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1 Public acceptance of resource efficiency strategies to mitigate climate change

2

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9

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

23 Current mitigation measures are failing to achieve the speed and scale of emissions reductions
24 needed to remain within the 2°C limit for dangerous climate change¹. A consumption-based
25 emissions accounting perspective can increase the scope of mitigation policy^{2,3}, which currently
26 focuses primarily on emissions directly produced within a country's territory (see Supplementary
27 Note 1 that describes the different accounting approaches). The consumption of materials and
28 products represents an increasing driver of carbon emissions, with 25% of global emissions
29 produced through industrial processes, which end up embodied in buildings, infrastructure,
30 vehicles, electronics, clothing and household goods⁴. Global resource use has increased eight-fold
31 over the twentieth-century⁵, making resource efficiency improvements a necessary precondition
32 for achieving global climate mitigation goals⁶⁻¹¹ and meeting the series of increasingly challenging
33 carbon budgets set out within the UK's Climate Change Act 2008. Household consumption
34 accounts for 80% of the UK carbon footprint (727 MtCO₂e). Nationally, 80% of carbon emissions
35 and 75% of materials consumed by residents (based on the model developed by Owen *et al.*¹²) are
36 embodied in just 25% of product groups consumed in the UK. A step change is thus needed to
37 reduce the industrial carbon emissions associated with material-intensive manufactured goods e.g.,
38 clothing, packaging, electronics, appliances, vehicles, and buildings.

39 Targeting these key product groups, one way to reduce material consumption is to successfully
40 implement resource efficiency strategies¹³ that enable products and services to be designed, used,
41 and delivered in new ways. Research has identified a range of strategies (grouped into three
42 categories - *Efficient products*, *Product sharing*, and *Product lifetimes* - see Table 1) that advocate shifting

43 towards a more circular, resource efficient economy. However, whilst these strategies are
 44 beginning to move up the policy agenda^{2,7,14,15}, they are rarely considered seriously as effective or
 45 mainstream climate policy responses. Whilst the degree to which consumption practices would
 46 need to change varies for each strategy, it is clear that their implementation is likely to reshape
 47 everyday life in unexpected ways. These innovative ways of producing and consuming materials,
 48 products and services are thus unlikely to be adopted successfully without public support.

49 **Table 1.** Summary of material efficiency strategies.

| | <i>Description</i> | <i>Examples</i> |
|----------------------------------|--|--|
| <i>Efficient products</i> | 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 |
| <i>Product sharing</i> | 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 |
| <i>Product lifetimes</i> | Strategies that increase product longevity by extending and optimising the useful lifetimes of products. | Extended producer responsibility Remanufacturing Product service systems |

50

51 Dominant techno-economic analyses of climate mitigation options are often criticised for narrowly
 52 representing the public as rational economic actors, making implicit assumptions about people’s
 53 beliefs, behaviours and social practices¹⁶. Modelling from the UK¹⁷ and USA¹⁸ suggests that the
 54 human component of demand reduction scenarios can be significant, achieving major emissions
 55 savings in developed nations through altered lifestyles. However, decades of research shows that
 56 theoretically achievable demand reductions are rarely achieved¹⁹ because assumptions about
 57 human behaviour prove partly or wholly unrealistic²⁰. Public perspectives must be considered
 58 within debates surrounding the transition towards a resource efficient economy, opening up a
 59 conversation surrounding the preconditions underpinning the public acceptability of different
 60 strategies. Research on public attitudes to future energy system change has highlighted the
 61 importance of considering wider citizen discourses, perspectives and values in developing climate
 62 policy. Key factors that determine broader public acceptability of energy system changes (efficiency
 63 and waste avoidance; reliability, affordability and availability of supply; improved product/service
 64 provision; and environmental protection)²¹ may be relevant to the public acceptability of resource
 65 efficiency strategies.

66 The indeterminate nature of public acceptability adds an additional layer of uncertainty for policy
 67 makers and industry²² beyond the techno-economic uncertainties usually considered in national
 68 energy scenarios. As such, the importance of engaging both publics and stakeholders with energy
 69 system change is now recognised as an explicit policy goal^{23,24}, especially in cases where policy

70 challenges do not have a single solution and affect the majority of the population. For instance,
71 the failure of the UK's Green Deal (a flagship home energy efficiency policy instigated in 2012)
72 was ascribed to a lack of understanding of the public reaction to a policy that required the uptake
73 of long-term, conditional loans and (often) significant household disruption as low carbon
74 technologies were installed²⁵. Cutting across most economic sectors and Government
75 departments, the issue of resource efficiency is particularly complex and evidence regarding public
76 acceptability of resource efficiency strategies will be essential before firm policy recommendations
77 can be made.

78 We combine analyses of the technical emissions reductions potential and the public acceptability
79 of resource efficiency strategies, to explore the potential role of such strategies in reducing the
80 UK's carbon footprint. We first quantify potential emissions savings for different strategies using
81 input-output analysis (IOA). IOA traces how sector-based emissions flow through complex
82 international supply chains and become embodied in the final consumption of products²⁶. We
83 quantify the emissions reduction potential of reducing demand for common household materials
84 and products (clothing and textiles; packaging; vehicles; electronics and appliances; furniture;
85 leisure equipment; construction) by intermediate and end-use sectors in the UK economy. We use
86 case study evidence to assess the range of impacts for each strategy on the basis of two different
87 variables: material ambition (the level of material reduction across different strategies using case
88 study evidence) and adoption (uptake by intermediate and final consumers to reduce material and
89 product use)(see Methods).

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

99 **Emissions reductions from resource efficiency strategies**

100 Figure 1 shows the range of greenhouse gas emission reductions across the three strategies
101 according to the IOA (see Methods). *Product lifetimes* and *Efficient products* have the largest potential
102 to reduce emissions (around 13 MtCO₂e each). Considering *Product lifetimes*, any reductions in final
103 demand for cars, clothes, furniture etc. will reduce the full materials supply chain emissions
104 associated with mining, manufacture and distribution. *Efficient products* only reduced emissions
105 associated with certain material inputs, not the demand for the products themselves, therefore
106 addressing only a proportion of embodied emissions. However, light-weighting is deemed more
107 feasible than increasing longevity for a greater range of products e.g., packaging, industrial
108 equipment and construction activities. Fewer products are deemed to have the potential to be
109 shared and/or used more intensively (in comparison to the ability to increase their longevity) and
110 as such the mitigation potential of *Product sharing* is lower (saving up to 7 MtCO₂e), e.g., electronics
111 identified with higher sharing potential were those used less frequently in households, such as
112 power tools and hoovers, not computers, mobiles and washing machines. Demand for some

113 products, such as cars, can be reduced across all strategies, e.g., cars can be redesigned (using less
 114 metal), can be used more intensively (through car clubs), or can be used longer before replacement.
 115 See Supplementary Note 2 for how we account for the emissions savings without double counting.

116

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

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

129 **Table 2:** Impact of material ambition and adoption on emissions savings (ktCO_{2e}).

| | <i>Efficient products</i> | | | <i>Product sharing</i> | | | <i>Product lifetimes</i> | | | |
|--------------------------|----------------------------|-------|--------|------------------------|-------|-------|--------------------------|-------|--------|-------|
| | Level of Material ambition | | | | | | | | | |
| | low | med | high | low | med | high | low | med | High | |
| <i>Level of Adoption</i> | 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 | |

130

131 Combined, the emissions savings (3-29 MtCO_{2e}) could reduce the UK's current household carbon
 132 footprint (727 MtCO_{2e}) between 0.4-4%, and the embodied emissions of our products of focus
 133 (75 MtCO_{2e}) between 4-39% (see Supplementary Data 1, sheet G). This is equivalent to up to 19%
 134 of UK GHGs emitted directly by UK households (151 MtCO_{2e} is emitted from home heating and
 135 private transport). The list of strategies is not exhaustive, however we have focused on available
 136 case studies from the literature. Cumulatively, 0.2-1.6 MtCO_{2e} would be reduced within the UK,
 137 compared to 3-27 MtCO_{2e} outside the UK. Whilst this would contribute to meeting UK carbon
 138 budgets, of which there is a shortfall given proposed and planned energy-dominated climate
 139 policies, adoption of our strategies will also lessen emissions pressures in countries outside the
 140 UK. Such an approach better satisfies the principles of the UNFCCC's common but differentiated
 141 responsibility and respective capabilities (CBDR-RC) as a means to allocate responsibility for
 142 climate mitigation to countries with very different historical and socio-economic profiles. See
 143 Supplementary Note 3 for a summary of this debate and motivations for reducing the UK's
 144 embodied emissions.

145 **Public acceptability of material efficiency strategies**

146 We now explore the public acceptability of proposed resource efficiency strategies, drawing on
 147 data from workshops with members of the UK public that deliberated on a range of strategies
 148 including the three analysed here (see Methods). Building on previous research, our analysis has
 149 demonstrated that there are strong public preferences and conditions surrounding transitioning
 150 towards a low-carbon, sustainable future that transcend any one technology or issue space²¹.
 151 Participants showed strong support for many of the policies and new business models discussed
 152 across all three resource efficiency strategies. Key meta-values surrounding environmental
 153 protection, avoiding waste, supporting jobs and a strong economy are clearly demonstrated as non-
 154 negotiable elements of any transition towards a more resource efficient economy. Table 3
 155 highlights overall responses to the strategies, and the recurring conditions of public acceptance
 156 that might facilitate or limit public uptake. Where appropriate, quotations from individuals are
 157 reported to illustrate the broad themes discussed by multiple participants across the workshops.

158 **Table 3:** Public acceptability of resource efficiency strategies.

| | <i>Overall public reception</i> | <i>Conditions of acceptance</i> |
|---------------------------|---|---|
| <i>Efficient products</i> | ++ + Product light-weighting + Modular and repairable design ++ Reduced/recyclable packaging | Policies/initiatives should focus on maintaining: <ul style="list-style-type: none"> • Affordable range of products and services • Product safety and quality guarantees |
| <i>Product sharing</i> | + + Reusing vehicles and products +/- Sharing of vehicles and products + Library of things | Policies/initiatives should focus on maintaining: <ul style="list-style-type: none"> • Trust between peers, organisers and businesses • Product safety, quality and hygiene • Affordable and convenient access to products |
| <i>Product lifetimes</i> | +/- ++ Extended producer responsibility + Remanufacturing - Product service systems | Policies/initiatives should focus on maintaining: <ul style="list-style-type: none"> • Trust between businesses and consumers • Fair and upfront distribution of responsibility • Long-term affordability (avoiding lock-in) |

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

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

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

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

195 **Conditions that underpin public preferences**

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

199 **Trust:** A strong distrust of other actors, particularly business, dominated discussion across all three
200 strategies. Only one objection was raised for *Efficient products*: that modularity may be used to
201 greenwash current business practices and increase rather than decrease sales. In contrast, trust was

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

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

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

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

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

257 **Discussion**

258 Highlighting the as yet untapped potential of resource efficiency measures to mitigate climate
259 change, our analysis of the IOA model results identifies potential carbon savings from resource
260 efficiency strategies of 3-29 MtCO₂e. We show that the carbon footprint of a range of common
261 household products (including clothing, footwear and textiles; packaging; vehicles; electronics and
262 appliances; furniture; leisure equipment; and construction) could be reduced by as much as 39%
263 in the UK, with each of the three resource efficiency strategies making a contribution to achieving
264 such carbon savings. To highlight points of congruence (where adoption rates are more likely to
265 coincide with high impact strategies) and dissonance (where progress may be more difficult to
266 achieve) between the technical and social potential of resource efficiency strategies, we then
267 assessed the public acceptability of these strategies. Issues of trust, responsibility and fairness,
268 affordability and convenience, and safety and hygiene, were found to be crucial determinants of
269 wider public acceptability.

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

284 In contrast, achieving the potential emissions reductions identified for *Product lifetimes* and *Product*
285 *sharing* may require greater ambition due to the more complex approach required. With the options
286 for achieving the reductions these strategies promise more varied, public acceptability is more
287 contingent on the case by case elements of each business or policy proposition. Approval was

288 often dependent on perceptions of new business models and the implications they might have for
289 personal consumption practices, with convenience, affordability, safety and hygiene all playing a
290 role in public acceptance. However, for both strategies, the strongest concerns surrounded issues
291 of trust in business and the fair and upfront distribution of responsibility, dampening public
292 acceptability and suggesting the need for an approach which aims to build trust through
293 transparency and accountability of business practices. Where such issues play a key role in public
294 concerns and ambivalence, we suggest focusing on developing stronger consumer rights packages
295 (through regulation and/or voluntary guarantees) to encourage confidence in new business models
296 and the novel relationships they require between businesses and their customers. Additionally, the
297 currently niche idea of a 'library of things' was very positively received. Providing funding and
298 support at the local authority and/or community level for the development of such activities may
299 help to encourage sharing more widely.

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

310 Beyond these more institutional issues, the static IOA model (where economic monetary
311 transactions is a proxy for material and product flows) does not consider how prices may change
312 within the economy, or the impact this may have on individual spending. It is therefore not clear
313 what effect policies supporting resource efficiency strategies would have on product costs or
314 household disposable income. It is possible that, while providing a potential revenue-generating
315 stream, less material intensive products could increase overall demand²⁹. There is also the
316 possibility of positive or negative spillover effects³⁰. Increased disposable income could lead to
317 unpredictable rebound effects³¹, with emissions savings possibly offset by additional money spent
318 on carbon intensive products/services. However, the economic benefits of resource efficiency
319 could offset the near term costs of an ambitious low carbon pathway, creating much needed low
320 carbon investment. These issues could not be considered in this paper due to the broad focus of
321 our analysis on wider resource efficiency strategies; future work should aim to understand the
322 implications of specific resource efficiency policies from a range of technical, financial and policy
323 perspectives.

324 From a social science perspective, the next steps could be to provide a deeper analysis of specific
325 resource efficiency strategies, individually assessing public acceptability, perceptions and practices
326 with both general publics and those already participating in such schemes. Our approach (perhaps
327 with additional quantitative surveys that provide more representative assessment of public
328 acceptability) should now be used to explore different resource efficiency strategies in more detail
329 and at the disaggregated level of specific products or policies. It would then be possible to use
330 public acceptability data as a model input, allowing for the exploration of the potential carbon

331 reductions from resource efficiency (and wider energy) policies at a granular level and teasing out
332 key issues and trade-offs that can support the development of specific policy recommendations.
333 Another direction for future research would be the development of interactive tools to engage
334 participants with trade-offs surrounding embodied and direct emissions at both a personal and
335 societal level (c.f., ref²¹). Combined, this approach could then be used to explore the public
336 acceptability of resource efficiency strategies in non-UK contexts.

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

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416

417 **Methods**

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

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

456 The UK multi-region input-output (MRIO)³² was used to calculate the emissions embodied in the
 457 consumption of goods and services by UK households for 2013 (see Supplementary Data 1, sheet
 458 B), the latest year available at the time of study. Goods and services are classified by 106 sectors
 459 according to the UK Standard Industrial Classification system³³ and we aggregate the global
 460 economy into a two region model of the UK and the Rest of the World (RoW) reflecting how the
 461 UK trades in goods and services. Embodied emissions are calculated using the standard Leontief
 462 demand-pull model³⁴. GHGs emitted directly by sectors in producer countries (simplified in our
 463 model to the UK and a RoW region) are reallocated to final consumers, in our case UK
 464 households, by following products through multiple trade and transformation steps using equation
 465 (1):

$$466 \quad (1) \quad \mathbf{Q} = \mathbf{f} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}_{UK\ hh}$$

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

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

$$488 \quad (2) \mathbf{V}_{\text{strategy}} = \mathbf{Q} - \mathbf{Q}^0$$

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

$$492 \quad (3) \mathbf{Q}^0 = \mathbf{f} (\mathbf{I} - \mathbf{A}^0)^{-1} \mathbf{y}_{UK\ hh}$$

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

$$495 \quad (4) \mathbf{Q}^0 = \mathbf{f} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{y}_{UK\ hh}^0$$

496 We did not model changes to the GHG efficiency of production sectors (\mathbf{f}).

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

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

$$505 \quad (5) \mathbf{a}_{ij}^0 = \mathbf{a}_{ij} * \left(1 - (\mathbf{m}_{ij}^s \mathbf{c}_{ij}^s)\right)$$

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

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

514
$$(6) \mathbf{y}_{ij\ hh}^0 = \mathbf{y}_{ij} * \left(1 - (\mathbf{m}_{ij}^s \mathbf{c}_{ij}^s)\right)$$

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

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

523 We chose not to model the rebound effect, where cost savings from reduced demand are re-spent
524 on additional products³⁶, as we do not presuppose that the pricing structures will not change as a
525 result of the implementation of the demand reduction strategies, however, this would add an
526 additional layer of uncertainty. Each case study was modelled in isolation then aggregated into 3
527 overarching strategies to avoid double counting.

528 **Methods for exploring public acceptance:** Aiming to explore the public acceptability of a range
529 of different strategies for reducing consumption based energy use by members of the public, the
530 research involved conducting deliberative work with members of the public, to explore the future
531 of consumption and the different implications these proposed strategies and business models may
532 have for everyday life. Deliberative workshops were chosen as the most appropriate method, as
533 they provide 1) an open space (both in terms of time and location) for participants to explore and
534 engage with issues and ideas that they may be unfamiliar with and 2) allow for critical and reflexive
535 discussion surrounding such issues. The workshops utilised established methods for engaging the
536 public with science and technology topics³⁷ that have been successful in exploring a range of
537 different energy related technologies³⁸⁻⁴¹, as well as public perceptions of whole-scale energy system
538 transitions⁴².

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

553 There are no standard rules determining the size and composition of deliberative workshops. In
554 total, 51 participants took part (N=11-14 per workshop). Recruitment was conducted by a neutral

555 third party company, and was topic blind, with participants only aware they would be taking part
556 in a workshop entitled ‘Exploring the future of consumption’. Supplementary Table 1 provides a
557 summary of the demographic characteristics for each workshop. Due to the exploratory nature of
558 this research, the aim was to recruit a diverse sample that although not fully representative of the
559 local or national population, could provide a rich and meaningful dataset regarding public
560 perceptions around resource efficiency strategies with some level of generalisability and
561 transferability⁴³. Although exact composition was influenced by variance in final attendance,
562 participants were recruited to achieve a gender balanced group that ensures a broad range of
563 attendees in terms of age, ethnic background and social status. Classifications of social status are
564 adopted from widely used market research based demographic classifications⁴⁴ that use an
565 individual’s income and occupation to place them on a scale from A-E: ABC1 represents a
566 spectrum of middle class professionals, whilst C2DE is equated with working class participants
567 (ranging from skilled workers to those currently unemployed). Unfortunately it was not possible
568 to recruit participants from socio-economic class A due to their relative infrequency and more
569 common disinterest in participation.

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

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

599 **Workshop data analysis:** All discussions were recorded using audio and/or video recording
600 devices. These recordings were then professionally transcribed, before being checked for accuracy
601 by the research team and then anonymised to remove names and any other identifying features of
602 the discussions. The dataset was coded within the NVivo qualitative analysis software package,
603 using a grounded approach to analysis derived from grounded theory⁴⁵⁻⁴⁸. This allowed a coding
604 framework to be developed that, rather than being prescribed prior to the analysis, was grounded
605 within the data. First open-coding is used to generate codes at different levels of theoretical
606 complexity (from simple descriptions to conceptual categories), between which constant
607 comparison is made to ensure good ‘fit’ with the data. These codes are then (re)grouped within
608 broader and more theoretically relevant meta-codes that reflect emerging thoughts, insights and
609 concepts.

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

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

636 Highlighting the fact that what can be easily modelled does not always match with what can be
637 easily discussed, there was therefore not a 1:1 correspondence between the model strategies and
638 the deliberative scenarios. To address this discrepancy, our approach was to design a series of
639 broad scenarios that matched with the modelled strategies. Each scenario then made use of a range
640 of appropriate concrete examples (as described in Table 1) that were carefully chosen to illustrate
641 the diversity of possible options, whilst still remaining coherent within the strategy. The Rethinking

642 products scenario represented *Efficient products*; in this scenario the examples chosen cohered well,
643 both conceptually and in terms of the implications they have for everyday life and behaviours. The
644 Rethinking community scenario represented *Product sharing*; here the implications of sharing as a
645 concept gave coherence to the examples, despite some differences between the practical
646 implications of different options (e.g., between peer-to-peer and business-to-consumer based
647 sharing).

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

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

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

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712

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722 **Author contributions**

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724 methodology, K.S and J.B.; Quantitative modelling analyses, K.S; Qualitative workshop design and
725 methodology, C.C. and N.P; Qualitative data analyses, C.C.; Writing - original draft, C.C. and K.S.;
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727 **Competing interests**

728 The Authors declare no competing interests.

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