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Towards improved solar energy justice: Exploring the complex inequities of household adoption of photovoltaic panels

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A R T I C L E I N F O

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A B S T R A C T

Solar energy, including household and community based solar photovoltaic panels, is the fastest growing source of low-carbon electricity worldwide, and it could become the single largest source of renewable energy by mid-century. But what negative equity and justice issues may be associated with its adoption? What risks are being accelerated as solar energy grows exponentially in its deployment? In this study, we rely on a mixed methods research design involving household solar interviews (N = 24), site visits (N = 4 solar neighbourhoods), and a literature review to investigate four types of inequities associated with household solar adoption. We utilize a novel framework looking at demographic inequities (between groups), spatial inequities (across geographic scales), interspecies inequities (between humans and non-humans), and temporal inequities (across present and future generations). This framework enables not only the identification of multiple and often interlinked inequities; it also points the way towards how to make solar energy adoption more sustainable and just, with direct implications for solar business practices (and supply chains) as well as energy and climate policy.

1. Introduction

Solar energy is often framed as one of the most optimal, affordable, and sustainable options available to homes or communities to decarbonize their electricity supply or improve diversification and distributed generation. Solar photovoltaic panels, for example, do not generate any direct greenhouse gases in operation and use (Nugent and Sovacool, 2014). They utilize ambient flows of energy in their surroundings at zero marginal "fuel" cost (Schmidt, 2014). They have completed all of the stages of commercialization – from early pilot developments to wide adoption and commercialization (Nemet, 2009, 2019). The conversion efficiency of panels has improved by roughly 0.5% *each year* for the past ten years, coupled with a sharp decline in production costs and retail prices, driven by repeated innovations in manufacturing and economies of scale (Atasu et al., 2021); as a result, the upfront costs per unit of electricity delivered are now at grid parity or lower than any other new source of supply in many markets (Karneyeva and Rolf, 2017). As the International Energy Agency (2021: 15) writes, "In most markets, solar PV … represents the cheapest available source of new electricity generation." Further cost reductions are expected to occur as solar is deployed and more affordable forms of finance become available (Egli et al., 2018). Future adoption rates will likely only increase due to further improvements in technology and performance, reductions in cost, the introduction of new policies, and changing household preferences (Beppler et al., 2021).

For perhaps these reasons, solar energy features heavily in projections of future energy use (International Energy Agency, 2019, 2021: 125). The International Renewable Energy Agency (2018) forecasted that the amount of installed solar PV capacity will likely rise from 223 GW (GW) in 2015 to 7122 GW by 2050—a growth rate of 3093.72%. Assessing these trends, Goodstein and Lovins (2019: 3) surmise that solar PV will unleash the "mother of all disruptive energy transitions" and predict that by 2030, solar panels – alongside emerging forms of energy storage - will provide "at least half of electric power globally, and possibly much more."

But is this bright future so assured for solar PV? Studies of emerging justice issues cast a shadow over some patterns of adoption, use and disposal of solar PV systems (Atasu et al., 2021; Mulvaney, 2013, 2014). Others have shown how solar PV adoption both reflects and reinforces existing socioeconomic disparities (Lacey-Barnacle, 2020; Balta-Ozkan et al., 2021) and how increased solar deployment can also can result in uneven or inequitable market dynamics, banking and financing

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patterns, and resource deployment (Knox et al., 2022; Sovacool et al. 2022).

The aim in this paper is to analyze the experience of solar inequities amongst early adopters and residents in a particular place (Brighton & Hove, UK), with a view to first, understand how that situated experience accords with solar injustices in the research literature, and second, discuss how these experiences might inform policies for a more socially just future rollout of solar PV. With this in mind, it is vital to ask: what negative equity and justice issues may be associated with the adoption of solar energy; and what inequities might be accelerated, which overcome, and how might new inequities emerge, as solar energy diffusion grows exponentially? In this study, we rely on a mixed methods research design involving household solar interviews, site visits, and a literature review to investigate four types of inequities associated with household solar adoption. We utilize a novel framework looking at demographic inequities (between groups), spatial inequities (across geographic scales), interspecies inequities (between humans and non-humans), and temporal inequities (across future generations). This framework enables not only the identification of multiple and often interlinked inequities; it also points the way clearly towards how to make solar energy adoption more sustainable and just, with direct implications for solar business practices (and supply chains) as well as energy and climate policy.

In doing so, our paper aims to make three contributions. First is its deployment of an inequity framework capable of looking more broadly at whole-systems energy justice issues—a novelty given most research continues to examine only direct issues of adoption and use, rather than indirect issues like mineral extraction and mining or waste flows. This also enables the study to examine distributional and other justice issues of procedure, recognition, and cosmopolitanism. Moreover, it enables the analysis to capture inequalities beyond race, gender, or class, and to include the intersection of others like generational equity and impacts on non-human species (e.g. going beyond Carley and Konisky, 2020; Barbose et al., 2021). Second, we aim to temper and challenge some of the recent literature arguing that solar energy *only* has positive effects, e.g. Heffron et al. (2021) who explicate only the justice benefits of solar law and policy around the world; Sovacool et al. (2020a) who document 30 technical, political, social, and environmental co-benefits to household solar adoption in Germany; or even Lovins (2002) classic work showcasing that distributed options like solar have 207 distinct benefits to adopters, utilities, businesses, and society. Whilst available in principle, such co-benefits might not be realised so readily or evenly in practice, with (household) adopters experiencing them differently, with implications for policy. Third, we examine solar inequities and injustices arising from adoption at the household scale, an underexplored area, rather than studies looking at the utility scale (Dolter and Boucher, 2018) or injustices such as land grabbing or dispossession associated with commercial solar parks (Yenneti and Day, 2016; Yenneti et al., 2016; Stock and Birkenholtz, 2019, 2020; Stock, 2021a).

The paper is structured as follows. In section two, we set the scene for our study with an overview of solar photovoltaics deployment in the UK and Brighton & Hove. We then set out our conceptual and methodological approach for analysing inequities (and remedies) in our fieldwork site in section three. Section four presents our results, which are then discussed in section five where conclusions and policy recommendations for the UK are made.

2. Overview of United Kingdom and Brighton & Hove context for solar PV growth

Once a niche technology (Smith et al., 2014), solar PV has expanded rapidly in the United Kingdom over the past decade. A variety of multi-level policy interventions have supported this growth; from the EU Renewables Directive 2009 which mandated renewable energy use amongst member states, to the domestic legislative requirements that emerged from both the Climate Change Act 2008 and Energy Act 2008 that supported and incentivised renewable electricity sources. In particular, the introduction of the UK's Feed-In Tariff (FIT) policy in 2010 guaranteed renewable power generators a higher price per unit (kwh) of electricity than fossil fuel electricity sources, which stimulated rapid growth in PV in particular. In 2008 the UK had just 22 MW of installed solar PV capacity. In contrast, according to recent statistics from the Department for Business, Energy and Industrial Strategy (BEIS), by August 2021 there was 13.5 GW of installed solar PV capacity in the UK. This growth is largely down to the introduction of FITs in combination with the global industrial and market dynamics outlined in section one.

Whilst FITs were integral to solar PV growth in the UK, the phase out of this measure from April 2019 has resulted in noticeable declines in domestic adoption (Castaneda et al., 2020). Nonetheless, 800,000–900,000 households have solar PV installed in the UK [McKenna et al., 2018] and local innovations in a diversity of business models means new solar deployment persists. This includes but is not limited to; private homeownership; utility farms; community projects; roof rentals; schools and civic buildings; council-led solar and social housing projects. With many of these models reliant on the previous FIT regime, new models are being forced to adapt to a less supportive post-subsidy market for solar. New evidence is also emerging around the possibilities brought about by digitalization, including prospects for greater local control and value capture in solar PV deployment (Sareen and Haarstad, 2021). However, recent research has pointed towards the risk for such digitalization processes to reinforce pre-existing social inequalities (Knox et al., 2022), in a similar fashion to the inequalities observed in the funding, organization and deployment of community energy schemes (Catney et al., 2014; Lacey-Barnacle, 2020).

Various sub-national, regional and local policy initiatives still offer support for the continued deployment of solar, as seen for example in the Welsh Government Energy Service in Wales (Welsh Government2021), the Community and Renewable Energy Scheme (CARES) in Scotland (Scottish Government2021) and the London Community Energy Fund and Solar Skills partnership (Greater London Authority2021a; 2021b). In addition, regulatory requirements mandate that certain energy suppliers pay small-scale generators for up to 5 MW of renewable electricity exported to the grid (Ofgem, 2021). A group-buying scheme for PV called "Solar Together" has seen over 160 councils across the UK working with local householders since 2015 to reduce the costs of solar PV and storage, including Brighton & Hove City Council.

The location of our study, Brighton & Hove, is a densely populated coastal city in Southern England in a designated UNESCO Biosphere reserve and adjacent to the South Downs National Park, with two universities and a mainly service economy. At the end of 2020, Brighton & Hove had a reported PV installation total capacity of 13.069 MW. That meant it was ranked 205th out of 391 local authorities reporting PV installations, with the largest capacity in Cornwall (595.6 MW) and the smallest in Carrickfergus (0.001 MW). Brighton & Hove City Council has ambitions to increase the local deployment of solar, in particular via two different schemes; a council-led "Housing Revenue Account Solar PV Distribution Programme," which targets social housing in four areas across Brighton (Whitehawk, Coldean, Bevendean and Hangleton & Knoll) and through the Solar Together scheme. Interestingly, the target demographic for each scheme differs considerably; the Solar Together scheme applies to homeowners only, whilst the Housing Revenue Account programme targets council tenants across areas high in council housing in Brighton & Hove. In it's first iteration, the Housing and Revenue Account Solar PV Distribution Programme was successful in installing 400 solar PV arrays on council housing in 2013. The council are now seeking £1.85 million of funding from central government to install between 500 and 1000 additional solar PV arrays between 2020 and 2023 in a second iteration of the programme (Brighton & Hove City Council, 2020).

3. Conceptual approach and research design

Inequities are a major source of injustices in energy transitions. So, we begin by first introducing our conceptual framework of whole systems energy justice before elaborating on our mixed-methods research design.

3.1. Multidimensional and intersectional energy justice

To capture a broad and multidimensional set of justice concerns and dimensions, we apply and extend a novel multidimensional, and intersectional, whole-systems energy justice framework. Energy justice refers most generally to a conceptual approach seeking to investigate the various *costs* of energy systems or transitions, the fairness (or unfairness) in ownership and *benefits*, the impartiality and representativeness of *procedures* as well as impacts on *recognition* and vulnerable groups (Sovacool et al., 2016). Energy justice thus combines elements of distributive justice and procedural justice and free prior informed consent, but also cosmopolitan concerns (of human rights or global externalities) and recognitional concerns (of vulnerable groups and dispossessed minorities) (McCauley et al., 2019).

Energy justice through a "whole systems" lens seeks to reveal the potential justice impacts that result not only from the use of an energy technology, but the often hidden "sacrifice zones" or "embodied injustices" within its lifecycle or supply chain (Healy et al., 2019). As Table 1 summarizes, a whole systems approach suggests that one examines a given energy technology or pathway across different scales and dimensions (Brock et al., 2021; Sovacool et al., 2019a; Sovacool 2021):

- Demographic injustices or inequities including unfair adoption patterns within social groups (often categorized by gender, income, age, or race);
- Spatial injustices including a separation from positive externalities (e.g., clean air, climate change mitigation) and negative externalities (pollution, carbon intensity);
- Interspecies equity including the destruction of ecosystems, habitats, and extinction of non-human species;
- Temporal injustices such as burdens shifted to future generations or issues of intergenerational equity.

Such an approach situates justice concerns across a multiplicity of scales, but also temporalities of an energy technology's lifecycle. It enables one to assess injustices across the entire system, including use and deployment (the focus of our empirical data), but also household experiences through the wider lens of inequities in other dimensions. Lastly, it recognizes past or recurring injustices alongside future ones, capturing experienced injustices but also anticipated or prospective ones.

The term utilized in Table 1 is equity or inequity, language 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 or negatively impacted). Our application of this framework is therefore used to reveal multiple interlinked and overlapping inequities in solar deployment, supported by the collection of novel primary data using a mixed-methods research design.

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

Demographic inequity (between groups):	*Spatial inequity (across geographic scales):*
• Adoption that may be strongly mandated by gender roles • Diffusion patterns substantially shaped by class, caste, income or wealth • Exclusion of non-homeowners or those without access to roofs • Adoption patterns favoring wealthier households and whiter communities, and disfavoring those struggling with illness or financial difficulty • Subsidies favoring wealthier households • Adoption patterns favoring higher income homes, larger homes, and homes with children • Dependence on education, training, or digital skills and awareness	• Erosion of some spiritual and cultural practices in rural communities • Increasing asymmetries in either urban or rural externalities • Lack of infrastructure in rural areas • Perpetuation of a "decarbonization divide" between Global North and Global South • Cross subsidization of energy costs that burden the poor • Unfair and at times exploitative labor practices • Bias towards urban areas and cities, especially wealthier cities and cities in the Global North
Interspecies inequity (between humans and non-humans):	*Temporal inequity (across future generations):*
• Building of infrastructure (roads, transmission networks, pipelines) or impingement of green spaces in urban areas • Increased air pollution, water consumption or use, or carbon emissions (direct or embodied) • Electronic waste streams releasing toxics into habitats • Solid waste streams or waste incineration • Environmental destruction and deforestation with mineral and material extraction • Fossil fuel use, occupational hazards and pollution from local manufacturing	• Failing to address the underlying causes of unsustainable practices • Cementing future domestic activities onto women or marginalized groups • The generation of toxic waste streams and disposal concerns for future generations • For-profit motivations germinating into future conflicts or tensions over values or pathways • Rebounds in increased driving, energy consumption, or resource use • Depletion of resources available for future generations

Source: Modified from Sovacool et al. (2022).

3.2. Mixed-methods research design

With our whole systems energy justice framework and conceptualization of inequity in place, we employed a mixed-methods research design involving (i) original household interviews, (ii) site visits of neighborhoods with solar adoption, and (iii) a review of the academic literature. Due to the nature of our funding, we were limited to examining solar PV adoption in Brighton & Hove, United Kingdom, where we targeted four different geographic neighborhoods to sample (see Fig. 1), each with significant household solar uptake: Hangleton and Knoll, Coldean, Bevendean, and Whitehawk. All of these areas were recipient neighborhoods of the local council's Housing Revenue Account solar PV distribution program.

Within these four neighborhoods, we approached approximately 150 homes for interviews, passing out leaflets (see Appendix I) to both solar adopters and non-adopters over the course of August and September 2021. Our leaflet mentioned the scope of our project (justice and equity in solar energy adoption) and offered a £30 voucher to participate in a household interview.

Thirty households responded to our leafletting and 24 interviews were completed. We asked our respondents a semi-structured set of questions (see Appendix II for our interview script) including their patterns of solar energy adoption, thoughts about inclusion and exclusion, and suggestions for improved support in adopting PV (e.g. policy). As is clear in Appendix II, questions were open and phrased in a way that invited households to share their experiences with PV in diverse ways.

Interviews lasted between 10 and 45 min and were fully transcribed and coded. To encourage candor and also protect privacy, all interviewees are presented anonymously. We refer to each household by a unique respondent number shown in Table 2, and sought a mix of respondents with different demographic types (old, young, male, female), housing types (homeowners, private renters, those in social/council

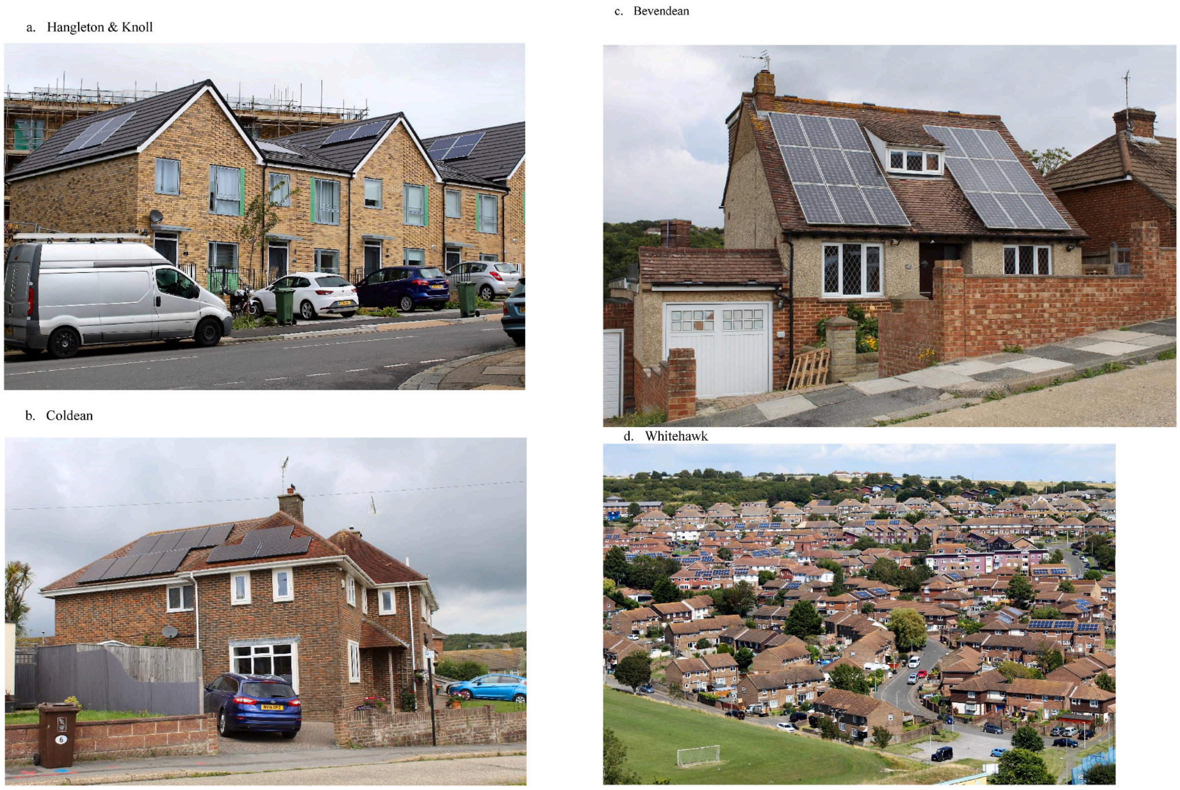

Fig. 1. Sampling strategy for community interviews and neighborhood site visits across four areas of Brighton and Hove, United Kingdom.
Source: Authors.

housing), and solar adopters and non-adopters. Fig. 2 offers an overview of some of the demographic details of our interview sample including gender, age, household size, and solar adoption. Interviews were transcribed and coded openly. The matrix of inequities was used afterwards to organize and analyze themes identified inductively in the interviews and their coding. Thus, the empirical material presented in our results (Section 4) holds insights for awareness of inequities amongst early adopters and residents in solar neighborhoods in Brighton & Hove, and of the kind likely to be shared with friends, family, colleagues, neighbors and researchers. These offer valuable insights for policy-makers concerned with making solar deployment more just and inclusive.

We supplemented our interviews with extensive site visits of each of the four neighborhoods, taking note of household solar installations as well as the quality of homes, automobiles, and other infrastructure. We also contrasted our interviews and ethnographic approach in the neighborhoods with a review of the academic literature on solar energy, equity, and energy justice, focusing on studies published within the past 10 years on Scopus, and referenced throughout our Results to contextualize or confirm our findings.

3.3. Limitations

Although we believe our sample of household interviews facilitates triangulation and has methodological merit, our research design does have some shortcomings. One drawback to anonymity is that there is no guarantee this study can be replicated, because readers cannot correlate the identity of respondents with interviewee statements. Additionally, our sampling of homes is not intended to be nationally representative, but instead offer a diverse and illustrative or purposive sample of those willing to engage with a research project on a topic focusing on equity and justice issues. Moreover, the paper is critical, exploring only injustices and not positive justices or co-benefits (which we plan to explore in future research). In simple terms: we explore the prospective injustices from deploying or adopting household solar panels, but not the injustices from *not* deploying them. Finally, we took an ethnographic approach that did not correct or problematize responses, so we present the data unfiltered (adhering to the justice principle of recognition), even if our respondents may have had misperceptions about their experiences.

While the two solar PV schemes mentioned in Section 2 are prominent in the Brighton & Hove City Council area, our data displayed a variety of different ownership and engagement models. Of the 24 interviews conducted, the majority of the homes had solar (n = 19), while the rest did not (n = 5). 10 household solar PV installations were "self-financed", 5 were owned and managed by the council and the remaining 4 were divided between: ownership by a private company (n = 1), solar PV already installed before the purchase of the house (n = 2) and therefore likely either owned by a private company or part of the home and finally, or delivered through the councils "Solar Together" scheme (n = 1). These different ownership and management models connect strongly to solar inequities, as we set out in the following section.

4. Results: Inventorying and classifying whole systems solar inequities

Our results align strongly with our whole systems energy justice framework, which we elaborate on in this section of the paper. As Table 3 indicates, we identified awareness amongst households of twelve analytically distinct inequities across our four different types of injustices. We explore each of them in turn. Section 5 will discuss interconnections between inequities and policy recommendations.

Table 2
Summary of household interviews completed for this study (N = 24).

Date	Respondent No.	Demographic details	Housing/ Tenure type	Solar adopter
13.07.2021	Whitehawk_01	Female	Council Housing	Y
21.07.2021	Whitehawk_02	Female, children at home	Council Housing	Y
21.07.2021	Coldean_03	Female	Homeowner	Y
22.07.2021	Coldean_04	Male	Homeowner	Y
22.07.2021	Coldean_05	Male, elderly/ retired	Homeowner	Y
23.07.2021	Hove_06	Female	Homeowner	Y
26.07.2021	Hove_07	Female	Homeowner	Y
27.07.2021	Hove_08	Male	Homeowner	Y
28.07.2021	Bevendean_09	Male	Homeowner	Y
29.07.2021	Bevendean_10	Female	Homeowner	Y
04.08.2021	Coldean_11	Male, young, single	Renting in private sector from landlord	N
04.08.2021	Coldean_12	Male, young, single	N/A	N
04.08.2021	Whitehawk_13	Male, elderly, widower	N/A	N
04.08.2021	Whitehawk_14	Female, elderly/retired, married but no children at home	Council Housing	Y
04.08.2021	Bevendean_15	Female, elderly/retired, married but no children at home	Council Housing	Y
04.08.2021	Whitehawk_16	Male, middle age, children at home	N/A	Y
06.08.2021	Hangleton&Knoll_17	Female, elderly/retired, married but no children at home	Homeowner	Y
06.08.2021	Whitehawk_18	Male, middle age, children at home	Council Housing	Y
06.08.2021	Bevendean_19	Female, young, single	N/A	N
9.08.2021	Coldean_20	Female, middle age, children at home	Homeowner	Y
10.08.2021	Hangleton&Knoll_21	Male, middle age, children at home	Homeowner	Y
10.08.2021	Hangleton&Knoll_22	Male, elderly/ retired, children left home	Homeowner	Y
10.08.2021	Hangleton&Knoll_23	Male, elderly/ retired, children left home	Homeowner	Y
26.8.2021	Hangleton&Knoll_24	Male, elderly/ retired, remarried widower	N/A	N

Source: Authors.

4.1. Demographic inequity (between groups)

Demographic injustices involved the themes of gender and gender roles, income and home ownership, and age, especially disparities among the young (students) or the elderly.

4.1.1. Patriarchal gender roles

The theme of gender relations and primarily male decision-making came up repeatedly within our sample, with multiple interviewees suggesting that decisions about energy, and solar adoption, were made by men with little to no input (or even awareness or understanding) on behalf of women. For example, Hove_06 stated that "my husband understands it [solar power] much better than I do (laughter)". Bevendean_15 commented that "my solar energy installation was installed by my late husband, about 10 years ago I think, I am not even sure it works anymore but I have kept it out of my respect and memory of him." Whitehawk_16 (a woman) stated that "This thing came with our house, I wasn't even sure if it was for electricity or hot water until we moved in. I don't really think about it, it seems not to perform that well and I can see it is discolored." Hangleton&Knoll_17 added that "I don't really manage energy bills within our house, my husband does that. I don't know of any digital technologies. All that energy stuff I find confusing, my husband manages all of that for me."

Notably, this theme of gendered decision-making and adoption was not mentioned in our literature review, signifying a finding not yet found in other studies.

4.1.2. Exclusion of low-income families

A second demographic inequity between groups relates to assets and wealth, represented in responses from homeowners vs. non-homeowners and in those with higher incomes versus those with lower incomes. Across our interview sample, for example, Fig. 3 shows self-reported financing patterns, it notes that most adopters were self-financed with cash and only 3 homes were able to receive solar through council programs aimed at dissemination among the poor. This proclivity for wealthier families and home owners to adopt solar was confirmed in multiple interviews. Hove_06 spoke about how "we are very lucky that my husband has had a very good job and has a very good pension, so I don't know what percentage of households there are in our particular situation, but nothing is equal, it would seem." Hove_07 thought that "the vast majority of people are excluded … It doesn't matter what level of income you're on … there's still a long way to go. I think there're still a lot of people who haven't got them who can afford them but don't install them." Bevendean_09 stipulated that:

> I find it to be quite an elite type of thing. We wouldn't have been able to afford any solar panels on a house. If they weren't there we probably wouldn't have been able to install them ourselves, just because of the cost of them. We were fortunate enough to have them when the property came.

Coldean_12 remarked "How much are they? I don't even know how much we pay for energy. But I am guessing we couldn't afford it … Groups like me can't afford it, I have enough trouble paying rent or getting food," and Whitehawk_13, who struggled to pay energy bills, noted that "Large families like me [have trouble adopting solar]—we do struggle to pay our bills including energy and are on a pre-paid metering account. Sometimes we don't have enough and our energy goes out." Hangleton&Knoll_22 also commented that "you need large amounts of cash to make solar work."

Interestingly, some respondents even calculated the specific assets needed to be able to afford solar, in many cases signifying substantial sums of money. Hangleton&Knoll_21 had to save up £5000 to buy solar, mostly from petrol savings from reduced travel during Covid. As they noted:

> Quite a few of the social houses are getting them put on, councils retrofitting for solar, but then I suppose if you're quite hard up, and maybe renting a property, don't fit into the social housing bracket, how you going to raise £5000 to put solar panels up, or convince your landlord it's a good idea?

Hangleton&Knoll_22 told us that they spent £8455 in cash to get

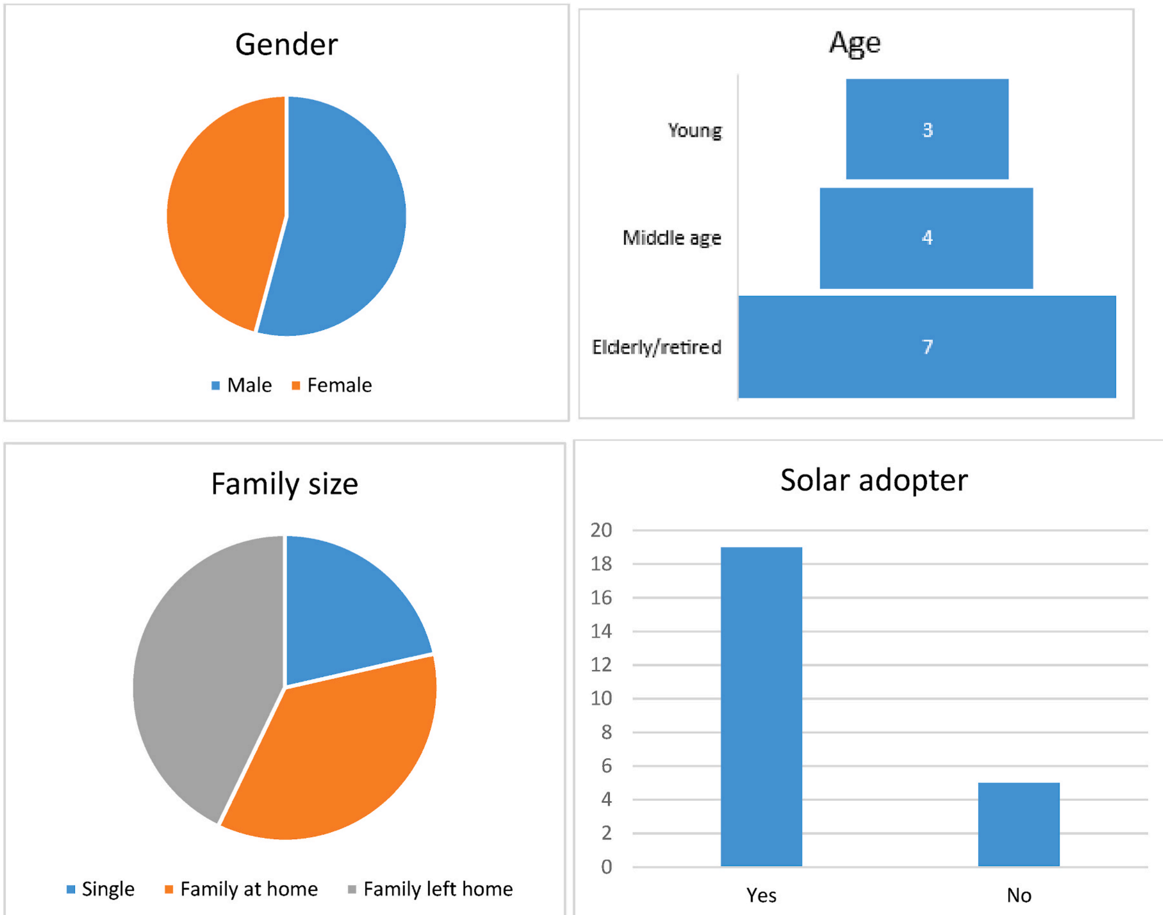

Fig. 2. Overview of demographic details of our interview respondents (N = 24).
Source: Authors. Note: Sums do not always equal 24 due to missing data or respondents wishing to keep such data confidential. Young = aged 18–30. Middle age = age 31 to 60. Elderly/retired equal 60+. Family at home refers to children or other relatives staying at home, not an individual and their partner.

Table 3
A matrix of inequities and vulnerabilities with solar energy adoption in Brighton & Hove, United Kingdom.

Demographic inequity (between groups):	*Spatial inequity (across geographic scales):*
• Adoption is linked to patriarchal gender roles • Adoption patterns are significantly shaped by income and home ownership • Adoption patterns exclude widowers and young adults (especially students)	• Creation of occupational hazards for manufacturing and exploitation of labor • Perpetuating of a decarbonization divide between those with and without skills and education • Disparities in infrastructure, policy or rural access
Interspecies inequity (between humans and non-humans):	*Temporal inequity (across future generations):*
• Embedded fossil fuels and environmental destruction in solar mineral extraction and mining • Pollution from solar energy manufacturing • Generation of toxic and electronic waste streams	• Breakdowns in systems and future financial burdens on adopters • Rebounds in future energy consumption • Accumulation of toxic waste streams and disposal concerns for future generations

Source: Authors.

their solar system installed in January 2015, remarking that “you need a tolerance for long payback periods” and expecting that the system wouldn’t break even until at least ten years later (in 2024). Hangleton&Knoll_23 also noted they had to save up £6000 in cash to have their system installed in 2012. Hangleton&Knoll_24 mentioned a need to reduce capital cost of panels and installation costs to make it more affordable, saying "It would have to be a greatly reduced installation and capital cost, not even sure what it is, but who has £5000 to £20,000 to invest in solar? Need to make it cheaper.”

Unlike the sub-theme of gender and patriarchy, disparities in solar access via home ownership or income were widely documented in our literature review. 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 (Dharshing, 2017). In the United Kingdom, this excludes the millions of people who do not own their own home, or who live in flats or social housing blocks without rights to using the roof or access to a garden or lawn (Sovacool et al., 2019b). In the United States, researchers have identified that solar adoption is almost exclusively secured by higher income households, creating disproportionate access to solar opportunities (Carley and Konisky, 2020). Utilizing a very comprehensive and nationally representative dataset, Barbose et al. (2021) note that in the United States, households adopting solar energy have a median income of $113,000

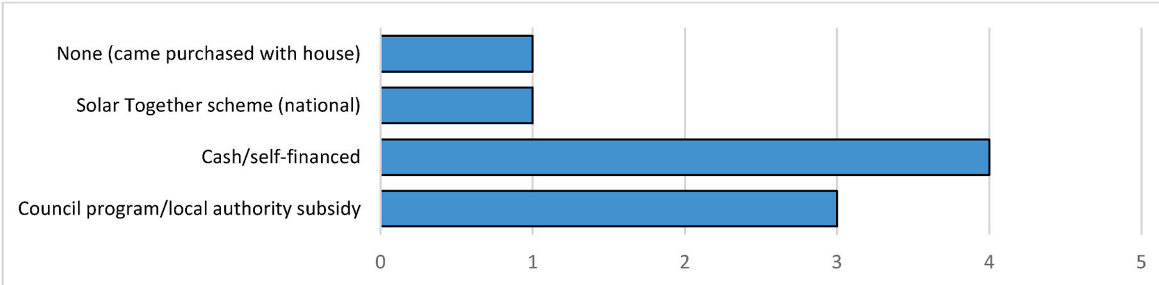

Fig. 3. Financing models for solar energy adoption in Brighton & Hove (by number of homes).
Source: Authors.

compared to the median income for all households of only $64,000, and a skew toward high incomes for those who own their systems and also pair them with storage units. They also noted that 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.

4.1.3. Exclusion of the elderly, renters, disabled or students

A final demographic theme emerging from our data was the exclusion of other groups not by gender or income, but by age, current stage of life or tenure type. One set of comments focused on age and disability. Hangleton&Knoll_22 remarked that "middle-aged people and young people are excluded, especially those who are moving." Hove_08 added that "a lot of people, they've got kids and mortgages, they can't afford it [at that time of their life], can they?" Hangleton&Knoll_23 discussed in particular how elderly couples are excluded or at least disincentivized given their age:

> I am 69, my wife is 65, we have spoken to friends, all around our age, most of them don't think it's worth it, as they won't be alive for the next 20–30 years, so the investment extends beyond their lifetime! That's a shame, as we have the savings but many families in their 40s and 50s don't have the extra funds.

Hangleton&Knoll_24 added that a class of other elderly households are excluded for living on fixed incomes, along with those with disabilities:

> Well, the disabled are excluded [from solar adoption], especially those with learning impediments, or those with eyesight problems, can't read the meters, or can't see bills or have eyesight necessary to check on a solar system … Also pensioners, who has that much cash lying around, on a low or fixed income?

Whitehawk_18 commented on widows and widowers also being excluded because they may not want to clear out their loft (attic) for storage:

> The elderly, disabled people, widows or widowers are sort of excluded in my view. Based on my circumstance, I work as a caretaker, I go door to door to help care for people. You realize everybody is different, the lady on the corner may not have anybody to help clear out her attic, she can't get solar because she is on her own … My neighbor is a low-income widow on basic, she couldn't get her attic cleaned out, and that was it, that was the big reason for her not adopting it.

Another set of comments mentioned students, especially those having to rent properties from landlords. Whitehawk_16 commented that "Students are excluded from solar adoption, I have two children in university and they have neither the money nor any capacity (a home, a house, a flat) to benefit from solar energy." Bevendean_10 remarked that:

> I feel like they are expensive to install so that would put a lot of people off. I guess as well, if people aren't going to be in the same house for a long time it is a big investment, and they might not get their money back within the first couple of years. I guess people that are going to settle down for years at a time, they are excluded. Yes, I guess people who are renting, especially students, their landlord is probably unlikely to put the money in to get solar panels, because it is not directly benefiting the landlord. It is benefitting the rental people. I guess renters and students, it is excluding them really.

This statement highlights how those who are not students but in the private rented sector are largely excluded as well. Bevendean_19 agreed and added that "Students are financially excluded … and even if I had the money, we are not allowed to have one in the house, my landlord forbids it"

Notably, themes of the elderly, disabled persons, and students being excluded from solar PV deployment were found by our review to receive insufficient attention in the literature, at least collectively, although some studies have identified individual groups at risk to exclusion. Bickerstaff et al. (2013) mention the exclusion of students, and Reames (2020) mentions the exclusion of renters. There is attention to the problem of "split incentives" in the private rented sector, whereby benefits from investment by landlords in energy infrastructure or upgrades accrue to the tenant rather than the property owner (Bird and Hernández, 2012). However, policy or market solutions to this problem remain underdeveloped.

4.2. Spatial inequity (across geographic scales)

A second class of inequities focused on space and included manufacturing hazards, a divide between those with skills and those without, and disparities in access to the grid or across rural areas.

4.2.1. Labor, occupational hazards and manufacturing issues

Although it did not come up frequently, two of our interviewees mentioned justice issues within the solar supply chain. Whitehawk_16 spoke about "the potential hazards of making solar panels" and Hangleton& Knoll_24 mentioned "accidents at factories" as a possible injustice. These claims are supported in the literature noting that solar manufacturing can at times rely on unfair and exploitative labor practices, resulting in boom and bust cycles for host communities and high levels of unanticipated unemployment, which occurred in Germany (Brock et al., 2021), or relying on low-wage transient workers. Solar workers face occupational hazards, especially those exposed to unsafe levels of cadmium, used in thin-film solar PV designs (Mulvaney, 2014). Murphy and Elimä (2021) even document the use of forced labor within the solar supply chain in the Uyghur Region of China where polysilicon manufacturers and quartz suppliers rely on forced labor transfers or are located within industrial parks where labor transfers are common. Stock

(2021b) also notes how the solar supply chain includes not only white-collar workers (managers) and blue-collar workers (installers and manufacturers) but also precarious, transient workers that must toil in hazardous working conditions and suffer environmental harms. One meta-analysis of hundreds of academic studies published on the sustainability of solar PV noted that many heavy metals embedded within solar systems are hazardous for workers or the environment, especially lead, lithium, tin, and cadmium, which can pose toxic risks during their manufacturing (Salim et al., 2019)

4.2.2. A skills or decarbonization divide

Another inequity concern arising from our data was a growing divide in skills needed to adopt solar (and coupled to innovations like digital apps or smart meters). Whitehawk_01 spoke about how "those with no internet access" or digital skills are "excluded from innovations." They went on to state that they never would have been able to afford solar without council support, saying that "'I'm not even on the internet, or anything like that […] because I can't afford it'." Whitehawk_02 agreed and spoke about how "lack of information or education" precludes adoption, and Bevendean_19 also noted how "educational skills and literacy are key to being a solar adopter." Coldean_03 spoke about how "awareness of digital innovations or solar" were strongly related to being familiar with green or eco innovations and having high degrees of knowledge or training. The literature sometimes refers to this as part of a "decarbonization divide" because it separates out epistemically adopters from non-adopters and neighborhoods that become low-carbon and resilient and other spaces that remain locked into higher-carbon dependency upon fossil fuels (Sovacool et al., 2020b). As an expensive piece of home technology, consumers need information and education in order to make an informed choice to purchase and use solar PV equipment. This is a potential equity problem to all consumers, but is most significant to those without access to the internet or installer company presence (Walker, 2008).

4.2.3. Disparities in infrastructure, policy or rural access

A final set of spatial injustices relate to disparities in access to the grid, access among rural areas, or uneven access to policy incentives. Hove_07 spoke about how solar "needs to be made easier" outside of urban areas like Brighton & Hove. Hove_06 spoke about infrastructure constraints given their location within the city, and they wished that "people could pay for our solar electricity rather than it just going into the grid, but that might mean an awful lot of pipework around the place, which wouldn't be such a good idea, given the location of our home." Coldean_20 articulated that they tried to subscribe to council programs but couldn't because public funds were already depleted, meaning they were placed on a waiting list (and were never deemed eligible). Hangleton&Knoll_24 also noted that solar was not "cost effective for him" given where he lived, noting that there, natural gas is so cheap, and grid access so expensive, "I don't like solar, we haven't adopted it, we have gas central heating, and a fairly new boiler, which is efficient."

Whitehawk_16 spoke about a different issue, one of saturation, noting that their location makes it difficult to trade electricity locally because there are already so many adopters. As they noted: "And, who would I trade with [if I adopted peer-to-peer trading]? Everyone around here already has solar, so I am not sure they would even need it or want to trade with me."

Extensive work on residential solar adoption has confirmed inequitable trends in diffusion, trends shaped by space, where solar adopters are more often in urban areas and also skew towards less rural states in the United States (Barbose et al., 2021). Modeling research 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. One study examining diffusion patterns in the United Kingdom warned that increased solar adoption risked transferring wealth between lower income and higher income consumers, given that feed in tariffs for solar PV are paid for by a levy on energy bills by all consumers (Strielkowski et al., 2017). Brockway et al. (2021) found that spatial inequities can even become built into grid access for solar in parts of the United States like California, where grid limits reduce connection possibilities for solar photovoltaics and also exacerbate existing inequities.

4.3. Interspecies inequity (between humans and non-humans)

This penultimate collection of inequities center on the environment, and include damages from fossil fuel extraction or mining, pollution from manufacturing, and embodied waste (especially streams of electronic waste).

4.3.1. Embedded fossil fuels in mineral extraction and mining

Although it came up only once in an interview (Coldean_20 who spoke about the "material footprint and mining" needed for solar as an injustice), this particular concern is supported by our literature review. The manufacturing supply chain for solar energy is cleaner than that for fossil fuels, but it still necessitates material extraction and mining, refining, and purification of the silicon and other required metals and minerals for the cells, glass, frame, inverters, and other required electronics, as well as the extraction and dependence on rare earth minerals (Nugent and Sovacool, 2014; Mulvaney, 2013)

4.3.2. Pollution from local manufacturing

A second environmental inequity related to pollution from factories, with Hangleton and Knoll_21 talking about "a huge waste of energy" involved in making the panels, manufacturing large amounts of solar energy and waste at "giga-factories." This concern, again, is mentioned in the literature, with household solar panels giving rise to some negative environmental externalities, including toxic materials utilized during manufacturing and assembly (Burger and Gochfeld, 2012; Sundqvist, 2004), along with petroleum extraction for plastics, natural gas extraction used for heating, and processing (Nugent and Sovacool, 2014; Mulvaney, 2013)

4.3.3. Waste streams releasing toxics

A final environmental inequity concern is embodied waste in the panels themselves, especially large volumes of electronic waste. Whitehawk_16 captured this aptly when they noted that:

> I am worried what will happen if it breaks down or is totally rubbish, who will come and collect it. Will I need to pay for that, you know? What will happen to it, other than becoming junk?

Coldean_20 spoke about how solar "still needs disposal of them when they reach their end of life."

This theme of waste is extensively described in the literature, with Cucchiella et al. (2015) suggesting that solar energy panels "represent the most significant waste stream" of electronic waste because they are by far the heaviest source by category of weight. While laptop computers may contain about 3.5 kg of waste and televisions up to 25 kg of waste, a typical household solar energy system generates a gargantuan 80 kg of waste (Cucchiella et al., 2015). A joint report between IRENA and IEA (IRENA and IEA-PVPS, 2016) estimated that at the upper range, global solar panel waste amounted to 250,000 metric tons in 2016. Despite the sheer magnitude and value of solar energy waste, however, such waste streams are only rarely recognized or currently accounted for, especially in the Global South (Mulvaney, 2013, 2014). One study traced discarded solar panels and their growing waste flows and showed how they negatively affected communities in Kenya (Cross and Murray, 2018). Another noted the rising contribution of solar panels to global stockpiles of electronic waste in Ghana (Sovacool et al. 2020a, 2020b). Atasu et al. (2021) write about how despite these concerns, the solar industry is "woefully unprepared for the deluge of waste" that will be generated by deployment patterns and that financial incentives for suppliers to account for recycling are weak, given that panels are mostly made of an extremely-low value material, glass. Price signals are skewed to only accelerate waste: in the United States, recycling a panel from First Solar costs about $20 to $30 per panel but sending that same panel to be buried in a landfill costs only $1 to $2 (Atasu et al., 2021). Collection and transport to recycling centers also poses hazards, given that solar panels are bulky, delicate pieces of equipment that need special labor requirements to uninstall, package, and deliver without being broken.

4.4. Temporal inequity (across future generations)

This final collection of inequities involves temporal injustices spread across time and future generations: the burden of breakdowns, rebounds in energy consumption, and accumulated disposal concerns.

4.4.1. Breakdowns and unexpected financial burdens of repair

One temporal inequity is the risk that systems will breakdown and thus require future capital or financial outlays to get them working again, or that interfere with the performance of the panel (meaning it fails to generate electricity or contribute to securing the feed-in tariff). Coldean_20 spoke about how:

> In fact things can go wrong with solar. I am a bit worried if things go wrong, with getting one, so I don't. It also doesn't help if you change suppliers. And I do that quite frequently, I get better deals that way.

Hangleton&Knoll_22 mentioned how they actually did have something go wrong, and had to pay almost £1000 when an inverter broke and another £4900 for batteries after the warranty expired:

> The warranty was only 5 years, so we had to pay out of pocket for the inverter, the company that installed the system initially was no longer operating, and the inverter was some Chinese firm that we couldn't even contact. We ended up having to pay £800 and the batteries were just under £4900, good for ten years. Now it won't pay for itself until 2030, if at all.

Multiple other respondents had similar difficulties with inverters (and additional, unexpected financial burdens), with Hove_08 saying that "I'm all for solar power … but it was a little bit disappointing that the inverter went"; Whitehawk_14 speaking about "my system stopped working a few months ago," and Hangleton&Knoll_22 noting that "there was a problem with the first inverter, had to fit another one a month later. It was working haphazardly, having many faults that interfered with our solar production." Hangleton&Knoll_23 reported inverter issues (again) and was worried about the warranty:

> The inverter did fail, about 2–3 years ago, a replacement was put in, within about 4–6 weeks, it was under warranty, 10 years, so thankfully I didn't have to pay. In a few months' time, early next year, out of warranty. Without it, cannot generate electricity that you need. It costs about £1500, so I am worried in case it fails.

They even indicated feeling "anxious" about solar given the inverter could fail "at any moment."

Other respondents discussed other unexpected damages and costs with solar adoption. Whitehawk_18 spoke instead about unexpected damage to their roof, which then caused leaking after they had their system installed:

> One area where it hurts is damage to my home. Because of solar, I had a leaky roof, speaking to the council, this seems a common problem with installation, a small minor leak, but a lot of aggravation, causing damage to the home, only problem had with it. A small drip, no big deal, but a common problem with installations. When I called and spoke to the roofing team, they said it was always so much trouble with these leaks with solar, and always the same spot, too.

Whitehawk_18 noted that parts of their solar system were stolen, which also interfered with its performance until replacement parts could arrive (paid by the council). Hangleton&Knoll_21 reported many problems with their solar system, noting:

Fig. 4. Discoloured and corroded solar panel systems in need of cleaning or repair in Whitehawk.
Source: Authors.

> We have had a few problems, the first one, the cable to the sensor clamp on the grid load in cable, cable running back, had to do a joint in the cable, and joined it in a way not per manufacturers recommendations, get interference from the DC cable from the panels, going down into the house and the inverter, all going past this clamp and sensor cable, not shielded. Interfere with the cables, AC cable, interfering with the signal, inverter using grid electricity when it shouldn't be, you don't want that happening, a huge waste of energy. I don't think the installers were too clued in on the final details.

We did notice many systems in states of poor maintenance or repair during our site visits, including those in Fig. 4.

4.4.2. Rebounds in energy consumption

A second temporal inequity involved "rebounds" or sudden increases in energy consumption, or a change in practices, after households had adopted solar energy. Whitehawk_18 was proud his solar system powers 4 TVs (!) so he can play lots of video games with his wife and family, and it also supports his tumble clothes dryer:

> I like that rather than use the washing line in the summer, my solar gives me free power and I can use the use tumble dryer. I don't really understand what I am using, what I am not using, I have 4 TVs, I play a lot of video games, my wife and I are high consumers, the family uses quite a lot of electrical, on a key meter, top it up as I go. You know. So the solar helps with that.

Coldean_20 spoke about a similar rebound with a washing machine and tumble dryer, buying those appliances and using them (rather than air drying clothes) once they had their solar system installed. Hangleton&Knoll_22 were proud their household solar went into powering a hot tub: "we actually run a hot tub with our solar energy, quite energy consuming, sometimes we are able to put 1 kW or 2 kW of solar energy into that hot tub."

Although our literature review did not find any evidence of solar rebounds in the United Kingdom, Beppler et al. (2021) have confirmed this trend in the United States. There they found that household solar adoption resulted in an increase or rebound in total electricity consumption, relative to a control group, of 28.5%, suggesting that "nearly a third of the electricity produced by a customer's solar panels is used for increased energy services, rather than reduced grid electricity consumption." They hypothesized that such a rebound was likely caused by an overall increase in electric space heating, an increase in central air conditioning, and/or further electrification of end use loads.

In Germany, Galvin et al. (2022) noted not only that some solar households (or "prosumers") increased their own electricity consumption as a result of adopting photovoltaics; but that other rebounds occurred as well. They identified "income" or "economic effects" where the high feed-in tariffs triggered by solar adoption enable households to then save up financial resources that they invested in "substantial" out-building projects, like buying a car or an extension to the home. They also identified "moral licensing" rebound effects where households felt that their large investment in solar energy (and consequent emissions reductions) justified and validated their "right" to consume more energy for other things (e.g., heating) or take more holidays abroad. Worryingly, Galvin et al. (2022) concluded that Germany's current regulatory and pricing regime actually *rewarded* consumers who overconsumed solar electricity and inadvertently promoted such rebound effects, compromising energy and climate policy goals.

4.4.3. Toxic waste streams and disposal concerns for future generations

Our final temporal inequity is connected to the waste flows in 3.3.3, but from the vantage point of future generations or decisions in the future. Our respondents discussed how solar energy can produce hazardous waste streams that present a likely burden for future generations. Coldean_20 mentioned issues of waste and recycling, worrying that it will "cost a fortune" to get rid of their solar system at the end of its useful life:

> What do we do when its life is over? I have no idea what would happen, WEEE[1] requirements and all, it will cost a fortune to get them off the roof.

The literature also confirms the mounting burden of waste from an intergenerational or future generations perspective. IRENA and IEA-PVPS (2016) calculate that by 2050, solar panels could become equivalent to 10% of *global* e-waste streams. They also projected that by 2050, cumulative volumes of end-of-life solar waste could reach 20 million tons in China, 10 million tons in the United States, and 7.5 million tons in Japan, or a worldwide total of 60–78 million tons of waste across all countries. This would make solar PV waste flows greater than *all* e-waste flows in 2018 (Kumar et al., 2017). Greenmatch (2017) put these numbers into perspective by noting that 60 million tons of solar waste in 2050 would represent a potential material influx—the amount of wasted solar materials and components—sufficient to produce 2 billion new panels, or 630 GW of installed capacity worth $11 to 15 billion in recoverable value.

Atasu et al. (2021) add that an additional problem contributing to future stockpiles of waste is that advances in technology keep happening so that households sometimes switch or replace their solar systems *before* the end of their useful lifetime, in order to capitalize on better performing systems. They refer to this as the "early retirement" problem with solar involving the mass disposal of "no failure" panels. Shockingly, in Fig. 5 they plotted expected early retirements for solar in the United States and estimated that such "no failure" retirements will become *greater* than normal retirements by 2050, creating a "solar trash wave." If these early replacements occur as predicted, they would generate 50 times more waste in just four years than policymakers expect, i.e. about 315,000 metric tons of unexpected, future waste. By 2035, they estimate that discarded panels would outweigh new units sold by 2.56 times. Moreover, if one accounts for these future waste streams, the levelized cost of energy for solar increases by a multitude of four—solar is four times more expensive than expected if you include expected costs (and volumes) of waste. This becomes a pressing temporal inequity given that it will almost certainly fall to future regulators, or consumers, to cover the costs of waste disposal and cleanup.

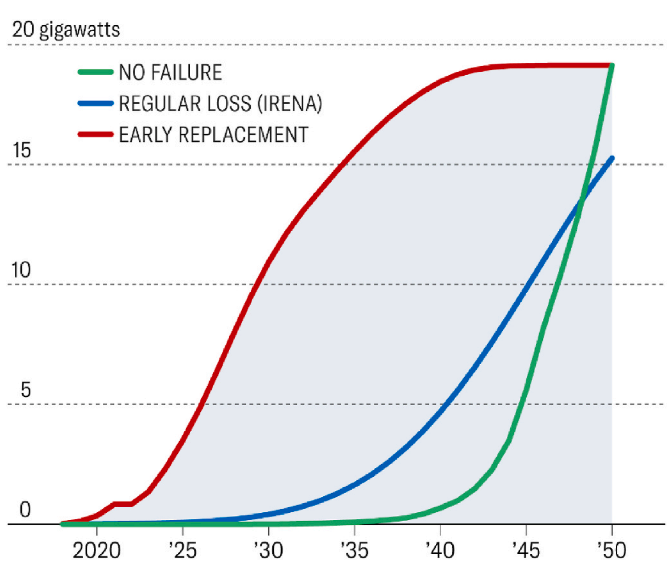

Fig. 5. Cumulative waste projections for solar energy in the United States, 2020 to 2050.
Note: Source: Atasu et al., 2021. The red line projects early replacements, the blue line normal replacements and the green line no failure replacements.

5. Conclusion and policy implications

Based on original data collected throughout four neighborhoods of Brighton, and supplemented with an academic literature review, we find that solar energy adoption can exacerbate demographic inequity and disparities in ownership, spatial inequity and disparities in skills or infrastructure, interspecies inequity in terms of pollution and waste, and temporal inequities including future burdens of maintenance and repair and rebounds in energy consumption. Although some of these inequities, such as the exclusion of low-income families, manufacturing hazards, disparities in access, and reliance on pollutive supply chains have been previously documented in the literature, others are novel to this study, notably patriarchal gender roles; the exclusion of the elderly, student renters, or the disabled; the temporal risk of breakdowns and unexpected failures; and qualitative explanations for solar rebounds.

Demographic inequities are particularly important here. Our data showed that the differences between council tenant and homeowner experiences are significant; while some council tenants will more likely be struggling to get by compared to wealthier homeowners, and perhaps sceptical or unaware of the benefits the solar provides and unable to experiment with other low-carbon technologies, they are also seemingly distant from digital technology adoption and experimentation. In stark contrast, our data shows that homeowners with solar are aware of the multiple benefits they are accruing from their solar installation, whilst some are using their solar to influence behaviour change to reduce costs from buying electricity from the grid or to charge their electric cars. Care has to be taken here, however, since our council housing residents were more likely to be recipients of solar granting programmes, and whilst appreciating the pro-environmental and economic benefits in some cases, they may not have had to explicitly weigh up pros and cons to the same degree as purchasers of private systems. Our evidence of severe divides according to both income and housing type may indicate differences of experience and perception but could also be linked to details in the design of PV distribution programmes (i.e. how public grants are implemented with households versus the profile of households making PV purchases in the market). Broad inequalities in experience between council tenants and homeowners' of the low-carbon transition need deeper contextualising than we have been able to give here.

[1] WEEE: Waste Electrical and Electronic Equipment.

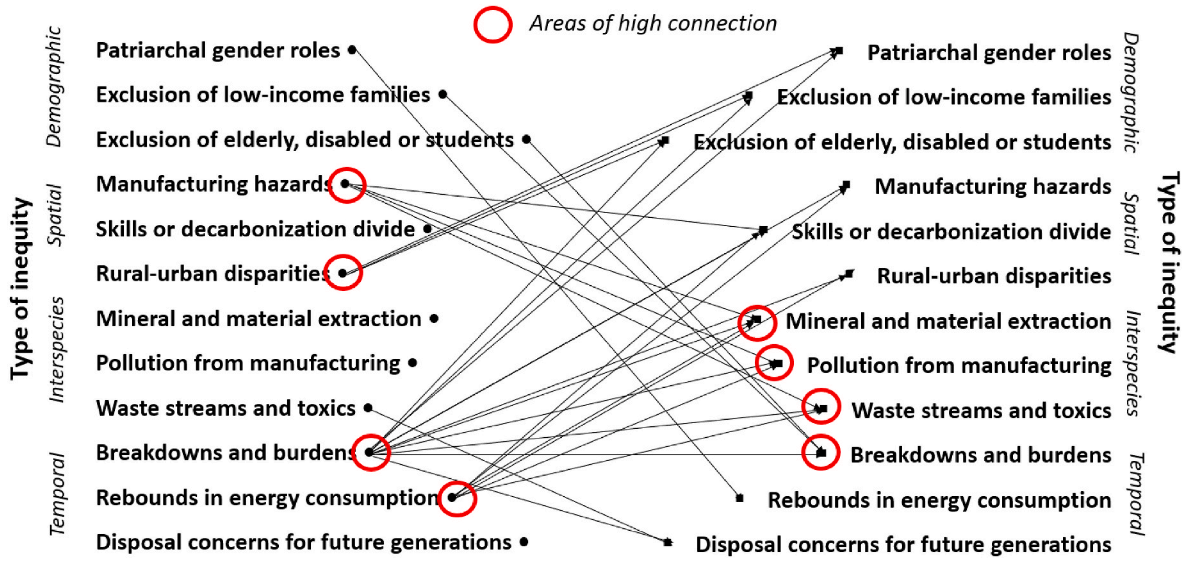

Fig. 6. Interconnected inequities and areas of high concentration among solar energy inequities.
Source: Authors. Evidence for the establishment of an inequity is provided by a mix of original empirical work as well as our literature review, with data collection and analytical methods summarized in Section 2.

Less evidence arose within our original data about spatial and interspecies inequity, although they did still exist. The least supported component of our framework was temporal inequity, although our study still provides some evidence of concerns surrounding future breakdowns or waste stream burdens on future generations.

Although we treat each of these classes of inequity as distinct, they are in fact deeply interconnected. Different types of inequity or inequality can compound each other. As Fig. 6 depicts, based both on our empirical data and literature review, patriarchal gender roles (3.1.1) such as privileging passive decision-making or convenience rather than sustainability can link to potential rebounds (3.4.2) in energy use after adoption. Inequities identified in Section 3.3.3 (waste streams releasing toxics) link to toxic disposal concerns for future generations (3.4.3). The exclusion of students or the poor (3.1.2) or elderly (3.1.3) can lead to greater financial burdens for those within this group that do adopt (3.4.3). Disparities in grid access (3.2.3) can further entrench inequalities among groups (3.1); and some of the labor and occupational hazards hurting workers (3.2.1) can also deepen a decarbonization divide (3.2.2) or harm the environment (3.3.1, 3.3.2, 3.3.3). Breakdowns (3.4.1) threaten to increase or magnify most other aspects of injustice (furthering the gender, class and age based demographic disparities in Section 3.1, the degree of spatial inequality in 3.2, and the intensity of environmental damages in 3.3). Finally, rebounds (3.4.2) threaten to worsen most spatial inequalities (Section 3.2) and the intensity of other environmental damages in Section 3.3. As Fig. 6 also reveals, at least one injustice in every dimension is linked to another, and injustices also concentrate in a few areas of exceptionally high connection. These areas of high connection could be the most fruitful leverage points for policymakers to tackle.

Table 4
Addressing inequities and vulnerabilities with solar energy adoption with a matrix of policy recommendations.

Demographic inequity (between groups): • Smaller scale options that require less capital • Energy service contract methods that do not require capital purchases • Shared-ownership business models (including cooperatives) • Council-led schemes that offer solar deployment and maintenance to homes unable to pay	*Spatial inequity (across geographic scales):* • Improved governance and accountability in supply chains, especially labor standards • Enhanced skills training and education • Policy incentives that lower the cost of rural adoption • Targeted interventions that prioritize areas high in deprivation
Interspecies inequity (between humans and non-humans): • Green or low-carbon mining • Best practices in solar manufacturing techniques • Stronger recycling and electronic waste requirements	*Temporal inequity (across future generations):* • The use of micro-inverters and better warranties to minimize system breakdown • Progressive energy tariffs or in-home displays that disincentivize rebounds • Extended producer responsibility and takeback schemes for broken or retired solar systems

Source: Authors, based on a mix of the empirical data and findings as well as the expert knowledge of the author team.

With this connection to policy in mind, each of these inequities perceived by households and our respondents points the way clearly towards specific policy mechanisms (summarized in Table 4) that can tackle, mitigate, or minimize many of the injustices identified. Whilst some of these inequities relate to structural injustices in society more generally (awareness of which is indicated in some of our respondent data), our analysis nevertheless points to measures that can be taken within policy and strategy for PV to improve the justness of future deployments. Demographic inequities can be partially remedied by cheaper, smaller systems or shared ownership business models. Spatial inequities can be offset by targeted skills training or policy incentives that seek to even out geographic adoption patterns. Interspecies equity can be addressed by more sustainable forms of mineral extraction or stronger recycling and waste requirements. Temporal inequities can be addressed through innovations in technology (especially inverters & via recycling PV materials) and extended producer responsibility.

Building upon some of our featured policy recommendations above, it is important to ask how might these policy recommendations work in practice in the UK. Here, we offer three specific recommendations. First, we call for improved governance and accountability in supply chains and labor standards. Shifts in domestic solar energy industry practices could entail a broad industry-wide recognition of a new supply chain transparency and traceability protocol, as advocated for by Solar Energy UK (2021). However, given this may not go far enough, industry and market actors could move beyond voluntary actions to more rigorous standards. Government could for example make specific amendments to the "Transparency in Supply Chains" provision in the Modern Slavery Act 2015 to target all low-carbon technologies (HM Government, 2015), to ensure the transition to a low-carbon economy in the UK is not directly connected to poor, illegal, or inhumane labor practices within solar supply chains.

Second, we call for policy incentives that lower the cost of rural adoption along with targeted interventions that prioritize areas high in deprivation. There is a growing recognition that financial innovations are key to increasing both social inclusion and widespread adoption in solar PV deployment. As seen in recent UK policy proposals for new interest-free loan systems to support the wider uptake of EV's across the UK (Trinkon, 2021), we feel such a system could be advanced in the UK, with a more holistic approach that features interest-free loans for solar PV, electric vehicles and batteries at the domestic scale. Where possible, this should also be supported by tax incentives and grants (Curtin et al., 2017). Financial innovations that target only one technology without considering the interlinked impacts on other energy services (e.g. interest-free loans for electric vehicles could raise low-income homes' electricity costs without other interventions) may result in new injustices. Cautious thinking needs to take place and innovative policy packages that cater to critical interlinkages between low-carbon technologies need to be supported by the UK government. For instance, a two-tier system could emerge that offers grants and interest-free loans for low-income homes (to reduce the payback period and potential financial risk) and interest-free loans and/or tax incentives for middle income homes in particularly underserved, remote and rural locations. Recent research shows these two groups, particularly when overlapping, to be some of the most vulnerable in low-carbon transitions (Simcock et al., 2021).

Thirdly, we call for shared-ownership business models, including cooperatives or council-led schemes that offer solar deployment and maintenance to homes unable to pay. As our findings made clear, students, renters and non-homeowners are largely excluded from solar PV deployment due to housing tenure and ownership type. We support further funding from central government to local government to support the increased distribution of solar PV to council tenants. For those that live in flats and shared accommodation, local government support for innovative shared ownership and co-operative models, as seen via Repowering in London (Fuller, 2017), could increase the potential for wider social inclusion. Repowering, with the support of local councils, have deployed multiple solar PV arrays across social housing estates in London. They offer solar panel making workshops and internships to local residents and recycle surplus revenues back into a Community Energy Efficiency Fund that organizes residential retrofits on the housing estates where the solar PV is installed.

As significant as the inequities associated with solar energy adoption are, and as pressing as the policy reforms mentioned in Table 4 and above may be deserving of implementation, they do not alter the future necessity and desirability of transitioning to low-carbon forms of electricity such as household and community solar energy. Nevertheless, failing to account for current patterns of demographic, spatial, interspecies, and temporal inequity minimizes and, in some cases, even reverses the benefits of adoption. Solar advocates, manufacturers, and policymakers can least afford to ignore the mounting justice issues associated with current patterns of adoption. These current patterns may make solar adoption not only detrimental to the environment and calamitous to workers, but self-defeating for the very homes and communities investing significant resources to adopt it. Solar business practices (and supply chains) as well as energy and climate policy must be transformed accordingly.

CRediT authorship contribution statement

Benjamin K. Sovacool: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing. **Max Lacey Barnacle:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing. **Adrian Smith:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing. **Marie Claire Brisbois:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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