Public acceptance of resource efficiency strategies to mitigate climate change

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Rapid action to improve resource efficiency is essential for achieving climate mitigation goals. Likely to reshape everyday life in unexpected ways, new products, policies and business models will need to consider the public acceptability of resource efficiency strategies, as well as technical emissions reductions potential. Here, using consumption-based emissions modelling and deliberative public workshops, we find significant public support for a range of resource efficiency strategies that combined could reduce the UK's carbon footprint by up to 29 MtCO2e (a 39% emissions reduction from household products such as cars, clothing, electronics, appliances and furniture). Public acceptability is already high for strategies that aim to develop more resource efficient products. Strategies that aim to encourage product sharing and extend product lifetimes were also perceived positively, although acceptance was dependent on meeting other important conditions, such as trustworthiness, responsibility, fairness, affordability, convenience, safety and hygiene.

Current mitigation measures are failing to achieve the speed and scale of emissions reductions needed to remain within the 2°C limit for dangerous climate change[1]. A consumption-based emissions accounting perspective can increase the scope of mitigation policy[2,3], which currently focuses primarily on emissions directly produced within a country's territory (see Supplementary Note 1 that describes the different accounting approaches). The consumption of materials and products represents an increasing driver of carbon emissions, with 25% of global emissions produced through industrial processes, which end up embodied in buildings, infrastructure, vehicles, electronics, clothing and household goods[4]. Global resource use has increased eight-fold over the twentieth-century[5], making resource efficiency improvements a necessary precondition for achieving global climate mitigation goals[6-11] and meeting the series of increasingly challenging carbon budgets set out within the UK's Climate Change Act 2008. Household consumption accounts for 80% of the UK carbon footprint (727 $MtCO_2e$). Nationally, 80% of carbon emissions and 75% of materials consumed by residents (based on the model developed by Owen *et al.*[12]) are embodied in just 25% of product groups consumed in the UK. A step change is thus needed to reduce the industrial carbon emissions associated with material-intensive manufactured goods e.g., clothing, packaging, electronics, appliances, vehicles, and buildings.

Targeting these key product groups, one way to reduce material consumption is to successfully implement resource efficiency strategies[13] that enable products and services to be designed, used, and delivered in new ways. Research has identified a range of strategies (grouped into three categories - *Efficient products*, *Product sharing*, and *Product lifetimes* - see Table 1) that advocate shifting towards a more circular, resource efficient economy. However, whilst these strategies are beginning to move up the policy agenda[2,7,14,15], they are rarely considered seriously as effective or mainstream climate policy responses. Whilst the degree to which consumption practices would need to change varies for each strategy, it is clear that their implementation is likely to reshape everyday life in unexpected ways. These innovative ways of producing and consuming materials, products and services are thus unlikely to be adopted successfully without public support.

Table 1. Summary of material efficiency strategies.

	Description	***Examples***
Efficient products	Strategies that increase the availability of resource efficient products, through the design for product durability, recyclability and/or reusability.	Product light-weighting Modular and repairable design Reduced/recyclable packaging
Product sharing	Strategies that increase asset utilisation, to make more efficient use of under-utilised products, through reuse and sharing economies.	Reusing vehicles and products Sharing of vehicles and products Library of things
Product lifetimes	Strategies that increase product longevity by extending and optimising the useful lifetimes of products.	Extended producer responsibility Remanufacturing Product service systems

Dominant techno-economic analyses of climate mitigation options are often criticised for narrowly representing the public as rational economic actors, making implicit assumptions about people's beliefs, behaviours and social practices[16]. Modelling from the UK[17] and USA[18] suggests that the human component of demand reduction scenarios can be significant, achieving major emissions savings in developed nations through altered lifestyles. However, decades of research shows that theoretically achievable demand reductions are rarely achieved[19] because assumptions about human behaviour prove partly or wholly unrealistic[20]. Public perspectives must be considered within debates surrounding the transition towards a resource efficient economy, opening up a conversation surrounding the preconditions underpinning the public acceptability of different strategies. Research on public attitudes to future energy system change has highlighted the importance of considering wider citizen discourses, perspectives and values in developing climate policy. Key factors that determine broader public acceptability of energy system changes (efficiency and waste avoidance; reliability, affordability and availability of supply; improved product/service provision; and environmental protection)[21] may be relevant to the public acceptability of resource efficiency strategies.

The indeterminate nature of public acceptability adds an additional layer of uncertainty for policy makers and industry[22] beyond the techno-economic uncertainties usually considered in national energy scenarios. As such, the importance of engaging both publics and stakeholders with energy system change is now recognised as an explicit policy goal[23,24], especially in cases where policy challenges do not have a single solution and affect the majority of the population. For instance, the failure of the UK's Green Deal (a flagship home energy efficiency policy instigated in 2012) was ascribed to a lack of understanding of the public reaction to a policy that required the uptake of long-term, conditional loans and (often) significant household disruption as low carbon technologies were installed[25]. Cutting across most economic sectors and Government departments, the issue of resource efficiency is particularly complex and evidence regarding public acceptability of resource efficiency strategies will be essential before firm policy recommendations can be made.

We combine analyses of the technical emissions reductions potential and the public acceptability of resource efficiency strategies, to explore the potential role of such strategies in reducing the UK's carbon footprint. We first quantify potential emissions savings for different strategies using input-output analysis (IOA). IOA traces how sector-based emissions flow through complex international supply chains and become embodied in the final consumption of products[26]. We quantify the emissions reduction potential of reducing demand for common household materials and products (clothing and textiles; packaging; vehicles; electronics and appliances; furniture; leisure equipment; construction) by intermediate and end-use sectors in the UK economy. We use case study evidence to assess the range of impacts for each strategy on the basis of two different variables: material ambition (the level of material reduction across different strategies using case study evidence) and adoption (uptake by intermediate and final consumers to reduce material and product use)(see Methods).

Public acceptability does not equate directly with levels of adoption. However, it nonetheless represents a critical component of decision making that is likely to be important in successful policy development and implementation. To provide evidence regarding the public discourses, perspectives and values surrounding transitioning towards a resource efficient future, as well as the caveats and conditions that underlie support for specific resource efficiency strategies, we conducted a series of deliberative workshops with members of the UK public (see Methods). Integrating the findings from both the IOA modelling and deliberative workshops, we bring together different lines of evidence that can contribute to the debate surrounding the potential of resource efficiency strategies for meeting climate mitigation goals.

Emissions reductions from resource efficiency strategies

Figure 1 shows the range of greenhouse gas emission reductions across the three strategies according to the IOA (see Methods). *Product lifetimes* and *Efficient products* have the largest potential to reduce emissions (around 13 $MtCO_2e$ each). Considering *Product lifetimes*, any reductions in final demand for cars, clothes, furniture etc. will reduce the full materials supply chain emissions associated with mining, manufacture and distribution. *Efficient products* only reduced emissions associated with certain material inputs, not the demand for the products themselves, therefore addressing only a proportion of embodied emissions. However, light-weighting is deemed more feasible than increasing longevity for a greater range of products e.g., packaging, industrial equipment and construction activities. Fewer products are deemed to have the potential to be shared and/or used more intensively (in comparison to the ability to increase their longevity) and as such the mitigation potential of *Product sharing* is lower (saving up to 7 $MtCO_2e$), e.g., electronics identified with higher sharing potential were those used less frequently in households, such as power tools and hoovers, not computers, mobiles and washing machines. Demand for some products, such as cars, can be reduced across all strategies, e.g., cars can be redesigned (using less metal), can be used more intensively (through car clubs), or can be used longer before replacement. See Supplementary Note 2 for how we account for the emissions savings without double counting.

Figure 1: Emissions savings from material productivity strategies. Emissions reductions across the three strategies in 2013 are disaggregated by reductions occurring within the UK (darker bar) compared to outside UK borders that are embodied in products sold to UK households (lighter bar). The bar represents savings under the middle material ambition and adoption rate, whereas the range shows potential reductions with lower and higher rates of ambition and adoption. Data are available in Supplementary Data 1, sheet E.

Table 2 displays the impact of material ambition and adoption to examine what effect each has on emissions savings. Across all strategies, high levels of ambition produce greater savings than high adoption rates, although the differences are not different in magnitude. For example, if *Product lifetimes* policies demonstrated high levels of ambition but low uptake they would save approximately 4.6 $MtCO_2e$. If material ambition were low but uptake was high they would save approximately 3.6 $MtCO_2e$. The less ambitious a strategy in terms of material use, the greater the need to demonstrate wide-scale adoption.

Table 2: Impact of material ambition and adoption on emissions savings ($ktCO_2e$).

		Efficient products			***Product sharing***			***Product lifetimes***		
		Level of Material ambition								
		low	med	high	low	med	high	low	med	High
Level of Adoption	low	1,460	2,968	7,316	513	1,055	2,004	1,187	2,868	4,583
	med	2,874	5,741	10,184	971	2,273	4,173	2,368	5,690	9,028
	high	4,286	8,408	12,663	1,934	3,577	6,455	3,577	8,550	13,464

Combined, the emissions savings (3-29 $MtCO_2e$) could reduce the UK's current household carbon footprint (727 $MtCO_2e$) between 0.4-4%, and the embodied emissions of our products of focus (75 $MtCO_2e$) between 4-39% (see Supplementary Data 1, sheet G). This is equivalent to up to 19% of UK GHGs emitted directly by UK households (151 $MtCO_2e$ is emitted from home heating and private transport). The list of strategies is not exhaustive, however we have focused on available case studies from the literature. Cumulatively, 0.2-1.6 $MtCO_2e$ would be reduced within the UK, compared to 3-27 $MtCO_2e$ outside the UK. Whilst this would contribute to meeting UK carbon budgets, of which there is a shortfall given proposed and planned energy-dominated climate policies, adoption of our strategies will also lessen emissions pressures in countries outside the UK. Such an approach better satisfies the principles of the UNFCCC's common but differentiated responsibility and respective capabilities (CBDR-RC) as a means to allocate responsibility for climate mitigation to countries with very different historical and socio-economic profiles. See Supplementary Note 3 for a summary of this debate and motivations for reducing the UK's embodied emissions.

Public acceptability of material efficiency strategies

We now explore the public acceptability of proposed resource efficiency strategies, drawing on data from workshops with members of the UK public that deliberated on a range of strategies including the three analysed here (see Methods). Building on previous research, our analysis has demonstrated that there are strong public preferences and conditions surrounding transitioning towards a low-carbon, sustainable future that transcend any one technology or issue space[21]. Participants showed strong support for many of the policies and new business models discussed across all three resource efficiency strategies. Key meta-values surrounding environmental protection, avoiding waste, supporting jobs and a strong economy are clearly demonstrated as non-negotiable elements of any transition towards a more resource efficient economy. Table 3 highlights overall responses to the strategies, and the recurring conditions of public acceptance that might facilitate or limit public uptake. Where appropriate, quotations from individuals are reported to illustrate the broad themes discussed by multiple participants across the workshops.

Table 3: Public acceptability of resource efficiency strategies.

	Overall public reception	***Conditions of acceptance***
Efficient products	++ + Product light-weighting + Modular and repairable design ++ Reduced/recyclable packaging	Policies/initiatives should focus on maintaining: • Affordable range of products and services • Product safety and quality guarantees
Product sharing	+ + Reusing vehicles and products +/- Sharing of vehicles and products + Library of things	Policies/initiatives should focus on maintaining: • Trust between peers, organisers and businesses • Product safety, quality and hygiene • Affordable and convenient access to products
Product lifetimes	+/- ++ Extended producer responsibility + Remanufacturing - Product service systems	Policies/initiatives should focus on maintaining: • Trust between businesses and consumers • Fair and upfront distribution of responsibility • Long-term affordability (avoiding lock-in)

Overall public reception key: ++ very positive; + positive; +/- divergent; - negative.

Efficient products: Rooted in wider desires to reduce waste and protect the environment, participants were generally positive about proposals to redesign products to be lightweight, modular, more durable, recyclable and/or reusable. Redesigning packaging was a clear policy winner across the workshops, with current packaging for food and products considered extremely wasteful, and introducing biodegradable packaging seen as 'the most straightforward way [to prevent] doing any harm to anything, animals or the environment' (Alfie, B2). More widely, there was a strong sense that, in the past 'things were built to last' (Amy, C2) and were much easier to get repaired. Inbuilt obsolescence, where products purposefully 'aren't designed to be fixed' (Tim, C1), was perceived as a significant barrier to resource efficiency and a key issue that needs to be addressed. Calls for regulation encouraging the development of materially efficient and/or longer lasting products were common: 'more companies should do it, it should be law' (Carole, B1).

Product sharing: Strategies enabling sharing, swapping or gifting of a range of products were received positively, and often not seen as a significant departure from current consumption patterns (e.g., peer-to-peer trading and gifting). Interest in second hand goods and sharing schemes was generally rooted in personal utility, affordability and convenience, while when considering sharing on a societal scale, community cohesion was identified as a key co-benefit: 'It just gets people communicating and involved in caring about stuff instead of in their own little pods thinking about themselves' (Lucy, B2). Increasing levels of loneliness and isolation were a concern and product sharing was seen as one route to increasing social interactions. In particular, the library of things was well received, viewed as a 'really good idea […] if you can borrow it cheaply rather than going to hire or buying something' (Sally, C2); a good way to both build community and provide access to otherwise unaffordable products. Sharing of rarely used products, was also seen as positive and a 'sensible' approach to consumption.

Product lifetimes: Building on a wider desire for quality, long-lasting and repairable products, participants were generally in favour of increasing product lifetimes and avoiding the premature disposal/replacement of products. Increased facilities to repair products, whether via community schemes or local businesses were welcomed, although some commented that 'it wouldn't stop people still wanting or desiring new things' (Chloe, B2). Extended Producer Responsibility (EPR), making businesses more responsible for products they produce and/or sell (e.g., through extended warrantees, product guarantees and repair services) was popular, and seen as a 'good idea [that would] make [products] last a lot longer and cut out all these upgrades' (Jim, C1). Product Service Systems (PSS) were a more controversial strategy that involves paying for services (e.g., washing or lighting) while providers retain ownership of products, thus incentivising producers to increase product lifespans through redesign and repair. Although sometimes seen as a 'good option', few participants were willing to consider PSS personally, due to a range of different concerns.

Conditions that underpin public preferences

Despite overall positivity surrounding many resource efficiency strategies, acceptance was often conditional on policies and business models meeting a number of shared social values that underpinned discussions of public acceptability.

Trust: A strong distrust of other actors, particularly business, dominated discussion across all three strategies. Only one objection was raised for *Efficient products*: that modularity may be used to greenwash current business practices and increase rather than decrease sales. In contrast, trust was a key concern regarding *Product lifetimes* (in particular EPR and PSS), often preventing these strategies from being seen as viable. Businesses were often seen as putting profits above other social/environmental responsibilities, and there was disbelief that effective or fair EPR schemes would ever be developed, due to perceived conflicts of interest between business and consumer needs: 'It just seems like that's something that they generally avoid doing to maximise profits' (Mark, B2). Additionally, whilst remanufacturing was not an unpopular strategy, concerns were raised that incentivised product return could lead to greenwashing, with businesses using the inherent value within returned products to increase profits and 'carry on with their unethical trading' (Sarah, B1). Distrust in business was also a key determinant of public acceptability of PSS. Dominating the discussion, uneasiness about entering into service contracts with businesses arose from beliefs that there are always catches and loopholes, designed in favour of businesses: 'there is always some sort of penalty that's hid away' (Ralph, B1). Trust issues relating to other individuals participating in sharing-based initiatives were also raised regarding *Product sharing*, following the idea that a small number of people may ruin things for everyone, as it only 'works if people bring things back and don't abuse the system' (Chantal, C2).

Responsibility and fairness: Whilst unproblematic for *Efficient products* (which effectively maintains current ownership practices), the fair and upfront distribution of responsibility was a key concern surrounding *Product lifetimes* and *Product sharing*. For EPR (*Product lifetimes*), the redistribution of responsibility for product condition towards the producer/retailer was positively received for incentivising sustainable design and increasing product longevity. In contrast, the distribution of responsibility for PSS (*Product lifetimes*) was linked to strong distrust in business and concerns about loopholes within contractual agreements. Many were wary of claims that product repair and maintenance would be included within the service package and, despite assurances, participants could not envisage a system where they were not personally responsible for product condition at all times, imagining situations in which products were damaged and incurring financial penalties: 'God forbid if your kid draws on the washing machine, do they still replace it?' (Phoebe, B1). Similarly, lack of trust in other citizens to use services and products fairly and correctly, pervaded discussion around community-based sharing (e.g., a library of things - *Product sharing*). Management schemes (be they local council, business or community based) were seen as essential to guarantee product quality and provide necessary insurance.

Affordability and convenience: Affordability and convenience arose as general caveats across all strategies. The cost of redesigned, 'eco-friendly' products (*Efficient products*), was a concern, following suggestions that new features/materials, however efficient, may make products unaffordable to many; few could believe that these costs would not be passed to consumers, leading to suspicions that products 'will come at a premium to us as a consumer at some point down the line' (Mia, B2). Where strategies involved new consumption practices (e.g., various forms of EPR - *Product lifetimes*), affordability was often seen as balanced against convenience (in terms of effort, time and location). Relative costs of products were deemed highly relevant, with participants commenting on 'finding it hard to imagine that somebody would go to that trouble to fix their toaster' (Arnie, B1) when 'you can buy a toaster in Asda for about £8.99' (Ralph, B1). Balancing affordable access to shared products against the need for access at a convenient time and location, was also important for *Product sharing*. Linked to wider distrust in business and contracts, PSS (*Product lifetimes*) also raised broader financial concerns surrounding financial stability: 'if I lose my job or something happens […] I don't know what the effects would be […]

I've got to give my washing machine back. I've got to give all this stuff back to the place that I'm borrowing it, because I can't afford to rent anymore' (Alfie, B2).

Safety and hygiene. Despite trust in designers as experts in their field, light-weighting and re-design of products (*Efficient products*) did raise safety concerns, as '[y]ou'd have to prove it to people or assure people that, you know that's still safe' (Amy, C2). *Product sharing* was questioned on the basis of safety and hygiene, with cleanliness of shared products (e.g., kitchen appliances, clothing and luggage) of particular importance: 'I would never want to borrow [that] unless it had been decontaminated' (Katie, B2). The safety of shared electrical appliances and tools was also crucial, again leading to desires for someone with knowledge/expertise to take responsibility for product condition and safety checks. This theme was not raised in relation to *Product lifetimes*, perhaps due to the provision of repair and maintenance within EPR and PSS.

Discussion

Highlighting the as yet untapped potential of resource efficiency measures to mitigate climate change, our analysis of the IOA model results identifies potential carbon savings from resource efficiency strategies of 3-29 $MtCO_2e$. We show that the carbon footprint of a range of common household products (including clothing, footwear and textiles; packaging; vehicles; electronics and appliances; furniture; leisure equipment; and construction) could be reduced by as much as 39% in the UK, with each of the three resource efficiency strategies making a contribution to achieving such carbon savings. To highlight points of congruence (where adoption rates are more likely to coincide with high impact strategies) and dissonance (where progress may be more difficult to achieve) between the technical and social potential of resource efficiency strategies, we then assessed the public acceptability of these strategies. Issues of trust, responsibility and fairness, affordability and convenience, and safety and hygiene, were found to be crucial determinants of wider public acceptability.

By focusing on resource efficiency in its broadest sense, our findings will allow policy makers and businesses to develop policy and business model propositions that fit within the protected public value set identified, thus increasing the chances for adoption and success. However, achieving change will be more difficult in some areas than others. Our analysis highlights that, initially, focusing efforts on developing *Efficient products* would be most effective, as this group of strategies combines high emissions reductions potential with wide scale public approval. Although conditional upon affordability and product safety, there is a good chance that more ambitious policies will find wider public acceptance and success if products are designed with lower carbon footprints and/or increased product lifetimes. Direct support for specific policy interventions was also identified in the data, such as for the introduction and extension of material and/or product standards for common household products and packaging (perhaps building on the EU's Ecodesign Directive to develop both national regulation and voluntary initiatives). Encouraging the redesign of such products would necessarily require an ambitious programme of engagement with business and manufacturing, focusing on the growing business case for resource efficiency[27,28].

In contrast, achieving the potential emissions reductions identified for *Product lifetimes* and *Product sharing* may require greater ambition due to the more complex approach required. With the options for achieving the reductions these strategies promise more varied, public acceptability is more contingent on the case by case elements of each business or policy proposition. Approval was often dependent on perceptions of new business models and the implications they might have for personal consumption practices, with convenience, affordability, safety and hygiene all playing a role in public acceptance. However, for both strategies, the strongest concerns surrounded issues of trust in business and the fair and upfront distribution of responsibility, dampening public acceptability and suggesting the need for an approach which aims to build trust through transparency and accountability of business practices. Where such issues play a key role in public concerns and ambivalence, we suggest focusing on developing stronger consumer rights packages (through regulation and/or voluntary guarantees) to encourage confidence in new business models and the novel relationships they require between businesses and their customers. Additionally, the currently niche idea of a 'library of things' was very positively received. Providing funding and support at the local authority and/or community level for the development of such activities may help to encourage sharing more widely.

Focusing on the carbon impacts of resource efficiency strategies in this way allowed us to highlight the significant embodied emissions reduction potential available. However, in reality there will be inherent trade-offs and unintended consequences when developing policies and business models that are not considered in this research. For example, trade-offs with direct emissions (e.g., from heating or travel) such as whether a longer-lasting product will remain the most efficient option available over its lifetime are not considered. Similarly, while focusing on public acceptability as a crucial component of policy development and implementation provides evidence of a strong public mandate for change in some areas, there are many other factors (i.e., governance, political, economic and legal constraints) that will act to support or prevent the development of successful policy and business models.

Beyond these more institutional issues, the static IOA model (where economic monetary transactions is a proxy for material and product flows) does not consider how prices may change within the economy, or the impact this may have on individual spending. It is therefore not clear what effect policies supporting resource efficiency strategies would have on product costs or household disposable income. It is possible that, while providing a potential revenue-generating stream, less material intensive products could increase overall demand[29]. There is also the possibility of positive or negative spillover effects[30]. Increased disposable income could lead to unpredictable rebound effects[31], with emissions savings possibly offset by additional money spent on carbon intensive products/services. However, the economic benefits of resource efficiency could offset the near term costs of an ambitious low carbon pathway, creating much needed low carbon investment. These issues could not be considered in this paper due to the broad focus of our analysis on wider resource efficiency strategies; future work should aim to understand the implications of specific resource efficiency policies from a range of technical, financial and policy perspectives.

From a social science perspective, the next steps could be to provide a deeper analysis of specific resource efficiency strategies, individually assessing public acceptability, perceptions and practices with both general publics and those already participating in such schemes. Our approach (perhaps with additional quantitative surveys that provide more representative assessment of public acceptability) should now be used to explore different resource efficiency strategies in more detail and at the disaggregated level of specific products or policies. It would then be possible to use public acceptability data as a model input, allowing for the exploration of the potential carbon reductions from resource efficiency (and wider energy) policies at a granular level and teasing out key issues and trade-offs that can support the development of specific policy recommendations. Another direction for future research would be the development of interactive tools to engage participants with trade-offs surrounding embodied and direct emissions at both a personal and societal level (c.f., ref[21]). Combined, this approach could then be used to explore the public acceptability of resource efficiency strategies in non-UK contexts.

Utilising both emissions modelling and public acceptance data to evaluate the efficacy of resource efficiency strategies forms a methodological template for further research and policy analysis in this domain. Only through understanding the complex interactions between technical potential and public acceptability, as well as their interactions with wider governance and economic factors, can we begin assessing the potential of strategies that encourage resource efficiency and the circular economy. Combining emissions and acceptability data in our analysis suggests a clear priority ordering of *Efficient products*, followed by *Product longevity*, and finally *Product sharing* if resource efficiency strategies are to achieve their full potential. Moreover, a clear conclusion of this study is that firm policy recommendations cannot be made on the basis of technical (emissions) and economic modelling alone, and must consider potential carbon savings, alongside public acceptability and associated conditions for adoption. This suggests a need to reframe emissions policy to encompass the full range of resource efficiency opportunities if we are not to fall short of what can be achieved from demand side responses.

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Methods

Modelling embodied emissions of UK households: In exploring the synergies between material and product demand with determinants of public preferences we only consider final demand by households, which represents 80% of the UK's carbon footprint. The remaining 20% is from government expenditure and large capital investments. Emissions embodied in household consumption in 2013 were 576 MtCO2e (727 $MtCO_2e$ including direct household energy use). Greenhouse gas emissions reductions from the adoption of material productivity measures by UK households are quantified using an input-output framework. We analyse the design of and demand for emissions intensive non-consumable materials and goods common to households: clothing, footwear and textiles; packaging; vehicle manufacture; consumer electronics and appliances; furniture; leisure equipment; and construction (buildings and transport infrastructure). Collectively they embody around 13% (75 $MtCO_2e$) of emissions satisfying household demand, although the majority of these are emitted along manufacturing supply chains existing outside the UK. We exclude: food and drink; chemicals including medicines, paints and cleaning agents; energy used directly for heating and car travel (which are the target of the majority of existing household climate policies). Food and chemicals in particular, represent high through-put products, requiring a very different range of resource efficiency strategies than those discussed here. Accordingly, the focus is on previously under-researched household goods and services.

First, we mapped 43 case studies onto the three resource efficiency strategies (see Supplementary Data 1, sheet C), enabling us to make some quantification of reduced material and product demands from the status quo today. Scaling up case study evidence, we identify how UK household goods can be (1) designed with less material inputs, (2) used more intensively through sharing, and (3) used for longer. Due to overlapping and interlinked schemes, some case studies could have been allocated to more than one strategy e.g., increasing remanufacturing requires both product redesign by manufacturers (*Efficient products)* and consumer adoption of remanufacturing schemes (*Product lifetimes*). From the evidence available, we varied the ambition of material and product reductions and explored different adoption rates (see Supplementary Data 1, sheet F), providing a range of emissions reductions indicative of mitigation potential dependant on their uptake. In most cases we modelled a 33%, 66% and 100% adoption rate across strategies to test potential emissions savings depending on how widely adopted they could become given the limited evidence on potential adoption rates. For *Efficient products* this achieved up to their maximum theoretical potential. Elsewhere, it reflected a beyond best practice example, achieving higher than maximum material saving identified across existing case studies. Similar to Dietz *et al.*[18], this approach introduces a behavioural realism to our estimates not included in analyses grounded solely in engineering or economics, recognising that unrealistic expectations about human behaviour mean energy demand reduction policies do not achieve 100% success. We chose not to change the carbon intensity of energy in the production and use of these products. This allowed us to quantify additional emissions savings to the mainstream decarbonisation agenda, isolating the effect of resource efficiency strategies as a mitigation option.

The UK multi-region input-output (MRIO)[32] was used to calculate the emissions embodied in the consumption of goods and services by UK households for 2013 (see Supplementary Data 1, sheet B), the latest year available at the time of study. Goods and services are classified by 106 sectors according to the UK Standard Industrial Classification system[33] and we aggregate the global economy into a two region model of the UK and the Rest of the World (RoW) reflecting how the UK trades in goods and services. Embodied emissions are calculated using the standard Leontief demand-pull model[34]. GHGs emitted directly by sectors in producer countries (simplified in our model to the UK and a RoW region) are reallocated to final consumers, in our case UK households, by following products through multiple trade and transformation steps using equation (1):

$$(1)\quad \mathbf{Q} = \mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-\mathbf{1}}\,\mathbf{y}_{UK\,hh}$$

where $\mathbf{Q}$ denotes embodied emissions (also known as a carbon footprint), $\mathbf{f}$ denotes the GHG efficiency of production sectors, $\mathbf{I}$ represents an identity matrix, $\mathbf{A}$ is the technical coefficients matrix and $\mathbf{Y}_{UK\,hh}$ is the final demand of UK households. The technical coefficients matrix ($\mathbf{A}$) accounts for the proportion of intermediate inputs, both domestic and foreign, that a sector within a country requires to produce one unit of output, also known as a production recipe. In this sense, the sectoral requirements of a region are decomposed into a domestic and import component. The term $(\mathbf{I}-\mathbf{A})^{-1}$ is known as the Leontief inverse ($\mathbf{L}$), which calculates the extent to which output rises in each sector derived from a unit increase in final demand for a good or service. GHGs embodied in UK households equal emissions from UK sectors producing goods for UK households, and emissions imported from RoW sectors producing goods for UK households. Any emissions produced in the UK for exports are excluded.

We then scaled up evidence from 43 case studies listed in Supplementary Data 1, sheet C, to indicate how our high impact household goods could be (1) designed with less material inputs, (2) used more intensively through sharing or (3) used for longer than the status quo today. Each case study was allocated to one of these strategies. Due to overlapping and interlinked schemes, some case studies could have been allocated to more than one strategy e.g., increasing remanufacturing requires both product redesign by manufacturers (*Efficient products)* and consumer adoption of remanufacturing schemes (*Product lifetimes*). See Supplementary Note 2 to see how we overcome double counting in our calculations. To calculate emissions savings (**V**) from each strategy we calculate a new emissions matrix $\mathbf{Q^0}$ which we subtract from the original emissions matrix $\mathbf{Q}$ (equation 2):

$$(2)\ \mathbf{V_{strategy}} = \mathbf{Q} - \mathbf{Q^0}$$

To calculate $\mathbf{Q^0}$ we generate a new version of the transactions matrix $\mathbf{A^0}$ and the household demand vector $\mathbf{y}^{\mathbf{0}}_{UK\,hh}$. For redesigning products a change was made to the production structure (**A**), as in equation (3):

$$(3)\ \mathbf{Q^0} = \mathbf{f}\,(\mathbf{I} - \mathbf{A^0})^{-1}\,\mathbf{y}_{UK\,hh}$$

and for asset utilisation and product longevity changes were made to household purchases ($\mathbf{y}_{hh}$), as done in Wood *et al.*[35] and shown in equation (4):

$$(4)\ \mathbf{Q^0} = \mathbf{f}\,(\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}^{\mathbf{0}}_{UK\,hh}$$

We did not model changes to the GHG efficiency of production sectors (**f**).

For each case study within the strategies we identified the supplier of the material/ product (i) and the consumer (j) according to the 106 sectors classified in the UK MRIO and the transactions flow affected in the input-output model ($\mathbf{a}_{ij}$ or $\mathbf{y}_{ij}$). The level of change of the transactions flow for each case study was determined by two variables: the ambition of the material saving (**m**) and the rate of adoption by the consumer (**c**) (see Supplementary Data 1, sheet F), providing a range of emissions reductions indicative of mitigation potential dependant on their uptake.

For each material input (row i) to an intermediate production recipe (column j) $\boldsymbol{a}_{ij}$ of the **A** matrix affected by an intervention is defined by equation (5):

$$(5)\ \mathbf{a}^0_{ij} = \mathbf{a}_{ij} * \left(1 - \left(\mathbf{m}^s_{ij}\mathbf{c}^s_{ij}\right)\right)$$

where $\mathbf{a}^0_{ij}$ is the new production recipe; $\mathbf{m}^s_{ij}$ is the unique level of material reduction of a given case study, s; and $\mathbf{c}^s_{ij}$ is the adoption rate of policies of a particular case study. $\mathbf{m}$ and $\mathbf{c}$ are on a scale of 0 to 1, with 0 representing no change and 1 representing maximum ambition and adoption defined by the case study evidence. Once all changes within one strategy were modified in the **A** matrix this becomes $\mathbf{A^0}$ and the combination of interventions into one calculation per strategy excludes any double counting.

Likewise, the same approach applies for each product input (row i) to households (column j) for the new household final demand $(\mathbf{y}^{\mathbf{0}}_{ij\,hh})$ as in equation (6):

$$(6)\ \mathbf{y}^{\mathbf{0}}_{ij\,hh} = \mathbf{y}_{ij} * \left(1 - \left(\mathbf{m}^{s}_{ij}\mathbf{c}^{s}_{ij}\right)\right)$$

Where the resulting vector with all interventions model generate $\mathbf{y}^{\mathbf{0}}_{UK\,hh}$.

A low, medium and high scenario was modelled for each case study to reflect an uncertainty range in the ambition ($\mathbf{m}$) and adoption ($\mathbf{c}$) of a given strategy from the 2013 baseline. The high estimate reflects a maximum technical potential in the case of redesigning products, or demand reduction levels higher than seen in existing case studies with 100% adoption in most cases. The lower level estimate reflects case studies of proven potential in terms of material ambition with relatively lower estimates of adoption in the region of 33% in most cases. The mid-estimate reflects best case estimates with 66% adoption.

We chose not to model the rebound effect, where cost savings from reduced demand are re-spent on additional products[36], as we do not presuppose that the pricing structures will not change as a result of the implementation of the demand reduction strategies, however, this would add an additional layer of uncertainty. Each case study was modelled in isolation then aggregated into 3 overarching strategies to avoid double counting.

Methods for exploring public acceptance: Aiming to explore the public acceptability of a range of different strategies for reducing consumption based energy use by members of the public, the research involved conducting deliberative work with members of the public, to explore the future of consumption and the different implications these proposed strategies and business models may have for everyday life. Deliberative workshops were chosen as the most appropriate method, as they provide 1) an open space (both in terms of time and location) for participants to explore and engage with issues and ideas that they may be unfamiliar with and 2) allow for critical and reflexive discussion surrounding such issues. The workshops utilised established methods for engaging the public with science and technology topics[37] that have been successful in exploring a range of different energy related technologies[38-41], as well as public perceptions of whole-scale energy system transitions[42].

Sample design and recruitment: A series of four two-day workshops were conducted. Due to the focus on consumption, income and social status were chosen as the key variable on which to select participants, rather than geographical location. Despite their relative geographic proximity, Cardiff and Bristol (situated in South East Wales and South West England respectively) were selected due to their different economic and demographic profiles. In each city two workshops were convened, one with a higher income group and one with a lower income group. All workshops were conducted between November 2016 and January 2017. Whilst it would have been desirable to conduct a further two groups in a different location, perhaps in a rural or suburban area, the final decision was a pragmatic one that reflected the fact that four-two day workshops already produced an extremely large dataset (over 80hrs of recorded discussions). Given the complexity and multiplicity of the different resource efficiency strategies discussed, it was agreed that it would be more effective to conduct longer two-day sessions. With a target sample of 25 participants from each city, it was deemed that the ensuing qualitative dataset was large enough to reflect a wide variety of views, whilst maintaining a manageable size for analysis.

There are no standard rules determining the size and composition of deliberative workshops. In total, 51 participants took part (N=11-14 per workshop). Recruitment was conducted by a neutral third party company, and was topic blind, with participants only aware they would be taking part in a workshop entitled 'Exploring the future of consumption'. Supplementary Table 1 provides a summary of the demographic characteristics for each workshop. Due to the exploratory nature of this research, the aim was to recruit a diverse sample that although not fully representative of the local or national population, could provide a rich and meaningful dataset regarding public perceptions around resource efficiency strategies with some level of generalisability and transferability[43]. Although exact composition was influenced by variance in final attendance, participants were recruited to achieve a gender balanced group that ensures a broad range of attendees in terms of age, ethnic background and social status. Classifications of social status are adopted from widely used market research based demographic classifications[44] that use an individual's income and occupation to place them on a scale from A-E: ABC1 represents a spectrum of middle class professionals, whilst C2DE is equated with working class participants (ranging from skilled workers to those currently unemployed). Unfortunately it was not possible to recruit participants from socio-economic class A due to their relative infrequency and more common disinterest in participation.

Workshop protocol: The deliberative workshops were designed to provide a social space for participants to debate ideas and opinions in a way that remained as true to 'normal' conversation as possible. As such, a range of activities were developed, aimed at eliciting both personal reflection surrounding current consumption practices and informed engagement with new ideas, services and products for reducing future material use (see Supplementary Methods 1 for full workshop protocol). Utilising a series of six 'Scenarios for a low material future' the primary focus of data collection was through two activities (the findings of which are reported within this paper) that explored a range of resource efficiency strategies and the implications they may have for future consumption practices. The scenarios were developed following a series of expert interviews that aimed to examine the intersection of resource efficiency strategies with everyday life. This led to the identification of six key areas of everyday life that might require rethinking for a low material future, and included: products, business, ownership, community, waste and lifestyles. For each scenario a set of resources was created, comprising a vignette and poster (see Supplementary Methods 2). These scenarios were not envisaged as distinct or diverging futures, but rather as different aspects of a low material future, which could be employed individually or simultaneously.

Dominating the first day of the workshop, the first of these activities entailed a series of small group discussion based around the scenario vignettes. These took the form of 'a day in your life' stories, which walked participants through an average day for each scenario (due to time constraints participants each explored four of the six scenarios), and aimed to encourage participants to imagine how their everyday life would change under the scenario and how they would feel about that. Following the reconvening of the workshops for a second day (designed in part to allow participants to reflect upon and discuss with others the first day's content) the poster activity was designed to remind participants of various resource efficiency strategies and provide an opportunity for group reflection on their pros and cons. The six A0 posters were placed around the room and participants were given time to read these, and asked to mark broadly how positive they felt towards each strategy (using coloured stickers – green for positive, yellow for neutral, red for negative). The group then came back together to discuss each of the posters in turn, focusing on which strategies they would find most acceptable (both personally and for society more generally).

Workshop data analysis: All discussions were recorded using audio and/or video recording devices. These recordings were then professionally transcribed, before being checked for accuracy by the research team and then anonymised to remove names and any other identifying features of the discussions. The dataset was coded within the NVivo qualitative analysis software package, using a grounded approach to analysis derived from grounded theory[45-48]. This allowed a coding framework to be developed that, rather than being prescribed prior to the analysis, was grounded within the data. First open-coding is used to generate codes at different levels of theoretical complexity (from simple descriptions to conceptual categories), between which constant comparison is made to ensure good 'fit' with the data. These codes are then (re)grouped within broader and more theoretically relevant meta-codes that reflect emerging thoughts, insights and concepts.

The classification of public responses to a range of resource efficiency strategies from positive to negative (see Table 3) was an interpretive process that utilised data from both the qualitative discussions and the poster activity. The qualitative data was assessed on the basis of the dominant themes emerging from the discourse surrounding each of the scenarios, the public acceptability of each strategy was assessed in relation to a) the salience of responses occurring consistently through all workshops, and b) the strength of feeling surrounding such responses (e.g., where participants strongly articulated that strategies 'must' be adopted). Data from the poster task (coloured dots red/yellow/green) were also considered as part of this process. However, due to different approaches to the activity taken by different participants (e.g., use of more/less/different coloured dots to make different points) the data from this activity cannot be used quantitatively as a measure of public acceptability.

Methodological innovation: In addition to demonstrating the potential carbon savings from a range of resource efficiency strategies and highlighting the value of utilising existing deliberative methodologies in exploring the complex implications of such strategies for everyday life, our study represents a first step in bringing social and technical research together in an attempt to explore energy system transitions more holistically. To do this, a key challenge was in designing and conducting the two analyses at a scale that was both meaningful for each separate analysis, but also comparable between the deliberative and modelling based datasets. For the IOA modelling, the analysis was necessarily at a generic level, focusing on the broad categories of *Efficient products*, *Product sharing,* and *Product lifetimes*. Due to the aggregation of products into 106 groups, results at the product level would be misleading, and in the IOA model we therefore focused on the potential of currently niche strategies to be upscaled across a broad range of product categories. In contrast, for the deliberative workshops, presenting participants with the overarching strategies alone would not have led to meaningful insights. Concrete examples of new products, services and business models were thus needed to illustrate each strategy and help participants to engage with the implications of each strategy for everyday life.

Highlighting the fact that what can be easily modelled does not always match with what can be easily discussed, there was therefore not a 1:1 correspondence between the model strategies and the deliberative scenarios. To address this discrepancy, our approach was to design a series of broad scenarios that matched with the modelled strategies. Each scenario then made use of a range of appropriate concrete examples (as described in Table 1) that were carefully chosen to illustrate the diversity of possible options, whilst still remaining coherent within the strategy. The Rethinking products scenario represented *Efficient products*; in this scenario the examples chosen cohered well, both conceptually and in terms of the implications they have for everyday life and behaviours. The Rethinking community scenario represented *Product sharing*; here the implications of sharing as a concept gave coherence to the examples, despite some differences between the practical implications of different options (e.g., between peer-to-peer and business-to-consumer based sharing).

Two scenarios, Rethinking business (focusing on extended producer responsibility) and Rethinking ownership (focusing on a service-based economy), represented *Product lifetimes*. Whilst these scenarios both focus on new business models that aim to extend product lifetimes, the decision was taken to split these in two because of the significant differences in the way this is achieved, both conceptually and in relation to the implications they have for behaviour and everyday life. It was not possible to disaggregate *Product lifetimes* within the IOA model and so we decided to retain the overall strategy, but to ensure that when discussing our deliberative findings we present them in a way that ensures the differences between responses to the two scenarios are highlighted and accounted for. Overall, the strength of our multi-disciplinary analysis is demonstrated in the fact that despite varying in salience on a product by product basis (due to the specifics of any given product, service or business model), a clear set of social values was identified as common across the strategies.

Ethical review statement: Prior to convening the workshops, informed consent was obtained from all participants in line with the Cardiff University, School of Psychology Ethics Committee. No individual identifiers are reported in any phase of the research and pseudonyms have been used throughout this article.

Data availability: The UK MRIO raw data cannot be made publicly available as it makes use of protected data from the Office of National Statistics (ONS). We calculate greenhouse gas footprints using the MRIO model and have provided the greenhouse gas emissions results in Supplementary Data 1, sheet B. Assumptions on the ambition and adoption rate of the material productivity strategies are provided in Supplementary Data 1, sheet C, and the emissions savings are given in Supplementary Data, sheet D. We will consider requests to share the MRIO tables (for research purposes only) on a case-by-case basis. In relation to the workshops, the audio files and transcripts cannot be made publicly available due to the need to respect participant confidentiality. However, we will consider requests to share the anonymised transcripts (for research purposes only) on a case-by-case basis after an embargo of two years, during which time our analysis continues. Any other data is available from the corresponding author upon reasonable request. The demographic data and deliberative workshop protocol and materials are available in Supplementary Table 1 and Supplementary Methods 1 and 2. Images have been redacted for copyright reasons.

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Author contributions

Conceptualisation of research, C.C., K.S., J.B. and N.P.; Quantitative modelling design and methodology, K.S and J.B.; Quantitative modelling analyses, K.S; Qualitative workshop design and methodology, C.C. and N.P; Qualitative data analyses, C.C.; Writing - original draft, C.C. and K.S.; Writing – review and editing, C.C., K.S., J.B. and N.P.; Funding acquisition, J.B. and N.P.

Competing interests

The Authors declare no competing interests.

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