We're on the Road to Net Zero?

Socioeconomic Inequality in Low-Carbon Technology Adoption

UKERC Working Paper

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1. Introduction

Consumer adoption of low carbon technologies (LCTs) is central to the UK's legally binding commitment to achieving net zero by 2050. It is difficult to overstate the role of consumers, as their potential adoption of LCTs, such as electric vehicles and solar panels, would represent nearly half (47%) of the UK's 2035 abatement target for the power sector (CCC, 2022). It is clear therefore that decarbonisation in the automotive and housing sectors is paramount if the low-carbon transition is to succeed. Indeed, according to the Climate Change Committee (CCC, 2022), surface transport and buildings contributed 43% of the UK's emissions. Despite these sectors being the UK's two largest sources of emissions, there are positive signs that *some* consumers have increasingly embraced more sustainable ways to live and travel[1].

The ability to make environmentally sustainable choices however is subject to financial and technological constraints which are encountered to different extents across society. The evidence from the United States (and California in particular where the adoption of LCT has been relatively rapid, thanks to the generous subsidies of the State's Government) reveals that ownership of LCTs is prevalent among high-income households (Borenstein and Davis, 2016; Barbose et al., 2022) potentially due to higher barriers to adoption for low-income households; this may result in questioning the equity of such policies (Borenstein, Fowlie and Sallee, 2021). The present paper helps bridge a gap in the literature by exploring socioeconomic inequality in LCT adoption and its underlying sources.

Over the last decade, the UK has witnessed a 60% reduction in the cost of installing domestic solar panels since 2010 (BEIS, 2021). Even though the UK's flagship subsidy scheme ended in 2019, the cumulative number of installations broke 1 million and has achieved a similar capacity to some nuclear power stations (MCS, 2022). The continued strength of (unsubsidised) demand for residential solar is perhaps unsurprising as consumers could realise significant levels of savings in the face of the rapid rise in wholesale energy prices during 2021 and 2022 (HM Government, 2023b).

All the while, the electric vehicle (EV) market gained traction. In 2021, fully electric vehicles (EV) and plug-in hybrids (PHEV) respectively made up 12% and 7% of all new vehicles sold in the UK (CCC, 2022). As of today, the UK has around 250,000 EVs on its roads and expects to reach 10 million by 2030 (Ofgem, 2023), coinciding with the UK's ban on all new petrol and diesel vehicles from 2030. Yet, alongside increasing annual costs of EV charging, potential adopters will also focus on the upfront cost of EVs, which are only expected to reach parity with similar sized petrol or diesel engines later this decade (HM Government, 2023c).

[1] It is important to note that the UK Government's Heat and Buildings Strategy (HM Government, 2021) endorses a target of 600,000 yearly heat pump installations up to 2028, but this target is perceived as unlikely to be achieved, e.g., see House of Lords Environment and Climate Change Committee (HM Government, 2023a).

A few studies explore inequality as a potential barrier to widespread diffusion of LCTs. Barbose et al. (2022) provided insights on how inequality may influence solar adoption by mapping the heterogeneous socioeconomic and demographic trends, across region and time, in the United States (US). They find that residential solar adoption appears favoured by white, highly educated, and high-income households working in professional or business/financial sectors; however, the authors argue that these disparities have been slowly reducing in recent years. Likewise solar panel installations appeared unequally distributed in the population by age, gender, education and, ethnicity (see Sunter et al., 2019; Sovacool et al., 2022) with a similar set of socioeconomic factors impacting EV adoption (see Axsen and Sovacool, 2019; Sovacool et al., 2022). Steadman et al. (2023) investigate local factors in solar PV adoption in the UK. They identify a significant role of community PV installation and the presence of newly built dwellings on the pattern of adoption. They also find evidence of clusters of high adoption in specific regions of the country, potentially related to local economic conditions. More broadly, recent research established (positive) causal effects of education on pro-climate outcomes which include attitudes towards renewable energy and energy efficiency, although the authors do not focus on adoption of specific LCTs explicitly (Angrist et al., 2023). By focusing on early-life education, Angrist et al. (2023) capture the total role of education on climate change outcomes (including energy efficiency behaviours and renewable energy attitudes), as well as the role of later life socio-economic position and other mediators, that come with an exogenous increase in schooling.

Some scholars suggest that the role of education, gender and ethnicity may be only weakly associated with solar panel uptake (Best et al., 2023). Much more limited is the work on the association between childhood socioeconomic status (SES) and LCTs, which focuses on developing countries and cleaner domestic fuel use (Mussida and Sciulli, 2022). Despite the lack of evidence on the direct association between parental SES and LCT adoption, parents have been found to influence the energy literacy (Pearce et al., 2020), environmental attitudes and energy saving behaviour of their children (Karatepe et al., 2012; Fell and Chiu, 2014).

Overall, inequalities in LCT adoption are understudied with most of the existing relevant literature focusing on specific disparities involving certain socioeconomic characteristics and often limited to non-nationally representative samples on *reported* LCT-related behaviours rather than *actual* purchases or installations (e.g., Alipour et al., 2021; Best et al. 2023). In this study, we aim to contribute to the literature by providing evidence on the presence of socioeconomic inequality in LCT adoption and its evolution over time using recent nationally representative UK panel data. Exploring the presence of socioeconomic inequalities in LCTs in the UK – a country responsible for the fifth largest per capita contributions to climate change (CCC, 2019) – has important policy implications for the low-carbon transition and the achievements of its ambitious legally binding environmental targets.

There is not only a dearth of evidence on inequality in LCT adoption, but also on which members of society have been at a disadvantage to adopt, as argued by scholars of the “just transition” to a low-carbon future (Carley and Konisky, 2020). Our analysis provides novel evidence on how early-life circumstances could directly and indirectly affect the adoption of LCTs, and thereby identify “sections of society” that have been hitherto overlooked in the processes aimed at promoting the energy transition (Jenkins et al., 2021).

Our paper contributes to the literature in a number of ways. First, we exploit the availability of nationally representative longitudinal data for the UK to explore the evolution in the adoption of three key LCTs (solar photovoltaics, solar heating, and electric vehicles) in light of their cost reductions and increasing consumer awareness of their merits (CCC, 2022). Second, we explore the aggregate role of observed socioeconomic characteristics in determining socioeconomic inequalities in LCT adoption, as opposed to specific socio-demographic groups. Building on the inequality of opportunity (IOp) literature (e.g., Roemer, 1998, 2002; Bourguignon et al., 2007; Ferreira and Gignoux, 2011), we employ factors that are economically exogenous to a large extent and largely beyond an individual’s control, which include family background (labelled as socioeconomic circumstances in the IOp framework). Focusing on predetermined circumstance variables, such as parental socioeconomic background, may alleviate endogeneity concerns in our analysis. For example, exploring later life socioeconomic factors, such as housing tenure or income, are more likely to result in endogeneity issues. If one assumes that tenure decisions themselves may be determined by one’s willingness and effort to improve housing conditions, which can include the installation of LCTs for heating and electricity; simultaneously, LCTs for heating and electricity may be themselves determined by house tenure given the limited agency of the renters to install housing improving technologies. Moreover, by employing predetermined socioeconomic characteristics we are able to explore their total role on determining current LCT inequalities, which includes their direct role in LCT adoption as well as their indirect role via later life efforts related to LCT adoption; both direct and indirect contributions shape the observed socioeconomic inequalities in the context of our inequality analysis. Overall, we found systematic socioeconomic inequality in LCTs that remained evident but reduced in magnitude over the last decade.

We further contribute to the literature by employing Shapley-decomposition techniques to explore the relative contribution of each socioeconomic variable to the total estimated socioeconomic inequality. Finally, we tested our inequality results when restricting our sample to certain longitudinal sequences of LCT adoption. This has allowed us to explore what drove the observed reduction in socioeconomic inequalities in LCT adoption over the last decade. Overall, our results show that socioeconomic inequalities in LCT are systematically higher for those who *persistently* adopt or do not adopt LCTs. These results reveal that those following transitory LCT adoption patterns, and especially those who have recently adopted LCTs, are contributing to the recent reduction in the observed socioeconomic inequalities.

The rest of the paper is organized as follows. Section 2 describes the methods used in our analysis as well as our data. The results of our analysis are presented and discussed in Section 3 and Section 4 concludes.

2. Methodology and data

We model the decision to adopt LCTs as a function of socioeconomic circumstances, in line with the IOp framework (Roemer, 1998, 2002; Bourguignon et al., 2007; Ferreira and Gignoux, 2011), so that each of our LCT adoption outcomes can be expressed as:

$$y_i = f(C_i, E(C_i, v_i), u_i) \tag{1}$$

where y_i denotes an outcome representing the adoption of a specific LCT by individual (i), C are observed circumstances for each individual (i) that are assumed to affect LCT adoption; E is a vector of effort variables that affects one's decision to adopt LCTs and for which individuals are (at least partially) responsible[2]. Socioeconomic circumstances are considered beyond an individual's control within the IOp framework, i.e. they are not affected by effort, while efforts may be influenced by circumstances (as specified in equation 1). The unobserved error term v_i captures random variations in effort that are independent of C, while u_i represents random variation on the LCT adoption, including measurement error, that is independent of both C and E[3]; these unobserved error terms are often labelled as 'luck' in the IOp literature (e.g., Lefranc and Trannoy, 2017).

In line with the IOp literature, we employ an *ex ante* approach to measure overall socioeconomic inequality in LCT adoption which can be attributed to our set of circumstances variables, as a share of total inequality. The main principle under the *ex ante* approach to IOp is the presence of equality of opportunity if all individuals face the same opportunity set, prior to their effort and outcomes being realised; in other words, there are no differences in outcomes of interest (i.e., LCT adoption) from being in different (socioeconomic) circumstances. The *ex-ante* approach can be implemented empirically using information on the observed circumstances variables and does not require effort measurement (e.g., Aaberge et al., 2011; Fleurbaey and Peragine, 2013; Davillas and Jones, 2021).

Specifically, according to the *ex ante* IOp approach, the expected conditional outcome for each of our LCT adoption variables can be expressed as:

$$\hat{y}_i = E(y_i | C_i) \tag{2}$$

[2] The decision to invest in energy and carbon saving technologies is complex, and the time and effort required to make an optimal decision are costly (Allcott and Greenstone, 2017). Effort can influence underinvestment in even more salient ways particularly if one faces hassle – such as going through the seemingly cumbersome process of applying for eligible government support (Fowlie et al., 2015).

[3] Outcomes of adoption of the LCT are the realisations of a random processes in the IOp framework; in our analysis we are unable to assess whether the unexplained component of these outcomes is attributed to unobserved circumstances, unobserved effort, measurement error or pure chance. It should be explicitly noted that in this study we aim to measure the component of LCT adoption decisions attributed to the variables capturing observed circumstances.

with equation (2) being estimated using a probit model of the chosen binary outcome variables. In the Roemerian IOp framework (Ferreira and Gignoux, 2011; Roemer, 1998, 2002), the partial correlations between effort and circumstances should also be treated as circumstances; this embodies the indirect effect of the unjust circumstances on our LCT outcomes that is channelled through effort and reflected in our reduced form specification (equation 2). For example, assuming that acquiring LCT literacy is a form of effort affecting an individual's adoption of solar panels, the potential influence of parental education (as a circumstance) on LCT adoption that comes through the impact of parental education on an individual's LCT literacy should be treated as a circumstance.

It follows that the observed socioeconomic inequality in our LCT adoption variables can be estimated by applying a suitable inequality measure, I(.), to $\hat{y}$:

$$\theta_I = I(\hat{y}) \tag{3}$$

Given that all the variation in vector $\hat{y}$ is exclusively due to circumstances, equation (3) refers to variations in LCT adoption outcomes attributed to our set of socioeconomic variables reflecting the circumstances captured in our analysis. The choice of the inequality measure I(.) depends mainly on the type of the outcome variable being examined. Following Davillas and Jones (2021) and Wendelspeiss Chávez Juárez and Soloaga (2014), given the binary nature of our outcomes, we employ a dissimilarly index in our analysis. An estimator of the dissimilarly index (Fajardo-Gonzalez, 2016) can be given by:

$$I(.) = \frac{2}{n\bar{y}} \sum_{i=1}^{n} |\hat{y}_i - \bar{y}| \tag{4}$$

where, $\hat{y}_i = E(y_i|C_i)$ and $\bar{y} = E(\hat{y}_i)$. The dissimilarity index ranges from zero to one, with zero indicating full socioeconomic equality and one full inequality. The index can be interpreted as the minimum fraction of the number of LCT adopters that needs to be redistributed across socioeconomic groups to achieve equality (Fajardo-Gonzalez, 2016). It should be explicitly noted here that in the presence of unobserved circumstances not accounted for in equation (2), our measure of socioeconomic inequality in LCT adoption should be considered at least as the lower-bound estimates of overall socioeconomic inequality, i.e., the inequality due to *all* socioeconomic circumstances not only to those observed in our analysis (Ferreira and Gignoux, 2011).

Our set of LCT measures are obtained from Wave 4 (January 2012 – May 2014) and from Wave 10 (January 2018 – May 2020) of UKHLS (Understanding Society – the UK Household Longitudinal Study) data; we estimate socioeconomic inequality in LCT adoption separately for each wave for a balanced sample (valid responses at both Wave 4 and 10), which allows us to compare the evolution in socioeconomic inequality as LCT adoption progresses over time. Moreover, capitalising on the advantage of our longitudinal measures of LCT adoption, we also estimate and compare socioeconomic inequality measures by restricting the sample to persistent innovators and non-adopters (i.e., those who always report adoption or non-adoption of LCTs respectively in Waves 4 and 10) as well as to additional sub-samples of our balanced working sample successively augmented by population groups that transition between adoption and non-adoption of LCTs between Wave 4 and 10.

2.1 Decomposing the socioeconomic inequality in LCT adoption

Shapley-Shorrocks decomposition analysis is employed to measure the contribution of our set of circumstances variables (C) to overall socioeconomic inequality (Shorrocks, 2013; Wendelspeiss Chávez Juárez and Soloaga, 2014; Davillas and Jones, 2021). The path-independent and exact additive (Shapley-Shorrocks) decomposition is implemented by computing the inequality index for all permutations of our set of observed circumstances, followed by averaging the marginal contribution of each circumstance (Wendelspeiss Chávez Juárez and Soloaga, 2014). Decomposition analysis is applied to the dissimilarity indices for the measurement of socioeconomic inequality in LCT adoption variables in Waves 4 and 10, as well as across our sub-sample analysis based on longitudinal patterns of LCT adoption.

2.2 Data

The data are obtained from Wave 4 (January 2012 – May 2014) and Wave 10 (January 2018 – May 2020) of the longitudinal, nationally representative UK survey UKHLS (University of Essex, 2022); Wave 10 contains the most recent and up to date data on ‘environmental related behaviour’, whereas Wave 4 provides the corresponding data for the January 2012 – May 2014 period. For the purpose of our analysis, we rely on the General Population Sample of the UKHLS, a representative sample of the UK adult residential population, consisting of 47,041 individuals in Wave 4 and 34,318 in Wave 10. Given that we aim to measure and compare the evolution of the socioeconomic inequality in LCT adoption between UKHLS Wave 4 and 10, we restrict our main analysis to a balanced sample of respondents between the two waves; this allows us to compare the levels of socioeconomic inequality in LCT adoption at different times, as well as implement the analysis on sub-samples characterised by distinct longitudinal LCT adoption patterns (e.g., those persistently reporting non-adoption or adoption of LCT in both Waves 4 and 10 or transitioning to adoption between these waves). After excluding all missing cases in our measures of technology adoption, and the circumstance variables included in our analysis, our final balanced sample contains 20,886 individuals (corresponding to 41,772 person-year observations for the two UKHLS waves).

Sample weights are used to ensure that our findings remain representative of the UK population. The weights were calculated using backward stepwise logistic regressions on observed predictors, adjusting the published UKHLS sample weights to account for attrition between Waves 4 and 10 (given our balanced working sample), item missingness and unit nonresponse for all variables used in our analysis.

2.3 Low-carbon technology outcomes

Our set of outcome variables reflects three types of LCT adopted by households: a) solar photovoltaics for electricity (*SOLARPV*) *installed* by households; b) solar heating (*SOLARHEAT*) *installed* by households; and c) hybrid or electric vehicles (HYBRIDEV) *owned* or continuously used by households.

Specifically, the *SOLARPV* variable takes the value of one if the respondent's household has installed solar panels for electricity; and zero otherwise. Similarly, *SOLARHEAT* is a dichotomous outcome taking the value of one if the respondent's household has installed solar panels for heating, and otherwise coded as zero. It is important to note here that, for both the *SOLARPV* and *SOLARHEAT* dichotomous outcomes, those individuals from households unable to adopt such technologies due to living in rented accommodation, those considering but not having adopted these LCTs and those who have not yet considered installing these technologies are coded as zero in the definition of our outcome variables. Our third outcome variable *HYBRIDEV* is a dichotomous variable taking the value of one if the respondent's household owns or has continuous use of either a hybrid (i.e., petrol and electric) or electric battery-operated vehicle (i.e., a car or van); otherwise, *HYBRIDEV* takes the value of zero.

Table 1 provides the description of our set of LCT adoption variables along with their mean values separately for UKHLS Wave 4 and 10. Our results show a considerable increase in those adopting solar panels for electricity and for heating between Wave 4 and 10; within a time period of six years, the proportion of individuals reporting having solar panels for electricity more than doubled, increasing from 3.3% to 7.6%; similarly, an increase in the proportion of respondents reporting solar heating technology is observed (from 1.6% in Wave 4 to 2.5% in Wave 10). Table 1 also shows that the increase in the proportion of our sample that report at least one electric or hybrid-electric vehicle available at the household level — an increase from less than 1% in 2012-2014 (Wave 4) to 3.2% in 2018-2020 (Wave 10), reflecting the increasing adoption of new low emission vehicles.

Table 1. Definitions and mean values – LCT outcomes

		Wave 4	Wave 10
Variables	Definition	Mean	
SOLARPV	1 = Individual belongs to a household which has installed solar panels for electricity; 0 = otherwise or not applicable/living in rented accommodation.	0.033	0.076
SOLARHEAT	1 = Individual belongs to a household which has installed solar heating; 0 = otherwise or not applicable/living in rented accommodation.	0.016	0.025
HYBRIDEV	1 = Individual belongs to a household which has at least one electric vehicle or hybrid-electric vehicle; 0 otherwise.	0.005	0.032
Sample size (balanced sample)		20,886	20,886

Note: Mean values are weighted using sample weights.

2.4 Socioeconomic circumstances

All our socioeconomic variables are measured using data from UKHLS Wave 4 (unless otherwise stated below) and are treated as time-invariant variables. The choice of our circumstance variables reflects the broader IOp framework and focuses on the factors regarded as sources of socioeconomic inequality in LCT adoption that are beyond the individual's control.[4] Limiting our inequality analysis to predetermined factors may help mitigate any endogeneity concerns; this also allows us to obtain the total contribution of these predetermined characteristics to the inequalities in LCT adoption, i.e., the contribution coming *directly* from predetermined circumstances, as well as from the *indirect* effects of predetermined circumstances via later life socioeconomic factors (and other mediators) which are also correlated with LCT adoption.

Birth cohorts[5] and gender are included in our set of circumstances, as existing literature has shown systematic differences in low-carbon energy adoption patterns by gender and across birth cohorts (Mills and Schleich, 2012; Day, 2015; Fraune, 2015; Berkeley et al., 2018; Petrova and Simcock, 2021; Han et al., 2022). Ethnicity is also included in our set of circumstance variables (NON-WHITE vs WHITE) as it has been shown that those of minority ethnicity backgrounds tend to have a lower rate of adoption of low carbon technologies in the United States, and even more so in low- and middle-income countries (Sovacool et al., 2022).

Childhood socioeconomic status (SES) is regarded as an important source within the broad IOp framework (for example, Bourguignon et al., 2007; Ferreira and Gignoux, 2011). With respect to LCTs, although there is limited literature that directly assesses

[4] Although income is potentially correlated with LCT adoption inequalities, it is important to emphasise that we focus on *predetermined* circumstances. Income is a later life outcome determined by one's effort and idiosyncratic characteristics.

[5] We create eight indicator variables for the following birth cohorts: those born before 1934; born between 1935 and 1944; born between 1945 and 1954; born between 1955 and 1964; born between 1965 and 1974; born between 1975 and 1984; born between 1985 and 1994; and born after 1995.

the effect of parental SES on LCT adoption, there is some evidence that parents influence childhood energy literacy (Pearce et al., 2020), environmental attitudes and energy saving behaviour (Karatepe et al., 2012; Fell and Chiu, 2014), and the choice of heating fuel in young households established outside of the home (Mussida and Sciulli, 2022). For the purpose of our study, parental occupational status when the respondent was aged 14 is used to proxy for childhood SES. Specifically, we employ one categorical variable for the mother's occupational status and one for the father's: not working (reference category), four occupation skill levels[6] and a category for missing data. Parental education is also employed as a second indicator of childhood SES. A combined categorical variable for the highest parental education level is employed given the high correlation between mother's and father's education (Kenkel et al., 2006); this is a four-category variable defined as: left school with no/some qualification, post-school qualification/certificate, degree, and a missing data category.

We include an individual's own education as a circumstance variable in our analysis; this is based on a normative assumption that the level of secondary schooling achieved by age 18 is highly influenced by parental and environmental factors during earlier life and, thus, is (at least partially) beyond an individual's responsibility (Davillas and Jones, 2020). The individual's own education is measured using a 5-category variable: no qualification (NOQUALS), basic qualification (BASICQUALS), O-Level, A-Level/post-secondary and DEGREE. Given that there is a small proportion of our sample still enrolled in education or who completed their degree between UKHLS Waves 4 and 10, the highest recorded educational attainment is used for the needs of our analysis.

Bar Gai et al. (2021) found education to be among the key barriers to solar adoption at the community level in the US; yet, in China, highly educated households were associated with EV but not solar panels uptake (Wen et al., 2023). Angrist et al. (2023), although they do not focus on adoption of specific LCTs explicitly, found a positive causal effects of education on pro-climate outcomes that include energy efficiency behaviours and attitudes towards renewable energy (Angrist et al., 2023). Summary statistics for all the socioeconomic variables used in our analysis can be found in Table A1 (Appendix 1).

[6] The occupational skill levels used to construct these variables are based on the Standard Occupational Classification 2010.

3. Results

3.1 Socioeconomic inequality in LCT adoption

Table 2 presents the dissimilarity indexes for our three LCT outcomes and their evolution over time (UKHLS Wave 4 vs Wave 10). Overall, our results show the presence of systematic socioeconomic inequalities in the adoption of solar panels for electricity (SOLARPV), solar heating (SOLARHEAT) and electric vehicle/hybrid-electric vehicle ownership (HYBRIDEV), with highly statistically significant dissimilarity indexes for both UKHLS Waves 4 and 10.

However, we observe that the level of socioeconomic inequality reduced in magnitude over time across all three LCT measures; this may indicate that the increasing adoption of LCTs over time has also evolved with a more equal distribution of these technologies across our set of socioeconomic factors. Specifically, the estimated dissimilarity index for electricity solar panels reduced from 0.281 in Wave 4 to 0.154 in Wave 10; this is a 45% reduction in the level of socioeconomic inequalities. Similarly, we observe a 37% (32%) reduction in socioeconomic inequality in solar heating adoption (low-carbon vehicles) over the same time period (i.e., over a 6-year period from baseline Wave 4, collected in January 2012 – May 2014, to Wave 10).

Table 2. Measures of socioeconomic inequality (Dissimilarity Indices) in LTC adoption

Specifications	SOLARPV	SOLARHEAT	HYBRIDEV
	(1)	(2)	(3)
Panel A. Wave 4			
θ_I	0.281***	0.338***	0.382***
	(0.004)	(0.003)	(0.002)
Observations	20,886	20,886	20,886
Panel B. Wave 10			
θ_I	0.154***	0.214***	0.259***
	(0.006)	(0.003)	(0.004)
Observations	20,886	20,886	20,886

Notes: Bootstrapped standard errors in parentheses (500 replications). Analysis is weighted using sample weights. *** $p < 0.01$

3.2 Decomposition of the observed socioeconomic inequality in LCT adoption

The results of the Shapley-Shorrocks decomposition presented in Table 3 allow us to explore the relative contribution of each of our circumstance variables to overall socioeconomic inequality. A graphical representation of these results is available in the Appendix (Figure A1). Overall, along with the observed reduction in socioeconomic inequality in the adoption of LCTs over time (Table 2), there are also variations in the contribution of our circumstance variables to the explained socioeconomic inequality.

With respect to explained socioeconomic inequality in the adoption of solar panels for electricity, birth cohort remains the most notable contributor to socioeconomic inequality, but its relative contribution slightly reduced over time (from about 57% in Wave 4 vs 51% in Wave 10); parental occupation remained the second most important contributor (Wave 10 vs Wave 4), while parental education became the third most important contributor in Wave 10 as opposed to individual's own education in the baseline results (Wave 4).

Turning to solar heating, we observe variations in the most important contributors to socioeconomic inequality over time. Birth cohort (about 32%), parental occupation (29%) and parental education (23%) are the three most important contributors to socioeconomic inequality in the adoption of solar for heating at the baseline (Wave 4), yet there is a shift in the ordering of the top three contributors, with parental occupation (47%), parental education (21%) and birth cohort (about 10%) being the first, second and third contributing factors to socioeconomic inequality in Wave 10.

Similarly, a shift in the order of the top contributing factors in socioeconomic inequality is observed in the adoption of low-carbon vehicles. Specifically, an individual's own education (about 39%), parental occupation (20%) and parental education (17%) became the first, second and third in the order of contributing factors most recently (Wave 10); the corresponding order of their relative contribution to socioeconomic inequality in low-carbon vehicles adoption in the baseline (Wave 4) is parental occupation (at almost 57%), followed by parental education (17%) and the individual's own education (12%).

Across all LCTs we observe a shift towards a larger contribution of gender and ethnicity in explaining the reduced socioeconomic inequalities over time, however their contributions remained relatively low in magnitude compared to all other circumstances. Overall, along with the observed reduction in socioeconomic inequality in LCT adoption over time, our decomposition results show that parental education and occupation along with an individual's own education (and birth cohort for the case of solar panels for electricity) remained the most prominent contributors.

Table 3. Decomposition of socioeconomic inequality (Dissimilarity Indices) in LCT adoption outcomes

Specifications	SOLARPV	SOLARHEAT	HYBRIDEV
	(1)	(2)	(3)
Panel A. Wave 4			
θ_I	**0.281**	**0.338**	**0.382**
	Contributions to inequality (%)		
Gender	3.70%	4.09%	2.81%
Birth cohort	56.94%	32.26%	5.83%
Ethnicity	2.97%	2.44%	5.46%
Education	8.41%	8.61%	12.16%
Parental occupation	20.68%	29.18%	56.61%
Parental education	7.28%	23.42%	17.13%
Total	**100%**	**100%**	**100%**
N	20,886	20,886	20,886
Panel B. Wave 10			
θ_I	**0.154**	**0.214**	**0.259**
	Contributions to inequality (%)		
Gender	8.48%	5.85%	7.07%
Birth cohort	50.87%	9.65%	10.38%
Ethnicity	10.33%	9.30%	6.52%
Education	5.80%	7.14%	38.57%
Parental occupation	13.87%	46.92%	20.02%
Parental education	10.65%	21.13%	17.44%
Total	**100%**	**100%**	**100%**
N	20,886	20,886	20,886

3.3 Distributional patterns of LTC adoption over time and by socioeconomic inequality

Table 4 describes the distribution of adoption of LCTs over time in our sample; it presents all the observed sequences of adoption of LCTs covering both Waves 4 and 10, resulting in (2^2=4) distinct sequences for each technology adoption outcome. Across all LCT outcomes, the vast majority of observations are characterised as persistent non-adopters (with the corresponding proportion ranging between 93% and 97.5%); persistent adopters within our time window (Wave 4 vs Wave 10) account between 0.2% and 2% of our sample. Turning to sequences reflecting transitions over time, transitions towards the adoption of LCT from non-adoption at the baseline ("No, Yes" sequences in Table 4) are the dominant sequences. For example, 4.1% of our (balanced) sample reported no solar panels for electricity at the baseline but have adopted this technology at Wave 10; the corresponding proportion transiting to the adoption of low-carbon vehicles is about 2.6%.

Table 4. Distribution of LTC adoption across Waves 4 and 10 (balanced sample=20,886)

	Low-carbon technology		Distribution	
Variables	Wave 4	Wave 10	Frequency	Percent
SOLARPV	No	No	19,483	93.00
	Yes	No	120	0.57
	No	Yes	851	4.07
	Yes	Yes	432	2.07
SOLARHEAT	No	No	20,364	97.50
	Yes	No	100	0.48
	No	Yes	239	1.14
	Yes	Yes	183	0.88
HYBRIDEV	No	No	20,255	97.00
	Yes	No	43	0.21
	No	Yes	541	2.59
	Yes	Yes	47	0.23

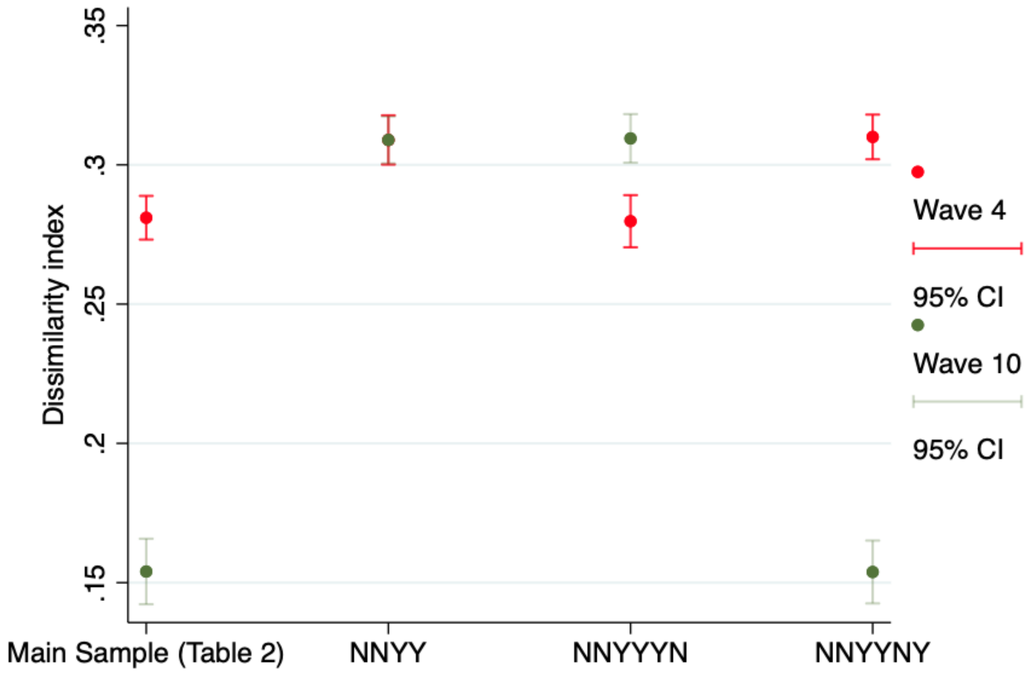
Capitalising on the availability of repeated outcomes of our LCT variables, Figure 1 presents estimates of socioeconomic inequality measures when restricting our sample to certain longitudinal sequences of adoption of LCTs.[7] For all our LCT adoption outcomes, socioeconomic inequalities are systematically higher when considering the sample of persistent adopters/non-adopters compared to the full sample for Waves 4 and 10 (presented in Table 2 and in Figure 1 for comparison purposes). This shows that socioeconomic inequalities are much larger among those who do not make the transition to LCT adoption over time. As expected, the increased socioeconomic inequalities when restricting our sample to persistent adopters/non-adopters are identical for both Waves 4 and 10, as there are no variations in the outcome variables and we use a time invariant set of circumstances.

To explore empirically what drives the aforementioned larger socioeconomic inequalities, we augment our sample of persistent adopters/non-adopters (NNYY) to include (separately) those transiting to a) non-adoption (NNYYYN) and b) adoption of LCTs (NNYYNY). Figure 1 shows that augmenting the sample of persistent non-adopters/adopters with those transitioning towards adopting an LCT between Waves 4 and 10 (NNYYNY). The observed socioeconomic inequality patterns for NNYYNY are similar to those observed for our full sample (confirming the presence of higher socioeconomic inequalities in Wave 4 as opposed to Wave 10). On the other hand, we observe an *increase* in inequalities for Wave 10 when augmenting the sample of persistent non-adopters/adopters with those transitioning to non-adoption (NNYYYN). Hence, by comparing NNYYYN to the main sample we may infer that it is disadvantaged individuals who were unable to retain LCTs, i.e., having relinquished the technologies over time. Overall, these results may indicate that the observed reduction in inequalities over time in the main sample (Table 2), is driven by those displaying transitory energy adoption patterns between Waves 4 and 10 and especially by those who recently adopted LCTs (as can be inferred by the similarly between the NNYYNY and the main sample results in Figure 1).

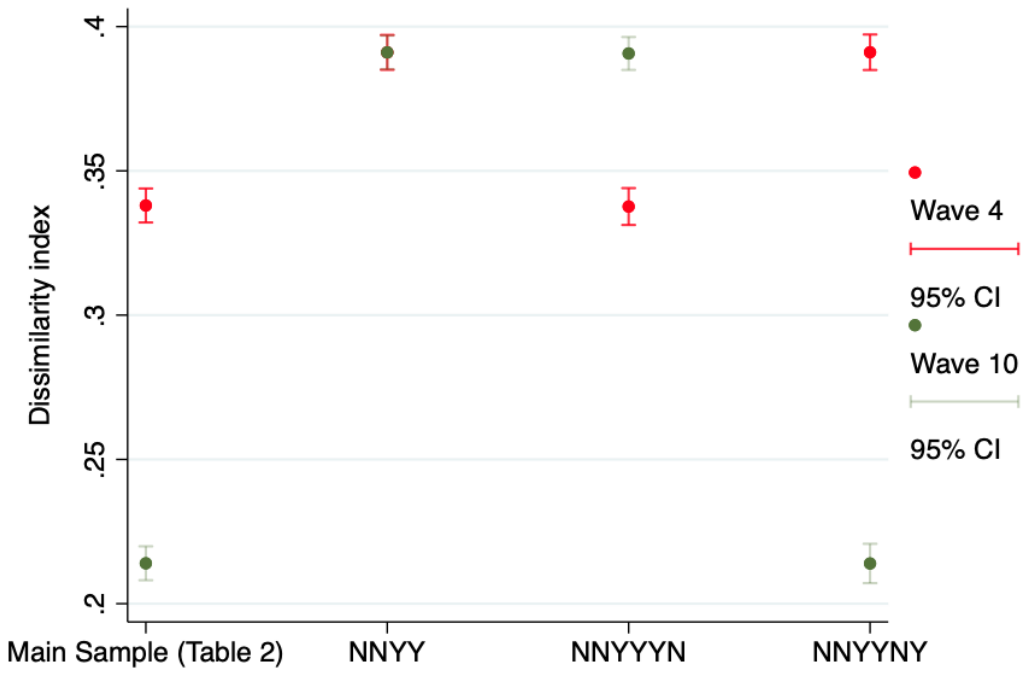
[7] A table of the corresponding results is available in the Appendix (Table A2).

Figure 1. Socioeconomic inequality of LCT adoption by subsets of longitudinal adoption patterns

Panel A. SOLARPV



Panel B. SOLARHEAT



Panel C. HYBRIDEV

To better understand the relative contribution of circumstance variables to the observed higher socioeconomic inequality (compared to our pooled sample; Table 2), Table 5 presents the corresponding Shapley-Shorrocks decomposition results.[8] Compared to the decomposition results for Wave 10 in our full sample, Table 5 shows that birth cohort and parental occupation exerted a larger contribution to socioeconomic inequality in the adoption of electricity solar panels for the persistent adopters/non-adopters sample; on the other hand, the contribution of gender and ethnicity is smaller compared to the full sample decomposition results for Wave 10.

Parental occupation, parental education and birth cohorts are the top three sources of the higher socioeconomic inequalities observed in the sample of persistent adopters/non-adopters. Of particular interest is a notable increase in the relative contribution of birth cohorts as opposed to the corresponding decomposition results for Wave 10 in our full sample. Overall, the shift towards an increased relative contribution of birth cohorts observed in the case of socioeconomic inequalities in persistent adopters/non-adopters, as opposed to the full Wave 10 sample, may reflect a more equal distribution of LCTs across generations and age groups over time given the evolution in LCT adoption.

Turning to the decomposition results for those who persistently adopt/do not adopt low carbon vehicles (Table 5, column 3), parental occupation, an individual's education and parental education are the first, second and third factors in order of magnitude. Compared with the corresponding decomposition results for Wave 10 in our full sample, we observe a notable shift towards a larger contribution of parental occupation and a reduced contribution of an individual's own education in the sample excluding any individuals who transitioned.

[8] As noted earlier, socioeconomic inequalities are identical for both Waves 4 and 10 when restricting our sample to persistent adopters/non-adopters and, thus, the same holds for the corresponding decomposition results.

Table 5. Decomposition of socioeconomic inequality (Dissimilarity Indices) in measures of LTC adoption: persistent adopters/non-adopters (YES, YES; NO, NO)

Specifications	SOLARPV	SOLARHEAT	HYBRIDEV
	(1)	(2)	(3)
θ_I	**0.309**	**0.391**	**0.407**
	Contributions to inequality (%)		
Gender	3.57%	4.08%	0.39%
Birth cohort	58.32%	22.85%	9.71%
Ethnicity	4.49%	10.01%	6.49%
Education	6.95%	5.39%	22.77%
Parental occupation	19.43%	32.75%	45.61%
Parental education	7.24%	24.92%	15.03%
Total	**100%**	**100%**	**100%**
N	19,915	20,547	20,302

4. Conclusions

Consumer adoption of LCTs is a cornerstone of the UK's target to achieve net zero carbon emissions by 2050. Even though LCTs have become more affordable over the last decade, their adoption may not be equally distributed across socioeconomic characteristics in the UK population. Using a set of socioeconomic factors that are largely exogenous and beyond the individual's control, we identified systematic socioeconomic inequalities in the adoption of LCTs. Our findings add to the literature by uncovering that the socioeconomic inequality in LCT adoption is decreasing over time: for all our LCTs outcomes (solar photovoltaics for electricity, solar heating, and hybrid/electric vehicles) our measures of socioeconomic inequality in LCTs decreased over the last decade while remaining statistically significant.

Interestingly, the observed reduction in socioeconomic inequality in LCT adoption over time is heterogenous with respect to the type of technology. Compared to solar panels for electricity, socioeconomic inequality has fallen by a smaller degree for solar heating over the last decade (respectively, 45% vs. 37%). This should lead to important policy considerations, not least because heating forms the largest share of UK household energy bills, and its cost can be considerably higher for those using only electricity for heating. Much lower is the percentage reduction in socioeconomic inequality in the adoption of hybrid/electric vehicles (32%). While the UK government still subsidises EVs at the point of sale, the subsidies could be better targeted towards individuals (or communities) in disadvantaged socioeconomic circumstances. Following the results of our analysis, these targeted policy interventions may help to mitigate socioeconomic inequalities in the adoption of LCTs which are still more prevalent amongst those from a more disadvantaged socioeconomic background.

By exploiting the availability of longitudinal data, we established further important empirical findings: a) socioeconomic inequality is highest for those persistently adopting (innovators) and those persistently not adopting (so-called late adopters or laggards); b) the innovators that relinquished their LCTs over time are more likely to have experienced disadvantaged socioeconomic circumstances; and c) more recent adopters (early-adopters) are contributing towards the reduced socioeconomic inequality in LCT adoption over the last decade. This last observation would suggest that the low-carbon transition is being progressively made by more disadvantaged individuals.

Decomposition analysis on the relative contribution of our socioeconomic variables to the observed socioeconomic inequalities show that while an individual's education, parental education and occupation remain the three main contributors, gender and ethnicity represent a small but growing share of socioeconomic inequality. These results reveal the total contribution of predetermined factors on shaping inequalities in LCT adoption — both via their direct effect and via their indirect effects on people's later life effort and socioeconomic circumstances that may affect LCT adoption.

From a normative point of view, the presence of inequalities in LCT adoption driven by parental socioeconomic background are considered unfair sources of inequality (as opposed to those driven by an individual's preferences) leading to calls for regulatory interventions. The limited related literature is broadly in line with our findings showing that, despite adoption rates being lower in elderly cohorts, early-life education is as a route to improve technology adoption more generally (Kämpfen and Maurer, 2018). Hence a multifaceted approach to policy design which accounts for intergenerational effects is necessary to support the low-carbon transition.

Moreover, our findings add to the growing debate on the economic (in)efficiency of individual uptake of LCTs, and whether such inefficiencies create more problems for vulnerable consumers than for other members of society. For example, in the context of solar adoption, rather than advocate for solar panels for anyone who adopted them, Borenstein (2022) argues for a shift towards community or utility-scale installations, which could reduce the burden of costly adoption and help bring down energy bills. Other scholars suggest targeted price-based interventions could be introduced to level the playing field (Best et al., 2021; Ravigné et al., 2022). It is crucial therefore to promote LCT adoption by the most vulnerable either at the household or community level; not least because, if such mechanisms were to remain out-of-reach, then socioeconomic inequality in LCTs may slow down a critical pathway to carbon abatement.

Our study is not free of limitations. Indeed, our analysis should be viewed as a way to measure socioeconomic inequality in LCT adoption and their underlying sources rather than providing causal analysis of the link between adverse circumstances and LCT adoption. Although we employ a set of predetermined circumstances which are largely beyond individual's control, endogeneity concerns still arise, for example, perhaps due to the omission of relevant circumstances which are not observable by the researcher. However, even in the presence of such unobserved circumstances, our inequality measures can be interpreted as the lower-bound estimates of the overall inequality due to all circumstances, not only those that are observed (Davillas and Jones, 2020). Finally, exploring the role of socioeconomic inequalities in the adoption of energy efficiency measures is beyond the scope of the present paper, as the relevant data is currently unavailable in UKHLS. Nonetheless, this is a worthy avenue for future research given the need for improved energy efficiency to achieve net zero targets.

Finally, it is important to emphasise that the presence of socioeconomic inequalities in the adoption LCTs may exacerbate broader socioeconomic inequalities by limiting the ability of the most disadvantaged to invest in technology which can lower energy costs. Our results lead us to support policies targeting specific socio-economic groups which will not only be crucial to mitigate the observed inequalities in LCTs but also relevant in promoting energy efficiency and resilience to high energy costs as we transition towards a low-carbon future.

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Appendix

Table A1. Variables' definitions and mean values (balanced sample)

Variable		Definition	Mean
Gender			
FEMALE (reference)		1 if female; 0 otherwise	0.564
MALE		1 if male; 0 otherwise	0.436
Birth cohort			
BEFORE-1934 (reference)		1 if born before 1934; 0 otherwise	0.029
1935-1944		1 if born between 1935 and 1944; 0 otherwise	0.136
1945-1954		1 if born between 1945 and 1954; 0 otherwise	0.255
1955-1964		1 if born between 1955 and 1964; 0 otherwise	0.248
1965-1974		1 if born between 1965 and 1974; 0 otherwise	0.208
1975-1984		1 if born between 1975 and 1984; 0 otherwise	0.098
1985-1994		1 if born between 1985 and 1994; 0 otherwise	0.026
AFTER_1995		1 if born after 1995; 0 otherwise	0.026
Ethnicity			
NON-WHITE (reference)		1 if non-white; 0 otherwise	0.070
WHITE		1 if white; 0 otherwise	0.930
Education			
NOQUALS (reference)		1 if no qualifications; 0 otherwise	0.348
BASICQUALS		1 if basic qualifications; 0 otherwise	0.347
OLEVELS		1 if O-level qualification; 0 otherwise	0.181
ALEVELS		1 if A-level qualification; 0 otherwise	0.079
DEGREE		1 if degree qualification; 0 otherwise	0.044
Parental occupation			
MOTHER-OCCUPATION-	NOTWORKING (reference)	1 if mother was not working (when respondent was 14), 0 otherwise	0.392
	SLEVEL1	1 if mother's job was skilled level 1 (when respondent was 14), 0 otherwise	0.070
	SLEVEL2	1 if mother's job was skilled level 2 (when respondent was 14), 0 otherwise	0.058
	SLEVEL3	1 if mother's job was skilled level 3 (when respondent was 14), 0 otherwise	0.198
	SLEVEL4	1 if mother's job was skilled level 4 (when respondent was 14), 0 otherwise	0.093
	MISSING	1 if mother's job market status is missing, 0 otherwise	0.190
FATHER-OCCUPATION	NOTWORKING (reference)	1 if father was not working (when respondent was 14), 0 otherwise	0.037
	SLEVEL1	1 if father's job was skilled level 1 (when respondent was 14), 0 otherwise	0.137
	SLEVEL2	1 if father's job was skilled level 2 (when respondent was 14), 0 otherwise	0.294
	SLEVEL3	1 if father's job was skilled level 3 (when respondent was 14), 0 otherwise	0.156
	SLEVEL4	1 if father's job was skilled level 4 (when respondent was 14), 0 otherwise	0.048
	MISSING	1 if father's job market status is missing, 0 otherwise	0.327
Parental education			
HIGHEST EDUCATION	NONE (reference)	1 if parents' highest qualification is left school with no/some qualification, 0 otherwise	0.506

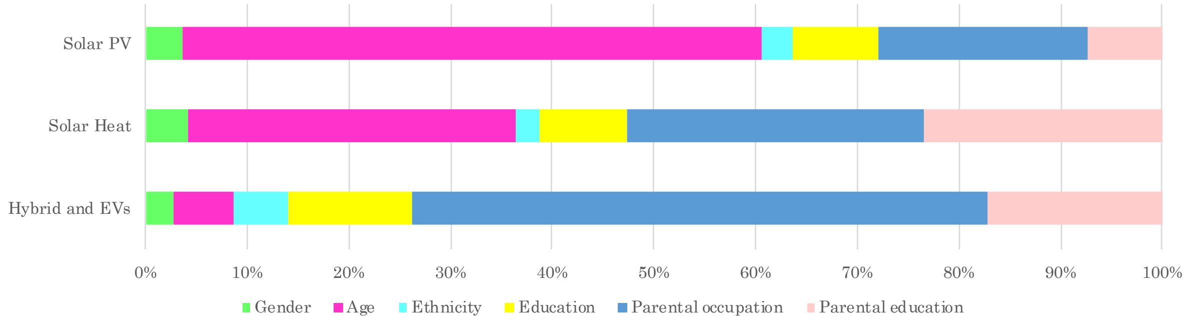
Table A2. Socioeconomic inequality (Dissimilarity Indices) in LCT adoption: different subsets of longitudinal adoption patterns

Specifications	SOLARPV (1)	SOLARHEAT (2)	HYBRIDEV (3)
Panel A. Wave 4			
θ_I : ALL	0.281***	0.338***	0.382***
	(0.004)	(0.003)	(0.002)
θ_I : NNYY	0.309***	0.391***	0.407***
	(0.005)	(0.003)	(0.002)
θ_I : NNYYYN	0.280***	0.338***	0.386***
	(0.005)	(0.003)	(0.002)
θ_I : NNYYNY	0.310***	0.391***	0.400***
	(0.004)	(0.003)	(0.002)
Panel B. Wave 10			
θ_I ALL	0.154***	0.214***	0.259***
	(0.006)	(0.003)	(0.004)
θ_I : NNYY	0.309***	0.391***	0.407***
	(0.004)	(0.003)	(0.002)
θ_I : NNYYYN	0.309***	0.391***	0.407***
	(0.004)	(0.003)	(0.002)
θ_I : NNYYNY	0.154***	0.214***	0.259***
	(0.006)	(0.003)	(0.004)

Notes: Bootstrapped standard errors in parentheses (500 replications). Analysis is weighted using sample weights.
*** $p < 0.01$

Figure A1. Decomposition of socioeconomic inequality in LCT adoption outcomes

Panel A. Wave 4



Panel B. Wave 10

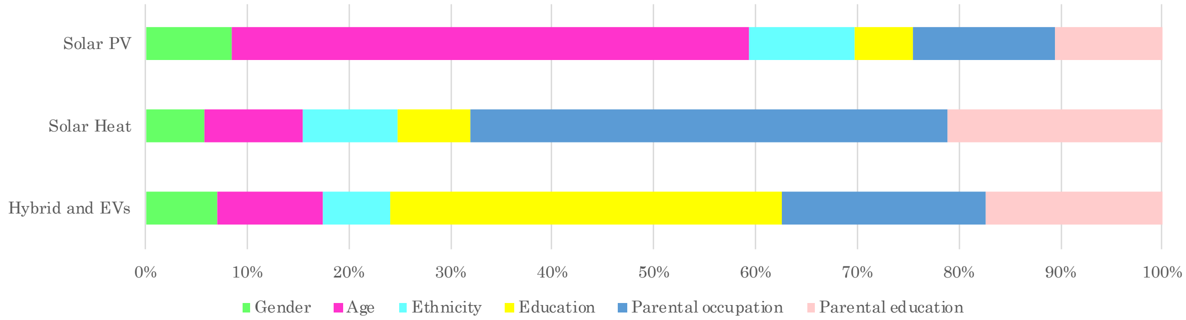


Figure A2. Decomposition of socioeconomic inequality in LCT adoption outcomes: persistent adopters/non-adopters only