.ac.uk

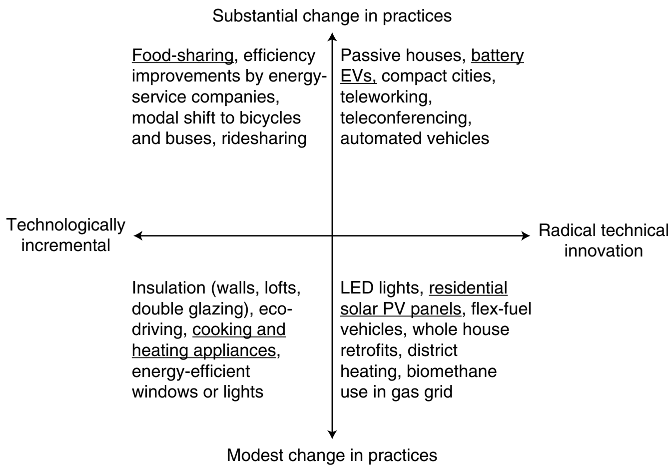

Fig. 1 | A technological and behavioural typology of sustainable behaviours and technologies. The four categories discussed in the text are divided into quadrants based on their level of change in behaviour or practice and the pace of technological innovation. The four examples that we cover in this article are underlined, with one in each quadrant. LED, light-emitting diode. Figure adapted with permission from ref. [150], Elsevier.

do not occur in a vacuum. They can both reinforce and introduce new inequities and disparities across populations and perpetuate environmental degradation. Examples of low-carbon and more sustainable technologies include hydroelectric dams, which provide clean electricity but may require the relocation of Indigenous communities or the deforestation of tropical areas[25]. Nuclear power creates problems of waste for future generations and the risk of accidents such as Fukushima[26]. Wind farms rely on carbon-intensive components such as concrete, fibreglass and steel, with many manufacturing externalities concentrated across the supply chain, especially in Asia[27]. More sustainable agriculture can rely on exploitative labour practices or land grabbing[28].

Similarly, sustainability behaviours and social practices can also impinge on equity. For example, low-carbon heating can generate a rebound effect, in which people waste excess heat and develop new standards of (higher) thermal comfort[29]. Retrofitting homes to be more energy efficient can reinforce classism and reward the status of wealthy homeowners[30]. In contexts such as the UK, vegan diets have been questioned for relying on food potentially imported from thousands of miles away[31]. In other contexts, healthy diets are unaffordable for almost half of the world because of the perishability of some nutritious foods and limited supply of foods such as fruits and vegetables[32]. Ridesharing activities in cars can displace more environmentally friendly forms of mobility such as walking, cycling or mass transit, and automating mobility has the potential to intensify exposure to antisocial and violent behaviours[33].

In this section of the paper, we review connections between sustainability and inequity through the lens of four specifically coupled technologies and behaviours shown in Fig. 1. Our Supplementary Information offers more extended case study descriptions across these technologies.

Incremental and modest: improved cooking and heating. Traditional cooking and heating practices around the world are surprisingly bad for the climate and dangerous for human health, but are deeply engrained in social practices. The latest numbers suggest that more than 2.6 billion people worldwide depend on dirty, inefficient or polluting stoves, patterns linked to about 2.5 million premature deaths annually[34]. Improved cookstoves, or cleaner cooking devices, are an incremental technology that require only a modest change in practices (for example, faster cooking times and reduced times for fuelwood collection), but can increase the fuel efficiency of cooking with consequent sustainability benefits via reduced fossil fuel use and deforestation[35–37], and health benefits due to decreased exposure to indoor air pollution[38].

Access to and use of these improved cookstoves, however, introduces some daunting equity challenges, including disparities in access and entrenchment of gendered work[36,37]. For example, such technologies can cement uneven patterns of work and domestic life because it is often women who do the cooking and caring for children[39,40]. The changes in cooking patterns and practices brought about by improved cookstoves leave many women responsible for maintaining the new stoves—and subject to anger or retaliation if those stoves break down or ruin meals. The benefits of more sustainable (and healthy) cooking, when they do occur, are often not equally or fairly distributed either and are mediated by gender roles and cultural norms[41,42]. Disparities in cookstove adoption are also strongly connected to race and ethnicity or oppressive caste systems[43,44]. In India, for example, one extensive survey of about 5,000 households across 500 villages in rural areas found that the probability of cooking with cleaner fuels such as liquified petroleum gas was "lowest for marginalized social groups"[45], especially those in lower castes or in 'fringe' areas[45]. Other work has found a lower rate of adoption of cleaner stoves in India by members of the lower castes, and that adoption patterns are skewed by both caste and gender, leading to 'graded patriarchies' that exclude especially women of lower castes from access[46].

Improved stoves can also impede local cultural practices. In India, for instance, *Chulha* stoves, because they are relatively inefficient, bring women together during the arduous and time-consuming process of collecting wood, and their smoke is seen as important for warming the centre of the home[47]. Similarly, in Botswana, open fires create a comfortable space where families gather around a *leiso* to discuss the events of the day. Consequently, substituting a normal fire with an improved stove disrupts these cultural practices[48]. Likewise, in Nigeria, wood smoke is particularly valued as a means of curing pre-salted fish or meat, a crucial form of food preservation given the lack of electricity for refrigeration[49].

Last, in some rural communities, residents still pray to 'hearth gods', and cookstove smoke is seen as a connection to spirits and even god[50]. In this way, spiritualism is threatened by modern smokeless cooking devices. Yet many national cookstove programmes have used sticks as well as carrots, punishing provinces who fail to adopt targets or removing support for rural communities that depend on dirtier stoves[51,52].

Radical and substantial: battery electric vehicles. Conventional automobility is strongly linked to transport-related carbon dioxide emissions and a host of other social and environmental calamities such as air pollution, car crashes and traffic congestion. Battery electric vehicles (EVs) are seen by many as a more sustainable option, especially if they also become connected with ridesharing, public transportation or automation[53], and are powered by low-carbon electricity sources.

EVs, however, run the risk of further embedding motorized, private automobility and increased driving according to a number of studies[54–58]. EVs further perpetuate forms of private, motorized mobility for future generations, shaping regimes to rely less on walking, active transport or public transport[59]. National-level EV transitions tend not to eliminate conventional cars either, even with 100% clean car mandates; these vehicles tend to instead be shifted to other countries with less stringent controls or standards on imports, such as Eastern Europe or Africa[56]. The ongoing EV transition in Norway has been critiqued for marginalizing the rural poor given that such areas often lack adequate public charging infrastructure and are not accessible to rural communities or those with disabilities[60]. In urban communities, EVs are impinging on many of the spaces needed for other forms of green mobility, including cycle tracks, bus lanes and walking paths[61], and planners are using EV adoption as an excuse to build new roads, even in restricted or sensitive areas[62]. In the USA, the majority of tax incentives for EVs go to wealthy households and rarely to low-income households[63]. In Northern Europe, it is predominantly men, those with higher levels of education in full-time employment (especially with occupations in civil society or academia) and in the age group of 30–45 years who are the most likely to buy them[64].

Last, EVs have their own environmental consequences by negatively affecting habitats and ecosystems and the often marginalized groups that inhabit them. EVs can exacerbate air pollution or contribute to climate change when charged on electricity grids with high shares of fossil fuels. Moreover, the electrification of transport can generally shift pollution flows from tailpipes in urban areas to power plants in rural areas. Additionally, the production and manufacturing of EVs is accelerating resource and energy demand, which intensifies reliance on unfair and exploitative mining practices for critical materials such as lithium or cobalt in places such as the Democratic Republic of the Congo[65]. At the backend of their lifecycle, EVs further 'unequal exchange' through their waste streams[66]. The majority of EVs rely on high-voltage lithium-ion batteries that are difficult to recycle and generate their own waste streams, and will eventually require car dismantling, scrapping and recycling[67–69]. This runs the risk of creating a 'decarbonization divide' that locks in cleaner places of diffusion such as Europe against those that remain based on extractive and polluting modes of production in Africa or Asia[69].

Radical and modest: household solar photovoltaic panels. Household solar panels are seen as a way to simultaneously self-generate electricity (thereby reducing demand and possible stress on electricity grids), potentially sell or exchange electricity via prosuming or net metering and decarbonize electricity by substituting for fossil-fuelled supply.

Similar to our other innovations, however, the benefits of existing solar panels are not evenly distributed. Indeed, in countries such as Germany, household solar energy is exclusionary insofar as adopters need to own a building or have access to space to mount and position the panels[70]. This excludes the millions of people who do not own their own home or who live in apartments or social housing blocks without a roof or access to a garden or lawn[71]. Those without access to the Internet or a company to install solar panels, and with poor health, previous financial difficulties and lower education levels also tend not to adopt them[72]. Extensive work on the adoption of residential solar panels in the USA has also confirmed inequitable trends in diffusion, trends shaped by race, space (urban versus rural adoption patterns), income and class (Fig. 2). Compared with the broader population, solar adopters tend to live in higher-value homes, have higher credit scores, are more educated, live in neighbourhoods that comprise mainly white people, are older and have steady jobs working in business and finance-related occupations[73]. Modelling research also suggests that solar photovoltaic (PV) panels favour richer consumers and particular network users who do not bear their fair share of total system distribution and transmission costs[74]. In Germany, increased electricity prices due to feed-in tariffs for solar panels are even argued to increase energy poverty, especially in densely populated urban areas where inhabitants have little possibility to install subsidized solar (or wind) energy installations[75].

Finally, household solar panels give rise to negative environmental externalities, including toxic materials utilized during manufacturing and installation, required integration with other systems and dependence on rare-earth mineral imports that have global whole-systems effects[76–79]. The manufacturing of solar panels can also rely on unfair and exploitative labour practices that result in boom and bust cycles for host communities and high levels of unanticipated unemployment in certain regions, which occurred in Germany[80], or rely on low-wage transient workers in China[81]. Workers that make solar panels face occupational hazards, especially those exposed to unsafe levels of cadmium used in thin-film solar PV designs[82]. Solar energy also produces hazardous waste streams that present a probable burden for future generations[69,83,84].

Incremental and substantial: food-sharing. The volume of food lost or wasted in most countries is staggering, with the statistic of at least one-third of all food wasted globally widely accepted in the policy community[85]. This makes food-sharing both an innovative solution to tackling waste and growing rates of food poverty and insecurity[86] (Supplementary Table 1).

Unlike our other three examples, food-sharing has a longer history. Sharing food was a necessary part of survival for early human communities dependent on hunting and gathering or dealing with resource scarcity in contexts such as East Africa or the Americas[87]. Eating from one plate or sharing food represents a human practice that is thousands if not hundreds of thousands of years old[88]. In Arab cultures, sharing food is seen to benefit families and communities, and refusing to share food can be perceived as a sign of hostility or enmity[89–91].

Despite the potential of mass food-sharing in these contexts to achieve sustainability objectives, it is also implicated in a multitude of equity issues. First, there is a strong urban and city bias to food-sharing adoption. One assessment of more than 4,000 food-sharing activities across 100 locations noted that population-dense urban areas had the greatest number of initiatives, with the major population centres of Chicago, London and New York serving as exemplars[92]. This fact obscures the reality that much of the food consumed in urban centres is imported from outside city boundaries, which raises questions about the suitability and resilience of urban food systems. The demographics of food-sharing are also tilted towards wealthier homes, larger homes and homes with children, as well as those with higher rates of digital literacy (which relate to food-sharing apps)[90,93,94]. Food-sharing among rural, Inuit communities in Canada has even reinforced economic and political inequality among settlements and unfair social structures[95]. In some contexts, food-sharing can even be unhealthy or illegal. In Switzerland, for example, food sharing of meat and fish exposed those with food allergies, disabilities or health conditions to increased susceptibility to food-borne illnesses, with sharers not always following accepted practices for safe labelling of ingredients, handling and refrigerating leftovers or serving expired products[96]. In Italy, food-sharing created concerns over health and safety, with food sharers accidentally contaminating food, mislabelling food or not respecting the dietary needs and food intolerances of consumers[97]. In some situations, improper storing, sorting and handling even increased net waste[97].

Finally, food-sharing efforts tend to be the most sustainable from a business standpoint if they adhere to a for-profit motive, but this can undermine its sustainability motivations and interfere with the ability for food sharing to promote social welfare or equity[98]. This for-profit model can be fiercely contested by others who see it as an encroachment of corporate businesses models into private and domestic spaces[90]. Thus, food-sharing efforts can lead to clashes in values and community disagreements[99]. Paradoxically, food-sharing is not always strongly connected to reducing food waste; it enables food-sharers to 'feel good about themselves' and allows them to have a clear conscience, but may do little to challenge the unsustainable food system itself[99].

Mapping multifarious vulnerabilities

Drawing from these four examples, we can identify multifarious dimensions of inequity and associated vulnerability to each.

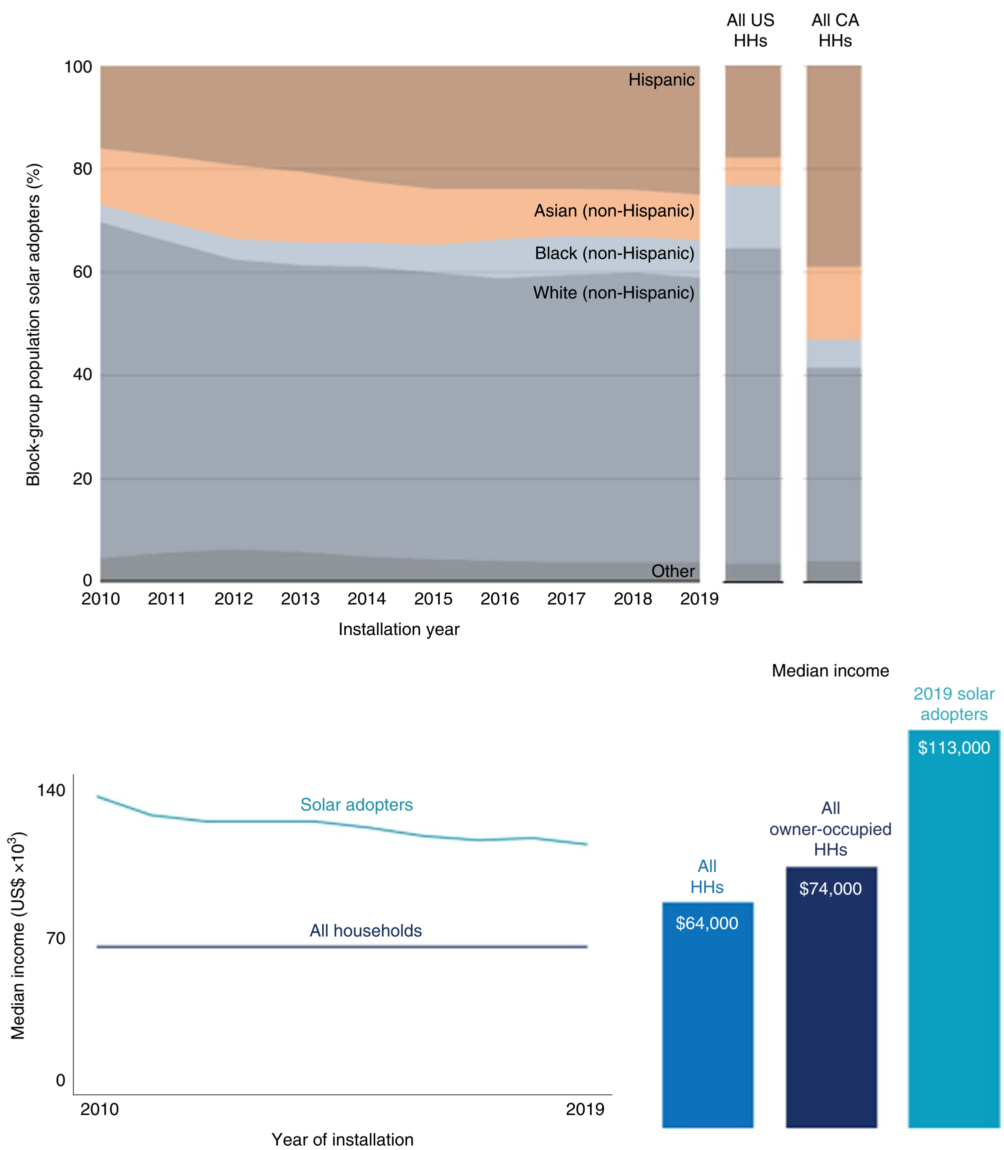

Fig. 2 | Demographic disparities by race and income in the adoption of solar energy in the USA. Adoption via race (top), adoption via income (bottom). Top, Results by census block-group showing that households (HHs) of white people (non-Hispanic) have consistently represented more than 50% of solar adopters. The 'All US HHs' chart shows cumulative trends across the entire sample for adoption for all households in the United States; 'All CA HHs' shows the same for California only. Bottom left, Solar adopters (households) by median income (US$), as measured in 2020, compared with all households and in the USA from 2010 to 2019. Note that income for both solar adopters and all households are for 2020 regardless of when adoption occurred. The median income of households with solar energy is consistently higher than the median income of all households. Bottom right: The median income of all US households, compared with the median income of all owner-occupied US households, and the median income of households who adopted solar power in 2019. Income was measured in 2020, as for the bottom-left chart. Figure reproduced with permission from ref. [73], © 2021 The Regents of the University of California, through the Lawrence Berkeley National Laboratory.

As Table 1 summarizes, these transcend demographic, spatial, interspecies and temporal dimensions. Vulnerability to inequity or injustice here is multifaceted and cross-cutting.

Demographic inequity. Our cases reveal how sustainable technology and behaviour becomes entwined with demographic disparities related to race, gender, class or even other attributes such as age or education. Income and wealth (and in some places, race[100]) strongly shape the diffusion patterns for things such as EV ownership or solar panel installations. Meanwhile, gender substantially shapes cookstove adoption patterns, and it is larger, wealthier families that tend to share food. Table 2 plots the characteristics for the adopters of each of these innovations, which indicates that adoption and potential adoption are generally associated with higher household income, with being younger or middle age, and typically with being male and in some cases higher educated across most, although not all, of the innovations.

Spatial inequity. Inequities emerge not only across demographic lines but also span across space, especially the urban–rural divide or into marginalized, peripheral communities. For example, improved cookstoves disrupt some rural food preservation and spiritual practices, rural areas have fewer charging points and supporting infrastructures for EVs and fewer resources for food sharing. Moreover, adoption patterns for solar energy favour urban areas. Solar energy is also more profitable in higher resource areas

Table 1 | A matrix of inequities and vulnerabilities with low-carbon and sustainable technologies and behaviours

Demographic inequity (between groups)	**Spatial inequity (across geographical scales)**
• Adoption is strongly mandated by gender roles (EVs, improved cookstoves, food-sharing) • Diffusion patterns substantially shaped by class, caste, income or wealth (improved cookstoves, EVs, solar panels, food-sharing) • Exclusion of non-homeowners or those without access to roofs (solar panels) • Adoption patterns favouring wealthier households and communities of mainly white people, and disfavouring those struggling with illness or financial difficulty (solar panels) • Subsidies favouring wealthier households (EVs, solar panels) • Adoption patterns favouring higher-income homes, larger homes and homes with children (food-sharing) • May entrench inequality and a gap in digital skills and awareness (food-sharing) • Can put those with food allergies or special needs at risk of contamination or illness (food-sharing) • Depends on a relatively advanced skillset of food preparation, handling, storage and refrigeration as well as disposal and waste (food-sharing)	• Erodes some spiritual and cultural practices in rural communities (for improved cookstoves) • Threatens rural food preservation based on smoke where alternatives are unavailable (for improved cookstoves) • Contributions to traffic congestion and automobile accidents in cities (EVs) • Lack of charging infrastructure in rural areas (EVs) • Perpetuation of a 'decarbonization divide' between Global North and Global South (EVs, solar panels) • Shifting of conventional cars to peripheral (non-low-carbon) areas (EVs) • Cross-subsidization of energy costs that burden the poor (solar panels) • Unfair and at times exploitative labour practices (solar panels) • Bias towards urban areas and cities, less rural states, and especially wealthier cities and cities in the Global North (food-sharing, solar panels)
Interspecies inequity (between humans and non-humans)	**Temporal inequity (across future generations)**
• Rebounds in increased driving or kilometres travelled impinging on forests or nature reserves (EVs) • Roadbuilding and impingement of green spaces or trees in urban areas (EVs) • Pushing of conventional cars to peripheral regions increasing air and water pollution (EVs) • Increased air pollution or carbon emissions from fossil-fuelled electricity (EVs) • Electronic waste streams releasing toxics into habitats (solar panels and EVs) • Environmental destruction and deforestation with mineral and material extraction (EVs and solar panels) • Fossil-fuel use, occupational hazards and pollution from local manufacturing (solar panels) • Potential rebounds in increased waste (and toxins) due to mistakes and improper sorting or handling (food-sharing)	• Embedding private motorized automobility for future generations (EVs) • Failing to address the underlying causes of food waste and unsustainable agriculture (food-sharing) • Cementing future burden of cooking and domestic activities onto women (for improved cookstoves) • Generation of toxic waste streams and disposal concerns for future generations (EVs, solar panels) • For-profit motivations can lead to conflict and community tension over future food pathways and limit sustainable change (food-sharing) • Can legitimize overproduction and food surplus and fail to address the root causes of food insecurity (food-sharing)

Table 2 | Characteristics of early adopters and potential mainstream consumers for improved cookstoves, battery EVs, solar panels and food-sharing

	Improved cooking	EVs	Solar panels	Food-sharing
Demographics				
Income	(+) Slightly higher	(+) Higher	(+) Higher	(+) Higher
Age	(+) Younger (parents with children)	(+) Middle age	(+) Middle age	(+) Younger to middle age
Gender	(+) Female	(+) Male	(+) Male	(+) Male
Education	(+) Higher	(+) Higher	(+) Higher	(+) Higher
Other details	(−) Members of lower castes		(+) White people and some Hispanic people	(+) Larger families
Other attributes				
Space	(+) Rural areas (−) Urban areas	(+) Commuters with high travel costs (−) Lack of home charging or community charging	(−) Lack of roof or space (−) Lack of home ownership	(+) Urban areas (−) Rural areas
Health	(+) Reduced illness from adopters (−) Reduced opportunities for socializing			(−) Those with food allergies or dietary concerns

Table adapted from ref. [33]. The (+) means that a group benefits from this innovation, the (−) that it tends not to benefit or suffers a risk. This table is not meant to be exhaustive but is representative of the literature that we relied on in preparation for this article.

such as deserts or dry, hot climates, which creates disparities in access—those living in sunny Arizona in the USA have far more capacity to benefit than those living in a cloudy Washington state, for example, and those living in Spain and Portugal have far more resource potential than the UK. There are also biases in all four of the innovations towards wealthier cities and wealthier countries. The connection between low-carbon energy and marginalized spaces in particular is stark, with a recent review concluding that some innovations, including EVs and solar panels, dispossess, displace or harm a striking number of Indigenous groups or ethnic minorities[81].

Interspecies inequity. Although sustainable behaviours can reduce environmental footprints and mitigate direct carbon emissions, they are also implicated in negative impacts that threaten other forms of non-human life. This quadrant of 'interspecies inequities' is meant to capture the connection between human actions and non-human groups, effects that are often stark, with consequences including the destruction of habitats and the degradation of ecosystems. This inclusion is in line with justice thinking that argues that we need to extend our justice concepts—including notions of social contract, capabilities and rights—to other species[101,102]. It is also supported by recent advances in ethics that suggest that animals be treated as stakeholders in decisions about population, habitat and health[103],

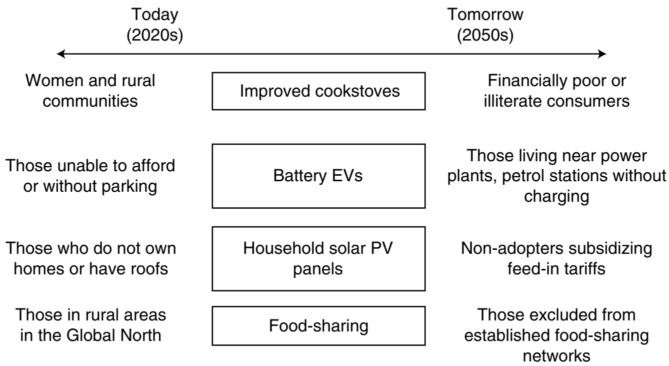

Fig. 3 | Differentiating current from future equity challenges over sustainable technology and behaviour. An illustration of how contemporary equity challenges for each of our innovations will differ considerably by mid-century. Figure adapted with permission from ref. [71], Elsevier.

that human altruism has a responsibility to expand to non-humans and protect 'planetary health'[104], and moral considerations focusing on 'non-human rights'[105].

Interspecies equity can be eroded through land use, deforestation and waste streams. For example, some improved cookstoves may still rely on fossil fuels (for example, liquid petroleum gas) or carbon-intensive electricity, and thus contribute to deforestation or climate change. EVs need roads and do not entirely displace conventional cars; those cars end up in other markets where they continue to contribute to air pollution and climate change. Solar panels are made with toxic materials and generate hazardous waste flows, and food-sharing can lead to missorted waste or wasted mishandled food. We return to this dimension below ('Expand equity considerations to non-humans').

Temporal inequity. A final class of concerns relate to future generations and futurity, or intergenerational inequity[106]. EVs can legitimize and embed patterns of motorized, private automobility into the future. Cookstoves can cement unfair domestic burdens related to food preparation and cooking. Solar panels can create substantial disposal concerns at their end of life that will burden future generations, and food-sharing can legitimize food surpluses and unsustainable agricultural practices. Furthermore, many of the effects of these four innovations entail temporally irreversible changes: power plants charging EVs convert fuel into thermal exhaust fumes, and industrial processes for solar energy or modern food production create pollution and toxic waste.

There is also a temporal dimension to the inequities we examine, as presented in Fig. 3. Cookstoves currently threaten some gendered and rural cultural practices, but in the future, market segments could emerge that are based purely on income or discriminate against those who are less financially literate. Current EVs are often unaffordable for those not able to purchase new cars or without access to off-road parking or charging points. Over time, EVs could also shift pollution patterns from tailpipes to power plants, 'cleaning' urban areas at the possible expense of rural areas. Those who do not currently own their own property or have access to a roof are functionally excluded from benefitting from solar PV panels unless they participate in community solar energy, which is only legally possible in some locations. However, in the future when household energy prices may vary in real time, then those with solar PV panels and storage could benefit by storing electricity when it is cheap and selling it later when prices rise, but those unable to afford the equipment, or unable to shift their consumption patterns, will be unable to adopt and benefit. Food-sharing may currently be widespread in urban areas today, but tomorrow, those excluded could be those lacking digital skills or failing to subscribe to online networks.

Policy insights and leverage points

Here, sticking with our catalogue of multifarious vulnerabilities, we chart potential policy options for addressing them.

Policy options for addressing demographic inequity. To address demographic inequities, one of most effective intervention points is governance innovations that include the active participation of a cross-section of society and especially those groups most likely to be affected by decarbonization policies. Climate and citizen assemblies, as adopted in the UK and France, for example, offer one way to use citizen engagement to identify and address potential trade-offs in the design of low-carbon policies[107]. Anticipatory governance mechanisms such as collaborative and participatory processes for envisioning strategy[108,109] can help policymakers to anticipate and avoid measures with regressive social impacts or put in place measures to offset these through fiscal support and subsidies to vulnerable groups. These latter approaches are an important complement to direct citizen engagement because excluded groups often lack the means (time off work), confidence (lack of education) or time (childcare or other caring responsibilities) to actively participate in invited spaces.

Another strategy to help to promote low-carbon innovations and sustainable behaviours to low- and moderate-income customers can be to harness pay-as-you-go schemes, leasing programmes or community and cooperative models that do not require customers to buy the given technology. Instead, these options avoid the need for expensive capital purchases or investment through the use of efforts such as solar-panel leasing programmes (already operating in the USA[110]) or the sharing and renting of solar panels in Zambia[111] and the USA (that is, community solar[112]). Pay-as-you-go schemes can even be included to help to promote better management and practices concerning waste, often via pay-as-you-throw or unit-pricing schemes[113]. These efforts collectively help address concerns over disparities in affordability and access.

As well as more general approaches, targeted engagements can be organized with civil society groups and intermediary organizations that work closely with women, the elderly or racially marginalized groups to help to anticipate and pre-empt unintended negative impacts of low-carbon measures on those groups as a mode of indirect participation. Around clean cooking, for example, focus groups with women would help with the design of cookstoves that minimize environmental and health impacts while avoiding further entrenching the unequal gender labour of cooking. Some cookstove manufacturers such as BURN in Kenya or Grameen Shakti in Bangladesh also deliberately employ more women in their workforce to improve their sensitivity to these issues.

Policy options for addressing spatial inequity. To be effective, policy interventions to deepen and accelerate low-carbon energy transitions need to reach as many regions and geographies within a territory as possible while being cognizant and accountable for impacts beyond sovereign borders. Each issue and location may require a tailored policy effort, and one that is inclusive—if not led by—the local community and affected populations.

For activities, behaviours and sectors over which states have direct responsibility, there are policy levers that can address regional inequalities. These levers can include tax breaks for investors in solar PV panels or EV car manufacturers to produce lower-cost models within the purchasing power of lower-income households and further fiscal support to consumers to cover the costs of installing charging points. Or they can involve regional development plans to boost jobs and income for deprived regions. Or they can involve deliberate attempts to retrain and compensate those disadvantaged from ongoing transition processes, as well as from the fossil-fuel regimes that are being displaced. Compensation, structural adjustment assistance and comprehensive adaptive support offer alternative pathways to redress spatially concentrated transitional impacts, with scholars pointing to instances where some such transitional assistance policies have worked in the past[114].

Regarding the extraterritorial effects of decarbonization policies such as EV production, it is necessary for governments to work with businesses to exercise a duty of care and due diligence in supply chains to anticipate, identify and address inequities passed on to poorer countries and social groups in the Global South in particular, as exposed by work on cobalt mining for EV battery production[65]. Although their effectiveness will vary by context and implementation, regulatory frameworks that set minimum social and environmental standards, supported by international trade, investment, labour and environmental organizations, have a clear role here. But private governance mechanisms, or 'civil regulation'[115], can complement them through voluntary standards, codes of conduct and certification, adapted to diverse contexts and supply chains aimed at minimizing the global production of inequities. Closed-loop supply chains based on circular economy ideas[116], as well as advancements in metallurgy, waste separation, materials science, waste processing and advanced recycling, can all enhance the longevity and continual reuse of minerals and metals[117]. Researchers estimate that 65% of the domestic cobalt demand in the USA by 2040 could be supplied by end-of-life lithium ion batteries, provided a robust take-back and recycling infrastructure is in place[118]. Extended producer responsibility offers another framework that stipulates that producers are responsible for the entire lifespan of a product, including at the end of its usefulness[83].

Policy options for addressing interspecies inequity. With regard to interspecies inequity, it is first important to note that all of the cases we cover here can deliver some substantive environmental benefits (for example, cookstoves displacing coal use or deforestation, EVs substituting for petroleum cars, solar panels helping to decarbonize electricity grids and food-sharing reducing organic waste). The challenge is for policy to address the negative environmental externalities and rebound effects that occur, especially in the context of equity and justice considerations, where they impact on poorer social groups within and between societies. More formal environmental and social impact assessments can anticipate, manage and reduce some of the negative impacts, but broader citizen-led processes of envisioning and futuring different scenarios can help to flush out potential negative environmental spillovers and unintended consequences[119]. There are a range of policy mechanisms that can promote core dimensions of equity, equality and justice, including altering block rate prices to minimize excess consumption, environmental bonds to compensate communities harmed by new energy projects, and the availability of legal aid to vulnerable groups[120].

Policy options for addressing temporal inequity. Politicians are often keen to pass more costly and political contentious policies onto their successors, whereas businesses and consumers routinely discount the future by prioritizing immediate profit and comfort, respectively, over longer-term consequences. This represents a vicious problem for expedient and ambitious climate action. One way to address it is through institutional innovations that aim to bring the voice of the future into the present through forms of indirect representation. The parliaments and assemblies of Wales, Hungary and Israel, for example, have ombudspeople for future generations that participate in policy to safeguard the interests of future generations[121]. Independent climate-change committees, such as that which exists in the UK, also have a role in setting and monitoring progress towards the achievement of carbon budgets and climate goals and holding governments to account where they fail to deliver. This can serve as a check against future discounting and moves to delay action.

Policy flexibility is also vital so that learning is built in by design. This means that longer-term unanticipated negative inequities—across demographic, spatial, environmental and temporal categories—can be avoided and minimized by revising policy and changing direction in the light of new evidence of the social and environmental impacts of low-carbon policies. To some extent, we are seeing evidence of this already, as EV manufacturers reduce the amount of minerals required to produce batteries. Moreover, the fact that only consumers with outdoor space can host charging points has led to the installation of charging points in streetlamps or charging points added to petrol stations.

Harnessing research insights for an equitable low-carbon future

Our Review also points the way towards seven fertile future research agendas.

Appreciate the relationality of vulnerability. Identifying the needs of vulnerable and hard-to-reach groups is a challenge as people migrate in and out of poverty—and therefore on and off the radars of policymakers—depending on fluctuating labour markets, economic shocks and changing personal economic circumstances. Confusingly, a particular household itself can be predisposed towards inequity in one area (for example, children with families tend to waste more food, and therefore benefit more from food-sharing), but only at the detriment to another (having spent their precious income on children, they have less capital available to purchase an EV or a household solar panel). Inequities are relative—not absolute. As another example, adoption patterns for food-sharing favour urban areas at the expense of rural ones, but adoption pattens for cookstoves favour rural areas at the expense of urban ones.

Marginalized groups are also often less engaged in formal politics for reasons such as a lack of time, precarious legal and economic status or scepticism that institutions will respond to their concerns or are trustworthy. Vulnerable populations are frequently susceptible to many shocks and often lack the adaptive capacity to absorb such shocks. As Fig. 4 indicates, this makes vulnerability dynamic and relational: dynamic as it is changing over time and relational as it is always relative to another group or a pre-existing baseline[122]. In some situations, vulnerability may be linked to dependence rooted in employment patterns, spending habits or the accumulation of household wealth. In others, though, it might relate to the strength or vitality of community institutions or the strength of governance regimes. In others still, it may relate to exposure to changes in energy prices, regional unemployment patterns or diminishing property values. The figure also shows how ongoing patterns of demographic, spatial, environmental and temporal inequity can compound and intersect with the relationality of vulnerability.

Yet the various spatial, temporal and intra-household dynamics shown in Fig. 4 are exceedingly difficult to measure and monitor in models or other policy analysis tools[123]. Low-carbon transitions may be slow, but the changes within specific communities are fast, and so fast that many are unprepared[124], although policymakers and other organizations in some regions have begun to develop strategies to address these diverse needs through gender tool kits and equalities assessments, for example[125].

Undertake more intersectional approaches. Intersectionality is a second promising research avenue. There are multiple vulnerabilities that intersect across class, race, gender, ability and more, as emphasized in Fig. 4 and above. Groundbreaking work include studies focusing on intersections of race, ethnicity and gender[126], feminism, class and power[127], and Indigenousness and gender[128]. As noted

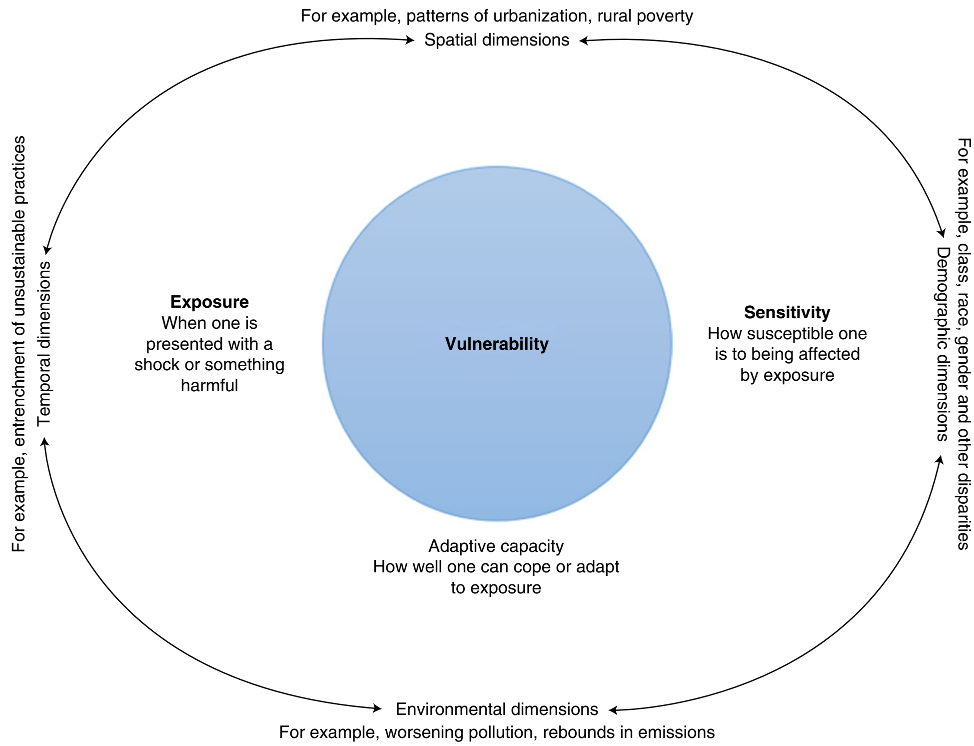

Fig. 4 | Visualizing the relationship between resilience and vulnerability. Vulnerability is a product of specific shocks (exposures), sensitivity to such shocks (sensitivity) and one's ability, or not, to adapt and cope (adaptive capacity). Figure adapted with permission from ref. [133], Springer Nature Limited.

above, these demographic inequities can be further complicated by temporal dimensions across the life courses of people[129].

Future inequalities and injustices that also warrant further attention include mental health, disability and age. For example, some users of technology (minority groups or individuals with a disability) can be persistently invisible in policy discussions, and their experiences of energy poverty are not well understood or recognized. A lack of recognition puts these users at risk of falling through the cracks[130]. A UK study found high levels of energy poverty among people with disabilities under the age of 60 years, a group unlikely to be eligible to receive the winter fuel allowance and a group that may struggle to access other energy-efficiency programmes such as the warm home discount scheme. Likewise, experiences with energy poverty can have detrimental impacts on the mental health and well-being of vulnerable households[131,132].

As we have emphasized in this Review, there are many different sources and types of inequities in the transition towards decarbonization, both related to the technological innovations and behavioural change that will be necessary to reach a net-zero goal. For such a transition to be fully just, we must therefore expand our conception of assistance strategies for a 'just transition' to include not just those who work in the legacy of fossil fuel industries but also those who are vulnerable in other ways[133]. More refined and nuanced analysis needs to be informed by intersectional approaches that take a more complete view of complex identities, social difference and just transitions, and not only employment or income.

Pursue whole-systems analysis. There is an increasingly acknowledged need to move beyond the false dichotomy of individual versus system change to recognizing individual and system change are not only required but often interconnected as part of "ecosystems of transformation"[134,135]. A key element of this is reshaping 'choice architectures' through proactive 'choice editing', which restricts carbon-intensive products and services coming to market in the first place, and it is a lot easier than changing behavioural lock-in around their adoption and use. At a deeper level, it also means addressing the drivers of unsustainable consumption in value systems[136], social inequalities[137] and the prevalence of advertising in advanced economies. Groundbreaking multiscalar work in this regard includes studies examining justice and solar commodity chains[79], microgeneration technologies[138] and embodied energy injustices with coal[139].

Recognize more nuanced behaviour. As the evidence presented in this Review clearly shows, agency as well as responsibility to enact low-carbon behaviours is unevenly distributed within and across societies according to income, gender, race, age and ability, among other factors. Although policy focus has traditionally been on individual and household behaviours, we all enjoy different levels of behavioural agency in the multiple spaces we occupy as citizens: at work, in political society, as family members as well as in our communities and the home[140]. Put another way, policy can be public or private, behaviour and decision-making can be individual, collective or organizational, and equity can be a function of income, country or other social characteristics[141].

Distinguishing between different groups and their behaviour may reveal that while many people have huge carbon footprints that need to drastically shrink, only a fraction of them have meaningful influence or direct agency over those behaviours. Wealthy people have, per definition, more money than the rest of us and can therefore buy more consumer goods and have larger carbon footprints. The powerful elite of oligarchs, finance executives, media magnates and chairpersons of large multinational companies are different. For these people, it is not their enormous carbon footprints as individuals that is the main issue, but rather how they use their influence over media reporting and political decisions. We must continue to distinguish between those who pollute mainly through their consumption patterns and those who pollute both through their exceedingly lavish lifestyles and by using their power to prevent or delay meaningful climate action as part of the "polluter elite"[142].

Some behaviours matter more than others; therefore, accounts of appropriate intervention to enable behavioural change need to be cognizant of this, as it opens up other avenues of engagement and action than simply nudging individuals and households. To operationalize a more nuanced take on behaviour—individual, organizational, private and public—we need a more rounded view of differential agency and we need to acknowledge that wealthy, overconsuming super-elites have a heightened responsibility to address their behaviour. This might include workplace schemes to support sustainable practices around travel, diets and energy use, for example, but also frequent flyer levies or restrictions on multiple home ownership to deter high-impact behaviours[143].

Moreover, industry, business organizations and civil society can take various actions that facilitate and promote sustainable energy choices, and remove important barriers for change, ones that can also accumulate into very large reductions in emissions across areas as diverse as transport, energy efficiency and forestry. Collectively, such subnational reductions in emissions could even be greater than those achieved by the Paris Agreement[144]. We need to better understand the psychological and behavioural effects of energy policies that aim to change the context in which decisions are made so that sustainable energy behaviour is made more attractive and feasible. Specifically, we need to increase our understanding of the conditions under which different strategies aimed at changing the context are most effective, how negative side effects can be prevented and how the role of governments and other stakeholders in creating and implementing different incentives for various groups can be enhanced.

Embrace anticipatory governance. Scholars of climate adaptation and resilience have embraced the idea of anticipatory governance to recognize the need for institutional innovations that can cope with the multiple and interacting risks, uncertainties and feedbacks that climate change greatly amplifies. Applied to the issues we address here, this can take a number of forms, from foresight panels, participatory futuring and scenario work to multicriteria mapping of the potential effects of particular technological pathways[145]. While these need to be adapted to the contexts and the purposes for which they used, they offer promise in helping those with governance responsibilities to foresee negative effects and evolve strategies to manage or avoid them and to reduce the level of future social backlash by validating proposals and co-designing interventions with representative cross-sections of society.

Expand equity considerations to non-humans. The question of providing justice for nature raises a series of challenges for philosophers and ethicists, as well as policymakers and researchers. This is especially the case given that most philosophical work conceptualizes equity in terms of human relations. But legal innovations in recent years have afforded legal protection and rights to forests, rivers and other natural ecosystems. Non-Western and Indigenous justice traditions take as given the rights of natural environments to be protected and to belong[146]. Initiatives are increasingly taking root from the USA to India, and Ecuador to Bolivia, Turkey and Nepal, that give rights to nature. For example, in 2019, voters in Toledo, Ohio, approved a ballot to give Lake Erie, suffering heavy pollution, rights that are normally associated with a person[15]. Meanwhile, in 2017, the New Zealand government passed legislation recognizing the Whanganui River as holding rights and responsibilities equivalent to a person[147]. The river—or those acting for it—will now be able to sue for its own protection under the law. Recognizing and valuing ecosystems in this way protects them from degradation and human consumption and suggests an important and often neglected justice dimension in discussions of low-carbon transitions. Taking the rights of nature seriously requires a broader view of environmental ethics and a less instrumental and anthropocentric approach to the benefits of different pathways.

Interrogate the causes of inequity. A final salient research theme is to unravel the causes or mechanisms behind inequity across our cases in relation to sustainable behaviours or low-carbon technical innovations. These causes are not so easily identified nor deterministic, often entangling a mix of technological design with the consequences or effects of the technology along with the policy regimes and governance aspects where that technology is being used, which is shaped further still by local culture and power structures. Moreover, these structural elements are all mediated by the agency of stakeholders and demographic attributes such as household income or community resilience. In simpler terms, issues of design become blended with use, or misuse, along with structural elements such as policy or culture. Within this complex milieu, some innovations can introduce new vulnerabilities, whereas others can merely cement old or pre-existing ones. For example, the nuclear transition in France introduced entirely new risks to winemakers that had occupied land adjacent to nuclear power plants for hundreds to thousands of years, and the solar transition in Germany introduced new bust and employment cycles to parts of Eastern Germany unique to that manufacturing boom[148]. Similarly, improved stoves—and other more energy-efficient household cooking devices—can introduce entirely new dynamics into a house that put more work on women. Simply put, they eliminate or reduce drudgery but can actually increase work[149]. However, the EV transition and its dependence on unfair labour practices for lithium and cobalt, and the electronic waste generated by smart meters, have only aggravated pre-existing vulnerabilities related to dispossession, ecological uneven exchange and extractivism[148]. More scholastic inquiry examining these causal relationships would enable a more refined understanding of how agency, structure and inequity interact.

Conclusion

Emerging innovations such as improved cookstoves, solar PV panels, EVs and food-sharing are often seen as solutions that will benefit society while transforming various energy, building or food systems. However, some communities see these as negatively affecting their social, cultural, economic and environmental realities. At the very worst, such innovations can sometimes disproportionately affect some groups while benefitting others, and thus serve to exacerbate inequality and injustice. At the very least, they can reflect unequal access to technologies and to incentives to adopt them and disparities in affordability.

To be very clear, the issues we raise here should not stand as justification to stop decarbonization or efforts to promote sustainable behaviour. We should not abandon such low-carbon actions in a blanket manner. Instead, we call for more robust and nuanced ways of managing trade-offs and negative side-effects of any decarbonization transition strategy, including more social inclusion in their design and selection. It may very well be that the costs of not adopting such innovations are far, far greater than adopting them.

Nevertheless, the risks of inequity abound in decarbonization pathways and behaviours. They can potentially arise both from misusing innovations (for example, incorrectly driving an EV, using toxic materials for the production of solar PV panels) but also properly using them (for example, embedding automobility via EVs, making one feel good via only an incremental and potentially non-impactful activity such as food-sharing). In other words, low-carbon innovations are not automatically just, equitable or even green. We must come to craft policy and action that is more aware of tensions in equity across demographic, spatial, environmental and temporal dimensions so that they can be minimized or maybe even eliminated. Ultimately, decarbonizing will change far more than the technologies at play to deliver energy, mobility or food; it will shape the desirability and scope of behaviour and it will intersect with principles of justice. Whether a future low-carbon society liberates and empowers vulnerable groups or threatens to further trap them into cycles of poverty and precarity will depend on the actions we collectively take in the next few decades.

Received: 1 June 2021; Accepted: 10 November 2021;
Published online: 31 January 2022

References

1. Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: a global, trade-linked analysis. *Environ. Sci. Technol.* **43**, 6414–6420 (2009).
2. Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C. & Vandenbergh, M. P. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proc. Natl Acad. Sci. USA* **106**, 18452–18456 (2009).
3. *A Systemic Approach to the Energy Transition in Europe* (SAPEA, 2021); https://www.sapea.info/topics/energy-transition/
4. *Global Energy Sector CO_2 Emissions Reductions by Current Technology Maturity Category in the Sustainable Development Scenrio relative to the Stated Policies Scenario, 2019–2070*, https://www.iea.org/data-and-statistics/charts/global-energy-sector-co2-emissions-reductions-by-current-technology-maturity-category-in-the-sustainable-development-scenario-relative-to-the-stated-policies-scenario-2019-2070 (International Energy Agency, 2020).
5. Sachs, J. D., Schmidt-Traub, G. & Williams, J. Pathways to zero emissions. *Nat. Geosci.* **9**, 799–801 (2016).
6. Nelson, S. & Allwood, J. M. Technology or behaviour? Balanced disruption in the race to net zero emissions. *Energy Res. Soc. Sci.* **78**, 102124 (2021).
7. Stephenson, J. et al. Energy cultures and national decarbonisation pathways. *Renew. Sustain. Energy Rev. 137* **137**, 110592 (2021).
8. IPCC. *Special Report on Global Warming of 1.5 °C.* (eds Masson-Delmotteeds, V. et al.) (WMO, 2018).
9. Newell, P. et al. Cambridge sustainability commission report on scaling behaviour change. *Rapid Transition Alliance* (13 April 2021).
10. Moberg, K. R. et al. Barriers, emotions and motivational levers for lifestyle transformation in Norwegian household decarbonization pathways. *Clim. Change* **165**, 3 (2021).
11. Ivanova, D. et al. Quantifying the potential for climate change mitigation of consumption options. *Environ. Res. Lett.* **15**, 093001 (2020).
12. Whitmarsh, L., Capstick, S., Moore, I., Kohler, J. & Le Quere, C. Use of aviation by climate change researchers: structural influences, personal attitudes, and information provision. *Glob. Environ. Change* **65**, 102184 (2020).
13. Dubois, G. et al. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. *Energy Res. Soc. Sci.* **52**, 144–158 (2019).
14. Lute, M. L., Attari, S. Z. & Sherman, S. J. Don't rush to flush. *J. Environ. Psychol.* **43**, 105–111 (2015).
15. Prior, R. An Ohio city has voted to grant Lake Erie the same rights as a person. *CNN News*, https://edition.cnn.com/2019/02/21/us/ohio-city-lake-erie-rights-trnd/index.html (27 February 2019).
16. Lewis A. et al. *1.5-Degree Lifestyles: Towards A Fair Consumption Space for All* (Hot or Cool Institute, 2021).
17. Klinsky, S. & Winkler, H. Building equity in: strategies for integrating equity into modelling for a 1.5 °C world. *Philos. Trans. A Math Phys. Eng. Sci.* **376**, 20160461 (2018).
18. Hoegh-Guldberg, O. et al. The human imperative of stabilizing global climate change at 1.5 °C. *Science* **365**, eaaw6974 (2019).
19. Lamb, W. F. et al. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. *Environ. Res. Lett.* **15**, 113006 (2020).
20. Kartha, S., Caney, S., Dubash, N. K. & Muttitt, G. Whose carbon is burnable? Equity considerations in the allocation of a 'right to extract. *Clim. Change* **150**, 117–129 (2018b).
21. Rendall, M. Discounting, climate change, and the ecological fallacy. *Ethics* **129**, 441–463 (2019).
22. IPCC. *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2021).
23. Creutzig, F. et al. Reviewing the scope and thematic focus of 100,000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation. *Environ. Res. Lett.* **16**, 033001 (2021).
24. Carley, S., Evans, T. P. & Konisky, D. M. Adaptation, culture, and the energy transition in American coal country. *Energy Res. Soc. Sci.* **37**, 133–139 (2018).
25. Asmal, K. Introduction: World Commission on dams report, dams and development. *Am. Univ. Int. Law Rev.* **16**, 1411–1433 (2001).
26. Kawaguchi, D. & Yukutake, N. Estimating the residential land damage of the Fukushima nuclear accident. *J. Urban Econ.* **99**, 148–160 (2017).
27. Sovacool, B. K., Perea, M. A. M., Matamoros, A. V. & Enevoldsen, P. Valuing the externalities of wind energy: assessing the environmental profit and loss of wind turbines in Northern Europe. *Wind Energy* **19**, 1623–1647 (2016).
28. Fairhead, J., Leach, M. & Scoones, I. Green grabbing: a new appropriation of nature? *J. Peasant Stud.* **39**, 237–261 (2012).
29. Druckman, A., Chitnis, M., Sorrell, S. & Jackson, T. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy* **39**, 3572–3581 (2011).
30. Sovacool, B. K. & Griffiths, S. Culture and low-carbon energy transitions. *Nat. Sustain.* **3**, 685–693 (2020).
31. Frankowska, A., Jeswani, H. K. & Azapagic, A. Environmental impacts of vegetables consumption in the UK. *Sci. Total Environ.* **682**, 80–105 (2019).
32. Herforth, A. et al. *Cost and Affordability of Healthy Diets across and within Countries: Background Paper for The State of Food Security and Nutrition in the World 2020. FAO Agricultural Development Economics Technical Study No. 9)* (FAO, 2020).
33. Axsen, J. & Sovacool, B. K. The roles of users in electric, shared, and automated mobility transitions. *Transp. Res. Part D Trans. Environ.* **71**, 1–21 (2019).
34. *Access to Clean Cooking* https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking (International Energy Agency, accessed 2 August 2 2021).
35. Brown, M. A. & B. K. Sovacool. *Climate Change and Global Energy Security: Technology and Policy Options* (MIT Press, 2011)
36. Bailis, R. et al. Arresting the killer in the kitchen: the promises and pitfalls of commercializing improved cookstoves. *World Develop.* **37**, 1694–1705 (2009).
37. Bailis, R., Drigo, R., Ghilardi, A. & Masera, O. The carbon footprint of traditional woodfuels. *Nat. Clim. Change* **5**, 266–272 (2015).
38. Smith, K. R. et al. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annu. Rev. Public Health* **35**, 185–206 (2014).
39. Das, K., Pradhan, G. & Nonhebel, S. Human energy and time spent by women using cooking energy systems: a case study of Nepal. *Energy* **182**, 493–501 (2019).
40. Sovacool, B. K. et al. The energy–enterprise–gender nexus: lessons from the Multifunctional Platform (MFP) in Mali. *Renew. Energy* **50**, 115–125 (2013).
41. Osunmuyiwa, O. & Ahlborg, H. Inclusiveness by design? Reviewing sustainable electricity access and entrepreneurship from a gender perspective. *Energy Res. Soc. Sci.* **53**, 145–158 (2019).
42. Johnson, O. W., Gerber, V. & Muhoza, C. Gender, culture and energy transitions in rural Africa. *Energy Res. Soc. Sci.* **49**, 169–179 (2019).
43. Bhattarai, D., Somanathan, E. & Nepal, M. Are renewable energy subsidies in Nepal reaching the poor? *Energy Sustain. Develop.* **43**, 114–122 (2018).
44. Jan, I. & Das Lohano, H. Uptake of energy efficient cookstoves in Pakistan. *Renew. Sustain. Energy Rev.* **137**, 110466 (2021).
45. Khanwilkar, S., Gould, C. F., DeFries, R., Habib, B. & Urpelainen, J. Firewood, forests, and fringe populations: exploring the inequitable socioeconomic dimensions of liquified petroleum gas (LPG) adoption in India. *Energy Res. Soc. Sci.* **75**, 102012 (2021).
46. Patnaik, S. & Jha, S. Caste, class and gender in determining access to energy: a critical review of LPG adoption in India. *Energy Res. Soc. Sci.* **67**, 101530 (2020).
47. Khandelwal, M. et al. Why have improved cook-stove initiatives in India failed? *World Dev.* **92**, 13–27 (2017).
48. Otte, P. P. A (new) cultural turn toward solar cooking—evidence from six case studies across India and Burkina Faso. *Energy Res. Soc. Sci.* **2**, 49–58 (2014).
49. Oluwakemi, A., Jewitt, S. & Clifford, M. Culture, tradition, and taboo: understanding the social shaping of fuel choices and cooking practices in Nigeria. *Energy Res. Soc. Sci.* **40**, 14–22 (2018).
50. Coyfe, R. Solar cooker dissemination and cultural variables. *Solar Cookers International Network* http://solarcooking.org/advocacy/ dissemination_and_culture.htm (2006).
51. Smith, K. R., Gu, S., Kun, H. & Daxiong, Q. One hundred million improved cookstoves in China: how was it done? *World Dev.* **21**, 941–961 (1993).
52. Kishore, V. V. N. & Ramana, P. V. Improved cookstoves in rural India: how improved are they? A critique of the perceived benefits from the National Programme on Improved Chulhas (NPIC). *Energy* **27**, 47–63 (2002).
53. Adler, M. W., Peer, S. & Sinozic, T. Autonomous, connected, electric shared vehicles (ACES) and public finance: an explorative analysis. *Transp. Res. Interdiscip. Perspect.* **2**, 100038 (2019).

54. Graham-Rowe, E. et al. Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations. *Transp. Res. Part A Policy Pract.* **46**, 140–153 (2012).
55. Seebauer, S. The psychology of rebound effects: explaining energy efficiency rebound behaviours with electric vehicles and building insulation in Austria. *Energy Res. Soc. Sci.* **46**, 311–320 (2018).
56. Sovacool, B. K., Hook, A., Martiskainen, M. & Baker, L. The whole systems energy injustice of four European low-carbon transitions. *Glob. Environ. Change* **58**, 101958 (2019).
57. Langbroek, J. H. M., Franklin, J. P. & Susilo, Y. O. How would you change your travel patterns if you used an electric vehicle? A stated adaptation approach. *Travel Behav. Soc.* **13**, 144–154 (2018).
58. Hamamoto, M. An empirical study on the behavior of hybrid-electric vehicle purchasers. *Energy Policy* **125**, 286–292 (2019).
59. Kester, J. et al. Novel or normal? Electric vehicles and the dialectic transition of Nordic automobility. *Energy Res. Soc. Sci*. **69**, 101642 (2020).
60. Sovacool, B. K. et al. Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Clim. Change* **155**, 581–619 (2019).
61. Henderson, J. M. EVs are not the answer: a mobility justice critique of electric vehicle transitions. *Ann. Am. Assoc. Geogr.* **110**, 1993–2010 (2020).
62. Sovacool, B. K., Kester, J., Noel, L. & de Rubens, G. Z. Energy injustice and Nordic electric mobility: inequality, elitism, and externalities in the electrification of vehicle-to-grid (V2G) transport. *Ecol. Econ.* **157**, 205–217 (2019).
63. Borenstein, S. & Davis, L. W. The distributional effects of U. S. clean energy tax credits. *Tax. Policy Econ.* **30**, 191–234 (2016).
64. Sovacool, B. K., Kester, J., Noel, L. & de Rubens, G. Z. The demographics of decarbonizing transport: the influence of gender, education, occupation, age, and household size on electric mobility preferences in the Nordic region. *Glob. Environ. Change* **52**, 86–100 (2018).
65. Sovacool, B. K. The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extr. Ind. Soc.* **6**, 915–939 (2019).
66. Hornborg, A. & Martinez-Alier, J. Ecologically unequal exchange and ecological debt. *J. Polit. Ecol.* **23**, 328–333 (2016).
67. Skeete, J.-P., Wells, P., Dong, X., Heidrich, O. & Harper, G. Beyond the EVent horizon: battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition. *Energy Res. Soc. Sci.* **69**, 101581 (2020).
68. Morse, I. A dead battery dilemma. *Science* **372**, 780–783 (2021).
69. Sovacool, B. K., Hook, A., Martiskainen, M., Brock, A. & Turnheim, B. The decarbonisation divide: contextualizing landscapes of low-carbon exploitation and toxicity in Africa. *Glob. Environ. Change* **60**, 102028 (2020).
70. Dharshing, S. Household dynamics of technology adoption: a spatial econometric analysis of residential solar photovoltaic (PV) systems in Germany. *Energy Res. Soc. Sci.* **23**, 113–124 (2017).
71. Sovacool, B. K., Lipson, M. & Chard, R. Temporality, vulnerability, and energy justice in household low carbon innovations. *Energy Policy* **128**, 495–504 (2019).
72. Walker, G. Decentralised systems and fuel poverty: are there any links or risks? *Energy Policy* **36**, 4514–4517 (2008).
73. Barbose, G. L., Forrester, S. O'Shaughnessy, E. & Darghouth, N. R. *Residential Solar-Adopter Income and Demographic Trends: 2021 Update* (Lawrence Berkeley National Laboratory, 2021).
74. Wadim, S., Štreimikienė, D. & Bilan, Y. Network charging and residential tariffs: a case of household photovoltaics in the United Kingdom. *Renew. Sustain. Energy Rev.* **77**, 461–473 (2017).
75. Weber, G. & Cabras, I. The transition of Germany's energy production, green economy, low-carbon economy, socio-environmental conflicts, and equitable society. *J. Clean. Prod.* **167**, 1222–1231 (2017).
76. Burger, J. & Gochfeld, M. A conceptual framework evaluating ecological footprints and monitoring renewable energy: wind, solar, hydro, and geothermal. *Energy Power Eng.* **4**, 303–314 (2012).
77. Sundqvist, T. What causes the disparity of electricity externality estimates? *Energy Policy* **32**, 1753–1766 (2004).
78. Nugent, D. & Sovacool, B. K. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. *Energy Policy* **64**, 229–244 (2014).
79. Mulvaney, D. Opening the black box of solar energy technologies: exploring tensions between innovation and environmental justice. *Sci. Cult.* **22**, 230–237 (2013).
80. Brock, A., Sovacool, B. K. & Hook, A. Volatile photovoltaics: green industrialization, sacrifice zones, and the political ecology of solar energy in Germany. *Ann. Am. Assoc. Geogr.* **111**, 1756–1778 (2021).
81. Sovacool, B. K. Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Res. Soc. Sci.* **73**, 101916 (2021).
82. Mulvaney, D. Are green jobs just jobs? Cadmium narratives in the life cycle of photovoltaics. *Geoforum* **54**, 178–186 (2014).
83. Cross, J. & Murray, D. The afterlives of solar power: waste and repair off the grid in Kenya. *Energy Res. Soc. Sci.* **44**, 100–109 (2018).
84. Salim, H. K., Stewart, R. A., Sahin, O. & Dudley, M. Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: a systematic literature review. *J. Clean. Prod.* **20**, 537–554 (2019).
85. National Academies of Sciences Engineering, and Medicine. *Reducing Impacts of Food Loss and Waste: Proceedings of a Workshop* (The National Academies Press, 2019).
86. Ciaghi, A. & Villafiorita, A. Beyond food sharing: supporting food waste reduction with ICTs. In *Proc. 2016 IEEE International Smart Cities Conference (ISC2)* 1–6 (IEEE, 2016).
87. Glynn, I. The food-sharing behavior of protohuman hominids. *Sci. Am.* **238**, 90–109 (1978).
88. Kafafi, Z. A. Sharing food eating from one plate: an ethno-archaeological study. *Adumatu* **July**, 7–18 (2014).
89. Gvion, L. Cuisines of poverty as means of empowerment: Arab food in Israel. *Agric. Hum. Values* **23**, 299–312 (2006).
90. Davies, A. R. & Legg, R. Fare sharing: interrogating the nexus of ICT, urban food sharing, and sustainability. *Food Cult. Soc.* **21**, 233–254 (2018).
91. Jehlička, P., Daněk, P. & Vávra, J. Rethinking resilience: home gardening, food sharing and everyday resistance. *Can. J. Develop. Stud.* **40**, 511–527 (2019).
92. Davies, A. R. et al. Making visible: interrogating the performance of food sharing across 100 urban areas. *Geoforum* **86**, 136–149 (2017).
93. Mattar, L. et al. Attitudes and behaviors shaping household food waste generation: lessons from Lebanon. *J. Clean. Prod.* **198**, 1219–1223 (2018).
94. Visschers, V. H. M., Wickli, N. & Siegrist, M. Sorting out food waste behaviour: a survey on the motivators and barriers of self-reported amounts of food waste in households. *J. Environ. Psychol.* **45**, 66–78 (2016).
95. Ready, E. & Power, E. A. Why wage earners hunt: food sharing, social structure, and influence in an Arctic mixed economy. *Curr. Anthropol.* **59**, 74–97 (2018).
96. Zurek, K. Food sharing in Europe: between regulating risks and the risks of regulating. *Eur. J. Risk Regul.* **7**, 675–687 (2016).
97. Morone, P. et al. Does food sharing lead to food waste reduction? An experimental analysis to assess challenges and opportunities of a new consumption model. *J. Clean. Prod.* **185**, 749–760 (2018).
98. Michelini, L., Principato, L. & Iasevoli, G. Understanding food sharing models to tackle sustainability challenges. *Ecol. Econ.* **145**, 205–217 (2018).
99. Schanes, K. & Stagl, S. Food waste fighters: what motivates people to engage in food sharing? *J. Clean. Prod.* **211**, 1491–1501 (2019).
100. Sunter, D. A., Castellanos, S. & Kammen, D. M. Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nat. Sustain.* **2**, 71–76 (2019).
101. Nussbaum, M. C. *Frontiers of Justice: Disability, Nationality, Species Membership* (Harvard Univ. Press, 2007).
102. Nash, R. *The Rights of Nature: A History of Environmental Ethics* (Univ. of Wisconsin Press, 1990).
103. Merskin, D. in *Communicating Responsible Diversity, Equality, and Inclusion. Public Relations for Social Responsibility: Affirming DEI Commitment with Action* (ed. Pompper, D.) 103–119 (Emerald Publishing, 2021).
104. Mackenbach, J. P. Inter-species health equity. *Eur. J. Public Health* **31**, 241 (2021).
105. Blount-Hill, K.-L. Proposing a social identity theory of interspecies dominance. *Biol. Conserv.* **254**, 108969 (2021).
106. Thiery, W. et al. Intergenerational inequities in exposure to climate extremes. *Science* **374**, 158–160 (2021).
107. *The Path to Net Zero: Climate Assembly UK Full Report* https://www.climateassembly.uk/report/ (Citizen Assembly UK, 2020).
108. Boyd, E. et al. Anticipatory governance for social-ecological resilience. *AMBIO* **44**, 149–161 (2015).
109. Folke, C., Hahn, T., Olsson, P. & Norberg, J. Adaptive governance of social ecological systems. *Annu. Rev. Environ. Resour.* **30**, 441–473 (2005).
110. Deason, J., Leventis, G. &. Murphy, S. *Performance of Solar Leasing for Low- and Middle-income Customers in Connecticut* (Lawrence Berkeley National Laboratory, 2021).
111. Ellegård, A., Arvidson, A., Nordström, M., Kalumiana, O. S. & Mwanza, C. Rural people pay for solar: experiences from the Zambia PV-ESCO project. *Renew. Energy* **29**, 1251–1263 (2004).
112. Chan, G., Evans, I., Grimley, M., Ihde, B. & Mazumder, P. Design choices and equity implications of community shared solar. *Electr. J.* **30**, 37–41 (2017).
113. Weber, G., Cabras, I., Calaf-Forn, M., Puig-Ventosa, I. & D'Alisa, G. Promoting waste degrowth and environmental justice at a local level: the case of unit-pricing schemes in Spain. *Ecol. Econ.* **156**, 306–317 (2019).

114. Green, F. & Gambhir, A. Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how? *Clim. Policy* **20**, 902–921 (2020).
115. Newell, P. Managing multinationals: the Governance of investment for the environment. *J. Int. Dev.* **13**, 907–919 (2001).
116. Zeng, X., Mathews, J. A. & Li, J. Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environ. Sci. Technol.* **52**, 4835–4841 (2018).
117. Lapko, Y., Trianni, A., Nuur, C. & Masi, D. In pursuit of closed loop supply chains for critical materials: an exploratory study in the green energy sector. *J. Ind. Ecol.* https://doi.org/10.1111/jiec.12741 (2018).
118. Recycling Workshop Highlights. *NAATBatt International* https://naatbatt.org/recycling- workshop-highlights-the- importance-of-recycling-ev- batteries/ (9–10 July 2019).
119. Chilvers, J. et al. A systemic approach to mapping participation with low-carbon energy transitions. *Nat. Energy* **6**, 250–259 (2021).
120. Sovacool, B. K & Dworkin, M. H. *Global Energy Justice. Problems, Principles, and Practices* (Cambridge Univ. Press, 2014).
121. Proposal for a High Commissioner/Ombudsperson for Future Generations: Reflections on the Negotiation Process. *World Future Council* http://sdg.iisd.org/commentary/guest- articles/proposal-for- a-high-commissionerombudsperson-for- futuregenerationsreflections-on-the-negotiation-process/ (23 April 2012).
122. Bouzarovski, S. & Simcock, N. Spatializing energy justice. *Energy Policy* **107**, 640–648 (2017).
123. Bell, S. et al. Sociality and electricity in the United Kingdom: the influence of household dynamics on everyday consumption. *Energy Res. Soc. Sci.* **9**, 98–106 (2015).
124. Carley, S., Engle, C. & Konisky, D. M. An analysis of energy justice programs across the United States. *Energy Policy* **152**, 112219 (2021).
125. *Gender Tool Kit: Energy: Going Beyond the Meter* (Asian Development Bank, 2012).
126. Lennon, M. Decolonizing energy: Black Lives Matter and technoscientific expertise amid solar transitions. *Energy Res. Soc. Sci.* **30**, 18–27 (2017).
127. Ryder, S. S. Developing an intersectionally-informed, multi-sited, critical policy ethnography to examine power and procedural justice in multiscalar energy and climate change decisionmaking processes. *Energy Res. Soc. Sci.* **45**, 266–275 (2018).
128. Lieu, J., Sorman, A. H., Johnson, O. W., Virla, L. D. & Resurrección, B. P. Three sides to every story: gender perspectives in energy transition pathways in Canada, Kenya and Spain. *Energy Res. Soc. Sci.* **68**, 101550 (2020).
129. Burningham, K. & Venn, S. Are lifecourse transitions opportunities for moving to more sustainable consumption? *J. Consum. Cult.* **20**, 102–121 (2020).
130. Snell, C., Bevan, M & Thomson, H. Justice, fuel poverty and disabled people in England. *Energy Res. Soc. Sci.* **10**, 123–132 (2015).
131. Mould, R. & Baker, K. J. Documenting fuel poverty from the householders' perspective. *Energy Res. Soc. Sci.* **31**, 21–31 (2017).
132. Hernández, D. Understanding 'energy insecurity' and why it matters to health. *Soc. Sci. Med.* **167**, 1–10 (2016).
133. Carley, S., Evans, T. P., Graff, M. & Konisky, D. M. A framework for evaluating geographic disparities in energy transition vulnerability. *Nat. Energy* **3**, 621–627 (2018).
134. Newell, P., Daley, F. & Twena, M. *Changing Our Ways? Behaviour Change and the Climate Crisis. Report of the Cambridge Sustainability Commission on Scaling Behaviour Change* (Cambridge Sustainability Commission, 2021).
135. *Emissions Gap Report 2020* (UNEP, 2020).
136. Kasser, T. *The High Price of Materialism* (MIT Press, 2002).
137. Wilkinson, R. G. & Pickett, K. *The Spirit Level: Why Equality Is Better for Everyone* (Allen Lane, 2009).
138. Adams, C., Taylor, P. & Bell, S. Equity dimensions of micro-generation: a whole systems approach. *J. Renew. Sustain. Energy* https://doi.org/10.1063/1.4759454 (2012).
139. Healy, N., Stephens, J. C. & Malin, S. A. Embodied energy injustices: unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. *Energy Res. Soc. Sci.* **48**, 219–234 (2019).
140. Capstick, S., Lorenzoni, I., Corner, A. & Whitmarsh, L. Prospects for radical emissions reduction through behavior and lifestyle change. *Carbon Manag.* **5**, 429–445 (2015).
141. Carley, S. Normative dimensions of sustainable energy policy. *Ethics Policy Environ.* **14**, 211–229 (2011).
142. Kenner, D. *Carbon Inequality: The Role of the Richest in Climate Change* (Routledge, 2019).
143. Newell, P., Twena, M. & Daley F. Scaling behaviour change for a 1.5 degree world: challenges and opportunities. *Global Sustainability* https://doi.org/10.1017/sus.2021.23 (2021).
144. Hsu, A. et al. Beyond states: harnessing sub-national actors for the deep decarbonisation of cities, regions, and businesses. *Energy Res. Soc. Sci.* **70**, 101738 (2020).
145. Stirling, A. Analysis, participation and power: justification and closure in participatory multi-criteria analysis. *Land Use Policy* **1**, 95–107 (2006).
146. Gilio-Whitaker, D. *As Long as Grass Grows: The Indigenous Fight for Environmental Justice, from Colonization to Standing Rock* (Beacon Press, 2019).
147. Roy, E. A. New Zealand river granted same legal rights as human being. *Guardian*, https://www.theguardian.com/world/2017/mar/16/new-zealand-river-granted-same-legal- rights-as-human-being (16 March 2017).
148. Sovacool, B. K., Turnheim, B., Hook, A., Brock, A. & Martiskainen, M. Dispossessed by decarbonisation: reducing vulnerability, injustice, and inequality in the lived experience of low-carbon pathways. *World Dev.* **137**, 105116 (2021).
149. Schwartz Cowan, R. *More Work for Mother: The Ironies of Household Technology from the Open Hearth to the Microwave* (Basic Books, 1983).
150. Geels, F. W. et al. Reducing energy demand through low carbon innovation: a sociotechnical transitions perspective and thirteen research debates. *Energy Res. Soc. Sci.* **40**, 23–35 (2018).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41562-021-01257-8.

Correspondence should be addressed to Benjamin K. Sovacool.

Peer review information *Nature Human Behaviour* thanks Fergus Green, Claire Hoolohan and Gabriel Weber for their contribution to the peer review of this work.