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

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Abstract: The world must ambitiously curtail greenhouse gas emissions to achieve climate stability. The literature often supposes that a low-carbon future will depend upon a mix of technological innovation—improving the performance of new technologies and systems—as well as more sustainable behaviors such as traveling less or reducing waste. To what extent are low carbon technologies, and their associated behaviors, currently equitable, and what are potential policy and research implications moving forward? In this Review, we examine how four innovations in technology and behavior—improved cookstoves and heating, battery electric vehicles, household solar panels, and food-sharing—create complications and force tradeoffs on different equity dimensions. We draw from these cases to discuss a typology of inequity cutting across demographic (e.g., gender, race, and class), spatial (e.g., urban/rural divides), interspecies (e.g., human and non-human), and temporal (e.g., 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 behaviors 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.

Keywords: climate justice; energy justice; just transition; climate change and equity; technological innovation; polluter elite; overconsumption

Word count (excluding tables, figures, abstract, references): 6950 words

1. Introduction

Achieving a low carbon society will require potentially transformative changes in both behavior (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 behavior 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 play 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 behavior are needed to achieve a "net-zero" or "zero emissions" society,[5] and coupling technical and behavioral change is critical to this endeavor[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 technology *and* human behavior are dually critical.[8] [9] [10] [11] [12] [13] [14]

However, these transitions in technology and behavior 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: consumers will need to reduce their footprint by a factor of 30 to stay in line with Paris Accord targets.[16] It therefore follows that behaviors such as flying frequently, 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 behavioral implications create complications and *force* tradeoffs on different equity concerns and criteria. We draw from these cases to discuss a typology of inequity dimensions, and discuss policy and research insights.

2. Equity, technology and behavior 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]

While there is an extensive and growing 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 behaviors that can lock-in or perpetuate injustices.[24]

This lacuna is unfortunate, given that innovations in technology and behavior, even those geared towards sustainability, 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, fiberglass, and steel with many manufacturing externalities concentrated across the supply chain, especially in Asia.[27] More sustainable agriculture can rely on exploitative labor practices or land grabbing.[28]

Similarly, sustainability behaviors and social practices can also impinge upon 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 United Kingdom, 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 behaviors.[33]

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

[Insert Figure 1 here]

2.1 Incremental and modest: Improved cooking and heating

Traditional cooking and heating practices around the world are surprisingly bad for the climate as well as dangerous for human health, but 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 a fairly incremental technology that require only a modest change in practices (e.g., faster cooking times, 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] [36] and health benefits due to decreased exposure to indoor air pollution. [37]

Access to and use of these improved cookstoves, however, introduces some dauting equity challenges, including disparities in access and entrenchment of gendered work.[38] [39] 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—in the developing world. [40] [41] 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 breakdown or ruin meals. The benefits of more sustainable (and healthy) cooking, when they do occur, are often not distributed equally or fairly either, and are mediated by gender roles and cultural norms [42] [43]. Disparities in cookstove adoption are also strongly connected to race and ethnicity, or oppressive caste systems. [44] [45] 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,” especially those in lower castes or in "fringe" areas.[46] 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.[47]

Improved stoves can also impede upon 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 center of the home[48]. Similarly, in Botswana, open fires create a comfortable space where families gather around a *leiso* to discuss the day's events; substituting a normal fire with an improved stove disrupts these cultural practices.[49] 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.[50]

Lastly, in some rural communities, residents still pray to "hearth gods" and cookstove smoke is seen as a connection to spirits and even God.[51] In this way, spiritualism is threatened by modern smokeless cooking devices. Yet many national cookstove programs have used sticks as well as carrots, punishing provinces failing to adopt targets or removing support for rural communities that depend on dirtier stoves.[52] [53]

2.2 Radical and substantial: Battery electric vehicles

Conventional automobility is linked strongly to transport-related carbon dioxide emissions as well as a host of other social and environmental calamities such as air pollution, car crashes, and traffic congestion. Battery electric vehicles are seen by many as a more sustainable option, especially if they also become connected with ridesharing, public transportation or automation,[54] and are powered by low-carbon electricity sources.

Electric vehicles, however, run the risk of further embedding motorized, private automobility as well as increased driving, according to a number of studies.[55] [56] [57] [58] [59] [60] [61] Electric vehicles further perpetuate forms of private, motorized mobility for future generations, shaping regimes to rely less on walking, active transport, or public transport.[62] 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.[63] The ongoing electric vehicle 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.[64] 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[65], and planners are using EV adoption as an excuse to build new roads, even in restricted or sensitive areas. [66] In the United States, the majority of tax incentives for EVs go to wealthy households, and rarely low-income households.[67] 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, who are the most likely to buy them.[68]

Lastly, electric vehicles 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—and 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 intensifyies 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.[69] At the backend of their lifecycle, EVs further "unequal exchange" through their waste streams. [70] The majority of EVs rely on high-voltage lithium-ion batteries that are difficult to recycle and that generate their own waste streams; and will eventually require car dismantling, scrapping and recycling.[71] [72] [73] 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.[74]

2.3 Radical and modest: Household solar photovoltaic (PV) panels

Household solar panels are seen as a way to simultaneously self-generate electricity (and thereby reduce demand and possible stress on electricity grids), potentially sell or exchange electricity via prosuming or net metering, and decarbonize electricity by substituting for fossil-fueled 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.[75] This excludes the millions of people who do not own their own home, or live in apartments or social housing blocks without a roof or access to a garden or lawn.[76] Those without access to the internet or installer company presence, and with poor health, previous financial difficulties and lower education levels also tend not to adopt them.[77] Extensive work on residential solar adoption in the United States has confirmed inequitable trends in diffusion as well[78], trends shaped by race, space (urban vs. rural adoption patterns), income, and class, as shown in Figure 2. Compared to the broader population, solar adopters tend to live in higher value homes, have higher credit scores, are more educated, live in white neighborhoods, are older, and have steady jobs working in business and finance related occupations.[79] Modeling research also suggests that solar PV favors richer consumers and particular network users who do not bear their fair share of total system distribution and transmission costs. [80] 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.[81]

[Insert Figure 2 here]

Finally, household solar panels give rise to some negative environmental externalities, including toxic materials utilized during manufacturing and installation, required integration with other systems, and dependence on rare earth mineral imports that do have global whole-systems impacts.[82, 83, 84, 85] Solar manufacturing can at times also rely on unfair and exploitative labor practices, resulting in boom and bust cycles for host communities and high levels of unanticipated unemployment in certain regions, which occurred in Germany,[86] or relying on low-wage transient workers in China.[87] Solar workers face occupational hazards, especially those exposed to unsafe levels of cadmium, used in thin-film solar PV designs.[88] Solar energy also produces hazardous waste streams that present a likely burden for future generations.[89, 90, 91]

2.4 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.[92] This makes food sharing both an innovative solution to tackling waste as well as growing rates of food poverty and insecurity.[93]

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.[94] Eating from one plate or sharing food represents a human practice thousands if not hundreds of thousands of years old.[95] 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.[96] .[97 98]

Despite the potential of mass food sharing in these contexts to achieve sustainability objectives, it is also implicated in a multitude of equity issues. Firstly, 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 centers of Chicago, London and New York serving as exemplars.[99] This fact obscures that much of the food consumed in urban centers 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).[100, 101, 102, 103] Food sharing among rural, Inuit communities in Canada has even reinforced economic and political inequality among settlements and unfair social structures.[104] 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 labeling of ingredients, handling and refrigerating leftovers, or serving expired products.[105] In Italy, food sharing created concerns over health and safety, with food sharers accidentally contaminating food, mislabeling food, or not respecting the dietary needs and food intolerances of consumers.[106] In some situations, improper storing, sorting and handling even *increased* net waste,

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.[107, 108] 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.[109] Thus, food sharing efforts can lead to clashes in values and community disagreements.[110] 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.[111]

3. Multifarious vulnerabilities: Mapping demographic, spatial, interspecies, and temporal inequities

Drawing from these four examples, we can identify multifarious dimensions of inequity and associated vulnerability to each. As Table 1 summarizes, these transcend demographic, spatial, interspecies, and temporal dimensions. Vulnerability to inequity or injustice here is multifaceted and also crosscutting.

Table 1: A matrix of inequities and vulnerabilities with low-carbon and sustainable technologies and behaviors

Demographic inequity (between groups): • Adoption is strongly mandated by gender roles (electric vehicles, improved cookstoves, food sharing) • Diffusion patterns substantially shaped by class, caste, income or wealth (improved cookstoves, electric vehicles, solar panels, food sharing) • Exclusion of non-homeowners or those without access to roofs (solar panels) • Adoption patterns favoring wealthier households and whiter communities, and disfavoring those struggling with illness or financial difficulty (solar panels) • Subsidies favoring wealthier households (electric vehicles, solar panels) • Adoption patterns favoring 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 upon a fairly advanced skillset of food preparation, handling, storage and refrigeration as well as disposal and waste (food sharing)	*Spatial inequity (across geographic scales):* • 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 (electric vehicles) • Lack of charging infrastructure in rural areas (electric vehicles) • Perpetuation of a "decarbonization divide" between Global North and Global South (electric vehicles, solar panels) • Shifting of conventional cars to peripheral (non-low-carbon) areas • Cross subsidization of energy costs that burden the poor (solar panels) • Unfair and at times exploitative labor 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 kilometers travelled impinging on forests or nature reserves (electric vehicles) • Roadbuilding and impingement of green spaces or trees in urban areas (electric vehicles) • Pushing of conventional cars to peripheral regions increasing air and water pollution (electric vehicles) • Increased air pollution or carbon emissions from fossil-fueled electricity (electric vehicles) • Electronic waste streams releasing toxics into habitats (solar panels and electric vehicles) • Environmental destruction and deforestation with mineral and material extraction (electric vehicles and solar panels) • Fossil fuel use, occupational hazards and pollution from local manufacturing (solar panels) • Potential rebounds in increased waste (and hazardous toxics) due to mistakes and improper sorting or handling (food sharing)	• Embedding private motorized automobility for future generations (electric vehicles) • Failing to address the underlying causes of food waste and unsustainable agriculture (food-sharing) • Cements future burden of cooking and domestic activities onto women (for improved cookstoves) • The generation of toxic waste streams and disposal concerns for future generations (electric vehicles, solar panels) • For profit motivations can lead to conflict and community tension over future food pathways and limit sustainable change (food sharing) • Can legitimate overproduction and food surplus and fail to address the root causes of food insecurity (food sharing)

3.1 Demographic inequity

Our cases reveal how sustainable technology and behavior 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[112]) strongly shape the diffusion patterns for things like electric vehicle ownership or solar panel installations; 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, indicating 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, though not all, of the innovations.

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

	Improved cooking	Electric vehicles	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, Caucasian, and some Hispanic	(+) 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

Source: Inspired by [113]. 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 it is representative of the literature that we relied on in preparation for this article,

3.2 Spatial inequity

Inequities emerge not only across demographic lines; they 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; and adoption patterns for solar energy favor urban areas. Solar energy is also more profitable in higher resource areas such as deserts or dry, hot climates, creating disparities in access—those living in sunny Arizona have far more capacity to benefit than those living in a cloudy Washington state, for example; 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. [114]

3.3 Interspecies inequity

Although sustainable behaviors 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, impacts 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.[115, 116] It is also supported by very recent advances in ethics suggesting that animals be treated as stakeholders in decisions about population, habitat, and health[117]; that human altruism has a responsibility to expand to non-humans and protect "planetary health"[118]; and moral considerations focusing on "non-human rights."[119]

Interspecies equity can be eroded through land use, deforestation, and waste streams. For example, some improved cookstoves may still rely on fossil fuels (e.g., LPG) or carbon-intensive electricity, and thus contribute to deforestation or climate change. EVs need roads and do not displace conventional cars entirely, 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 in Section 5.6.

3.4 Temporal inequity

A final class of concerns relate to future generations and futurity, or intergenerational inequity[120]. EVs can legitimate 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 significant disposal concerns at their end of life that will burden future generations, and food sharing can legitimate food surpluses and unsustainable agricultural practices. Furthermore, many of the impacts of these four innovations entail temporally irreversible changes: power plants charging electric vehicles convert fuel into thermal exhaust fumes; industrial processes behind 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 Figure 3. Cookstoves currently threaten some gendered and rural cultural practices, but in the future market segments could emerge 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, unless they participate in community solar, 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 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.

[Insert Figure 3 here]

4. Policy insights and leverage points

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

4.1 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 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.[121] Anticipatory governance mechanisms such as collaborative and participatory processes for envisioning strategy[122] can help policymakers 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 promote low-carbon innovations and sustainable behaviors to low- and moderate-income customers can be to harness pay-as-you-go schemes, leasing programs, 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 like solar leasing programs (already operating in the United States[123]) or the sharing and renting of solar panels in Zambia[124] and the United States (i.e., community solar[125]). Pay-as-you-go schemes can even be included to help promote better management and practices concerning waste, often via pay-as you-throw or unit pricing schemes.[126] 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 anticipate and preempt 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 labor 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.

4.2 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, behaviors 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 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, it can involve regional development plans to boost jobs and income for deprived regions. Or, it can involve deliberative attempts to retrain and compensate the losers 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.[127]

Regarding the extra-territorial impacts 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.[128] Although their effectiveness will vary by context and implementation, regulatory frameworks that set minimum social and environmental standards, supported by international trade, investment, labor and environmental organizations, have a clear role to play here. But private governance mechanisms, or "civil regulation"[129] 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[130], 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.[131] Researchers estimate 65% of the domestic cobalt demand in the United States by 2040 could be supplied by end-of-life lithium ion batteries, provided a robust take-back and recycling infrastructure is in place.[132] 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.[133]

4.3 Policy options for addressing interspecies inequity

With regard to interspecies inequity, it is firstly important to note that all of the cases we cover here can deliver some substantive environmental benefits (e.g., cookstoves displacing coal use or deforestation, EVs substituting for petroleum cars, solar panels helping decarbonize electricity grids, 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 upon 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 spill-overs and unintended consequences.[134] 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.[135]

4.4 Policy options for addressing temporal inequity

Politicians are often keen to pass more costly and political contentious policies onto their successors, while businesses and consumers routinely discount the future by prioritizing immediate profit and comfort, respectively, over longer-term consequences. This represents a wicked 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.[136] Independent climate change committees, such as that which exists in the UK, also have a role to play 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, and as evidence that only consumers with outdoor space can host charging points leads to the installation of charging points in street lamps, or charging points are added to petrol garages.

5. Harnessing research insights for an equitable low-carbon future

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

5.1 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 thus on and off policymakers' radars—depending on fluctuating labor markets, economic shocks, and changing personal economic circumstances. Confusingly, a particular household itself can be predisposed towards inequity in one area (e.g., children with families tend to waste more food, and thus 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 electric vehicle or household solar panel). Inequities are relative—not absolute. As another example, adoption patterns for food-sharing favor urban areas at the expense of rural ones, but adoption pattens for cookstoves favor 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 skepticism that institutions will respond to their concerns or are trustworthy. Vulnerable populations are frequently vulnerable to many shocks, and often lack the adaptive capacity to absorb such shocks. As Figure 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 preexisting baseline.[137] 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 still others, 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.

[Insert Figure 4 here]

Yet the various spatial, temporal, an intra-household dynamics shown in Figure 4 are exceedingly difficult to measure and monitor in models and other policy analysis tools.[138] Low-carbon transitions may be slow, but the changes within specific communities are fast, and so fast that many are unprepared,[139] 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.[140]

5.2 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 Figure 4 above.[141] Groundbreaking work include studies focusing on intersections of race, ethnicity, and gender[142]; feminism, class, and power[143]; and indigenousness and gender[144]. As noted above, these demographic inequities can be further complicated by temporal dimensions across peoples' life courses.[145]

Future inequalities and injustices that also warrant further attention include mental health, disability, and age. For example, some users of technology (disabled persons, or minorities) can be persistently invisible in policy discussions and their experiences of energy poverty are not well understood or recognized.[146] A lack of recognition puts these users at risk of 'falling through the cracks'.[147] A UK study found high levels of energy poverty among disabled people under 60, a group unlikely to be eligible to receive the Winter Fuel Allowance (WFA), and a group that may struggle to access other energy efficiency programs such as the Warm Home Discount (WHD) scheme. Likewise, experiences with energy poverty can have detrimental impacts on the mental health and wellbeing of vulnerable households.[148] [149]

As we have emphasized in this article, there are many different sources and types of inequities in the transition toward decarbonization, both related to the technological innovations and behavioral 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 and 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.[150] More refined and nuanced analysis needs to be informed by intersectional approaches that take a more complete view of complex identifies, social difference and just transitions, and not just employment or income.

5.3 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'.[151] 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 is a lot easier than changing behavioral lock-in around their adoption and use. At a deeper level it also means addressing the drivers of unsustainable consumption in value systems,[152] social inequalities[153] and the prevalence of advertising in advanced economies. Groundbreaking multi-scalar work in this regard includes studies examining justice and solar commodity chains[154], microgeneration technologies[155], and embodied energy injustices with coal[156].

5.4 Recognize more nuanced behavior

As the evidence presented in this paper clearly shows, agency as well as responsibility to enact low-carbon behaviors is unevenly distributed within and across societies according to income, gender, race, age and ability, among other things. While traditionally, policy focus has been on individual and household behaviors, we all enjoy different levels of behavioral 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.[157] Put another way, policy can be public or private; behavior and decision-making can be individual, collective or organizational; equity can be a function of income, country, or other social characteristics[158].

Distinguishing between different groups and their behavior may reveal that while many people have huge carbon footprints that need to shrink drastically, only a fraction of them have significant influence or direct agency over those behaviors. 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".[159]

Some behaviors matter more than others, and thus accounts of appropriate intervention points to enable behavior change need to be cognizant of this for it opens up other avenues of engagement and action than simply "nudging" individuals and households. To operationalize a more nuanced take on behavior—individual, organizational, private, 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 behavior. 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 behaviors.[160]

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 significant emissions reductions across areas as diverse as transport, energy efficiency and forestry; collectively such subnational emissions reductions could even be greater than those achieved by the Paris Accord.[161] We need to better understand the psychological and behavioral effects of energy policies that aim to change the context in which decisions are made, as to make sustainable energy behavior 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 the role of governments and other actors in creating and implementing different incentives for various actors enhanced.

5.5 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 impacts of particular technological pathways.[162] While these need to be adapted to the contexts and the purposes for which they used, they offer some promise of 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 proofing proposals and co-designing interventions with representative cross-sections of society.

5.6 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 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.[163] Initiatives are increasingly taking root from the US 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 normally associated with a person while in 2017, the New Zealand government passed legislation recognizing the Whanganui River as holding rights and responsibilities equivalent to a person. 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.

5.7 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 behaviors 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, shaped further still by local culture and power structures. Moreover, these structural elements are all mediated by the agency of actors and demographic attributes such as household income or community resilience. In simpler terms, issues of design become blended in 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 preexisting ones. For example, the French nuclear transition introduced entirely new risks to winemakers that had occupied land adjacent to nuclear power plants for hundreds to thousands of years, and the German solar transition introduced new bust and employment cycles to parts of Eastern Germany unique to that manufacturing boom.[164] Similarly, improved stoves—and other more energy efficiency 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.[165] However, the electric vehicle transition and its dependence on unfair labor practices for lithium and cobalt, and the electronic waste generated by smart meters, have only aggravated preexisting vulnerabilities related dispossession, ecological uneven exchange, and extractivism.[166] More scholastic inquiry examining these causal relationships would enable a more refined understanding of how agency, structure, and inequity interact.

6. Conclusion

Emerging innovations such as improved cookstoves, solar panels, electric vehicles, 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 impacting upon 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 behavior. We should not blanketly abandon such low-carbon actions. 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 decarbonation pathways and behaviors. They can potentially arise both from misusing innovations (e.g., driving an EV wrongly, using toxic materials for the production of solar PV) but also properly using them (e.g., embedding automobility, making one feel good via only an incremental and potentially non-impactful activity like 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 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 behavior, and it will also 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 take collectively in the next few decades.

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