

Beyond Ownership: Sufficiency and inequality shape product-sharing's sustainability potential

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Abstract

Moving beyond ownership models does not necessarily benefit the environment: outcomes depend on which consumers change consumption habits, which practices they adopt and the conditions under which they do so. We couple a dynamic general equilibrium model with material-flow analysis and behavioural modelling of lifestyle dynamics to assess product-service systems (PSS) in Japan. We examine twelve combinations of lifestyle drivers and enabling-infrastructure settings, with lifestyle drivers characterised by cognitions, behaviours and contexts. We show that environmental footprints fall when higher-income groups reduce ownership through sufficiency but rise when they continue consuming through ownership. Because PSS becomes more costly relative to ownership as wages rise, enabling infrastructure alone does not shift households away from ownership. A trilemma emerges: no combination simultaneously delivers environmental benefits, equitable energy-service access and welfare equity. Making access-based consumption environmentally beneficial therefore requires attention to both the distribution of behavioural change and the relative cost of PSS.

Keywords: Circular Economy, Demand-side Mitigation, Sustainable Consumption, Just Transition, Integrated Assessment

We live in a culture of ownership. The desire for the newest products, accelerated by technological change, drives up material use, waste and CO₂ emissions^{1,2}. Yet, habits of buying, owning and replacing before things wear out undermine the circular economy's (CE) environmental potential. Demand-side CE strategies³⁻⁵ that change how people access, use and own goods, and potentially slow resource loops⁶⁻⁸, are therefore needed to reduce these environmental impacts. Product-service systems (PSS), in which consumers access services (e.g., mobility, clean clothes) rather than owning the products that deliver them, are gaining attention⁹⁻¹². However, moving from ownership to access does not necessarily reduce environmental impacts. Two consumption practices are particularly relevant to moving beyond ownership: sharing, which shifts how energy services are provided, and sufficiency, which reduces demand for energy-using goods. These practices may therefore have different environmental consequences depending on consumers' lifestyles and the availability of infrastructure enabling their adoption.

Lifestyle barriers to PSS include status and materialistic orientation⁸, which sustain high carbon footprints and increase inequality¹³⁻¹⁶. Even those who care about the environment can buy more than they need, letting material desires override their green intentions^{17,18}. Others lack agency or knowledge to change how they consume, slowing the adoption of sustainable consumption habits¹⁹⁻²². These behaviours are shaped by material and social contexts^{21,23}, including infrastructure²⁴, urban morphology and regulations^{21,25-28}. Limited access to infrastructure can particularly constrain lower-income groups, who often have fewer affordable, low-carbon options^{23,24}. These differences raise a broader question for demand-side CE strategies: how do lifestyle dynamics and enabling infrastructure shape the environmental and distributional consequences of moving beyond ownership? It remains unclear whether alternatives to ownership lead consumers towards less resource-intensive consumption or reinforce existing differences in consumption practices.

Enabling infrastructure may amplify lifestyle dynamics rather than simply facilitate access-based consumption. Whether broader access reduces inequality or reinforces it depends on who is willing and able to substitute market-provided services for ownership. Although

lifestyle barriers and infrastructure have been studied as determinants of PSS adoption, their interaction in shaping environmental and distributional outcomes remains poorly understood.

We address this question with a stylised dynamic general equilibrium model integrating material-flow analysis (MFA) with behavioural modelling of lifestyle characteristics (Fig. 1b), namely cognitions, behaviours and contexts^{14,21} (see Methods, *Modelling Framework*). Households belong to three lifestyle groups differing in these characteristics and can engage in two circular practices: sharing, which shifts the provision of energy services from household-owned goods towards market-provided services, and sufficiency, which reduces purchases of energy-using goods. For each practice, the Ecoactive driver strengthens low-carbon cognitions among higher- and medium-income lifestyle groups, whereas the Affordability driver captures greater engagement among lower-income groups motivated by budget constraints (context). We consider four combinations: both practices Ecoactive-driven, both Affordability-driven, Ecoactive-driven sharing and Affordability-driven sufficiency, and Affordability-driven sharing and Ecoactive-driven sufficiency (Fig. 1; see Methods, *Lifestyle drivers and infrastructure enablement*). Motivated by evidence of positive behavioural spillovers between pro-environmental practices²⁹, the same-driver combinations represent conditions for aligned engagement, whereas the mixed-driver combinations allow engagement to diverge without assuming positive spillovers. Engagement in each practice is calibrated from the LIFE model²¹ and evolves endogenously through lifestyle–economic feedback. Combining the four lifestyle-driver combinations with three infrastructure-enablement settings gives twelve scenarios.

Infrastructure enablement governs households' ability to substitute market-provided energy services for services produced through ownership of energy-using goods. In practice, this depends on conditions such as the availability of car-sharing stations, the digital skills and payment methods required for PSS platforms, and service locations. We represent these conditions through the substitution elasticity between these options. 'Current enablement' reflects Japan's present infrastructure, with low substitution^{30–32} and slightly higher substitution for higher-income groups, who live in denser, better-connected areas where PSS is more available. 'Broad' and 'Concentrated' reach higher substitution by 2050, respectively extending access to lower-income groups or concentrating it among higher-income groups (Fig. 1a).

All scenarios are compared with a reference SSP2 run for Japan (population decline; energy prices and energy efficiency from the model WITCH³³, Supplementary Figure 1) without lifestyle heterogeneity and with low infrastructure enablement. In this reference, engagement in circular practices is driven by relative prices and budget constraints. This isolates the environmental and distributional effects of lifestyle dynamics and shows how outcomes differ when lifestyle mechanisms are endogenous rather than when social and behavioural processes are treated as exogenous^{34,35}.

We use Japan because of its developing sharing market^{30–32} and related policy frameworks (2025 Environment White Paper and METI's CE Vision), and because national household survey data are available on non-ownership engagement^{20,30,32} (see Methods, *Context*). The PSS market remains small: in 2018, it accounted for 5.8% of household spending on energy services, about US\$ 17 billion or 0.34% of GDP in our calibration, close to the Ministry of Economy, Trade and Industry's (METI) estimate of 0.4% for the sharing economy.

We show that moving beyond ownership is not a sustainability strategy in itself: its environmental and distributional outcomes depend on which groups change consumption, which practices they adopt and how relative costs evolve. Higher-income groups' sufficiency drives environmental benefits, whereas sharing alone does not necessarily reduce environmental footprints. Enabling infrastructure amplifies existing behavioural tendencies rather than determining shifts away from ownership, particularly as market-provided energy services become more expensive relative to home production. Finally, greater equality in energy-service access does not necessarily improve welfare equity, revealing a trade-off

Results

Enabling infrastructure amplifies rather than determines shifts away from ownership.

The effort to reduce ownership (Refuse, Fig. 2a,b) is highest among those practising sufficiency, whereas the pull towards ownership strengthens for disengaging groups: lower-income groups under Ecoactive, and medium- and higher-income groups under Affordability. As wages and labour productivity grow under SSP2, the provision of energy services from the PSS market becomes more expensive relative to home production because labour costs are explicitly priced in market provision, whereas household labour used in home production is not remunerated. This relative cost effect is largest for the disengaging lifestyle group, reaching 43% for lower-income groups under Ecoactive and 25% for higher-income groups under Affordability (Supplementary Figure 2). Infrastructure enablement changes how strongly lifestyle groups respond to this price signal rather than determining its direction. More enabling infrastructure (Broad and Concentrated enablement) amplifies each group's existing tendency: it strengthens the shift towards ownership among disengaging groups (lower-income group in Ecoactive and higher-income groups in Affordability) and weakens the shift towards PSS among groups practising sufficiency (Refuse and Rethink, Fig. 2b,c). The effect depends on the level rather than the distribution of enablement: the lower-income group's Refuse response rises by 6.7 p.p. from Current to either higher-enablement setting but differs by only 0.03 p.p. between Broad and Concentrated. The shift towards PSS energy services peaks between 2030 and 2035 (Rethink, Fig. 2c) under Broad and Concentrated enablement before reversing, whereas it continues to rise through 2050 under Current.

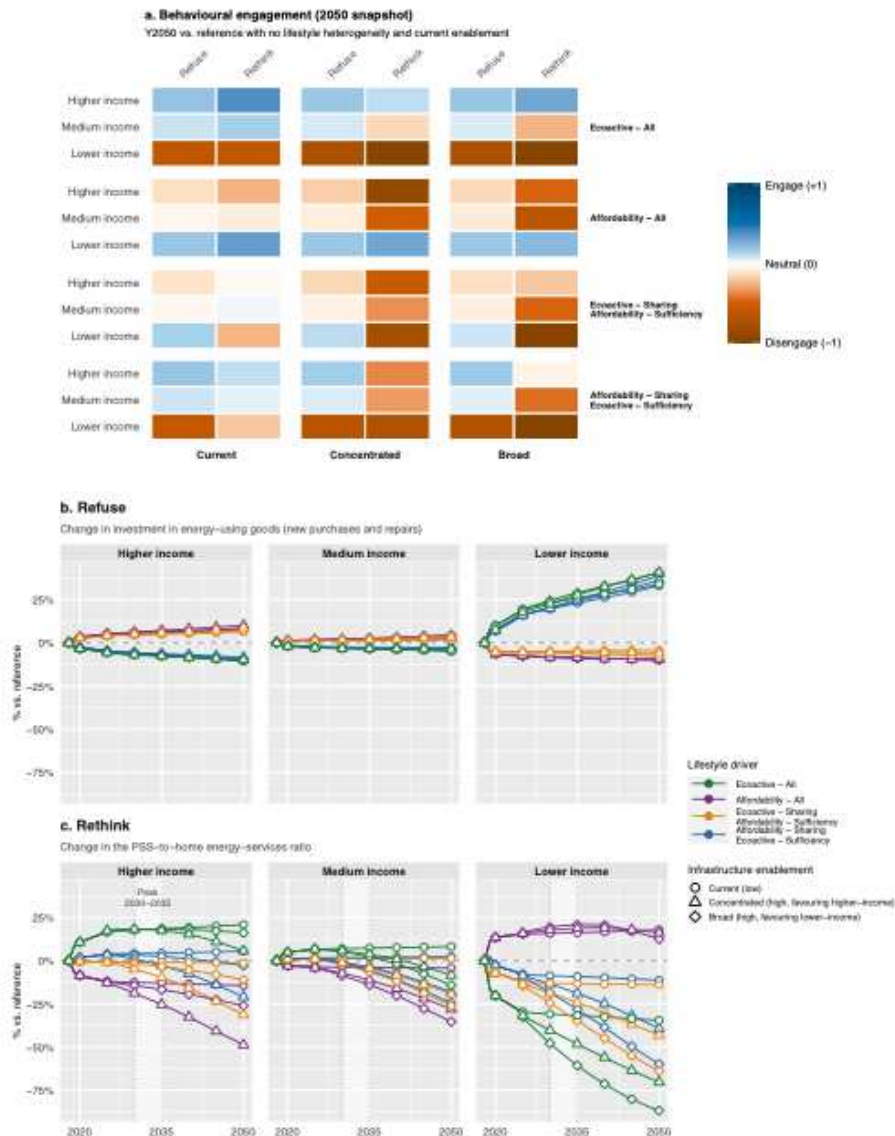


Figure 2 | Behavioural engagement across lifestyle groups. (a) Behavioural engagement, 2050 snapshot. Refuse is the change in total investment in energy-using goods (new purchases plus repairs), with a reduction counted as positive engagement in sufficiency. Rethink is the change in the market-to-home energy-service consumption ratio, where a shift towards market (non-ownership) energy services counts as engagement. Blue indicates engagement, red disengagement, white no change. Behavioural engagement in Rethink and Refuse is expressed as a percentage change relative to the Reference, and the values are normalised to the 95th percentile of absolute values and bounded to $[-1, 1]$ for the colour scale. According to the colour scale, lifestyle groups never reach full engagement in circular consumption activities, but they can fully disengage. (b) shows the change in energy-using goods purchases compared to the Reference. (c) shows the change in the market-to-home energy-service consumption ratio. Source: CIRCEE-LIFE runs.

Behavioural shifts have limited effects on households' environmental footprints.

Across scenarios, carbon footprints change by no more than 3% in either direction, and waste and material footprints change by less than 1% (Fig. 3a). Sharing does not necessarily reduce footprints, whereas sufficiency can: footprints fall when higher- and medium-income groups adopt sufficiency but rise when lower-income groups adopt it (Fig. 3a). These changes are limited because most household carbon footprints arise from direct energy use associated with

ownership models rather than from the goods and services targeted by Refuse and Rethink. Direct energy use accounts for around nine-tenths of the total carbon footprint for lower-income groups, compared with less than half for higher-income groups (Fig. 3b). Even when Refuse and Rethink change significantly, the resulting change in direct energy use is smaller than the behavioural shift itself. Relative prices further limit the environmental effect of these practices, as the price changes associated with PSS provision partly offset the behavioural shift towards reduced ownership.

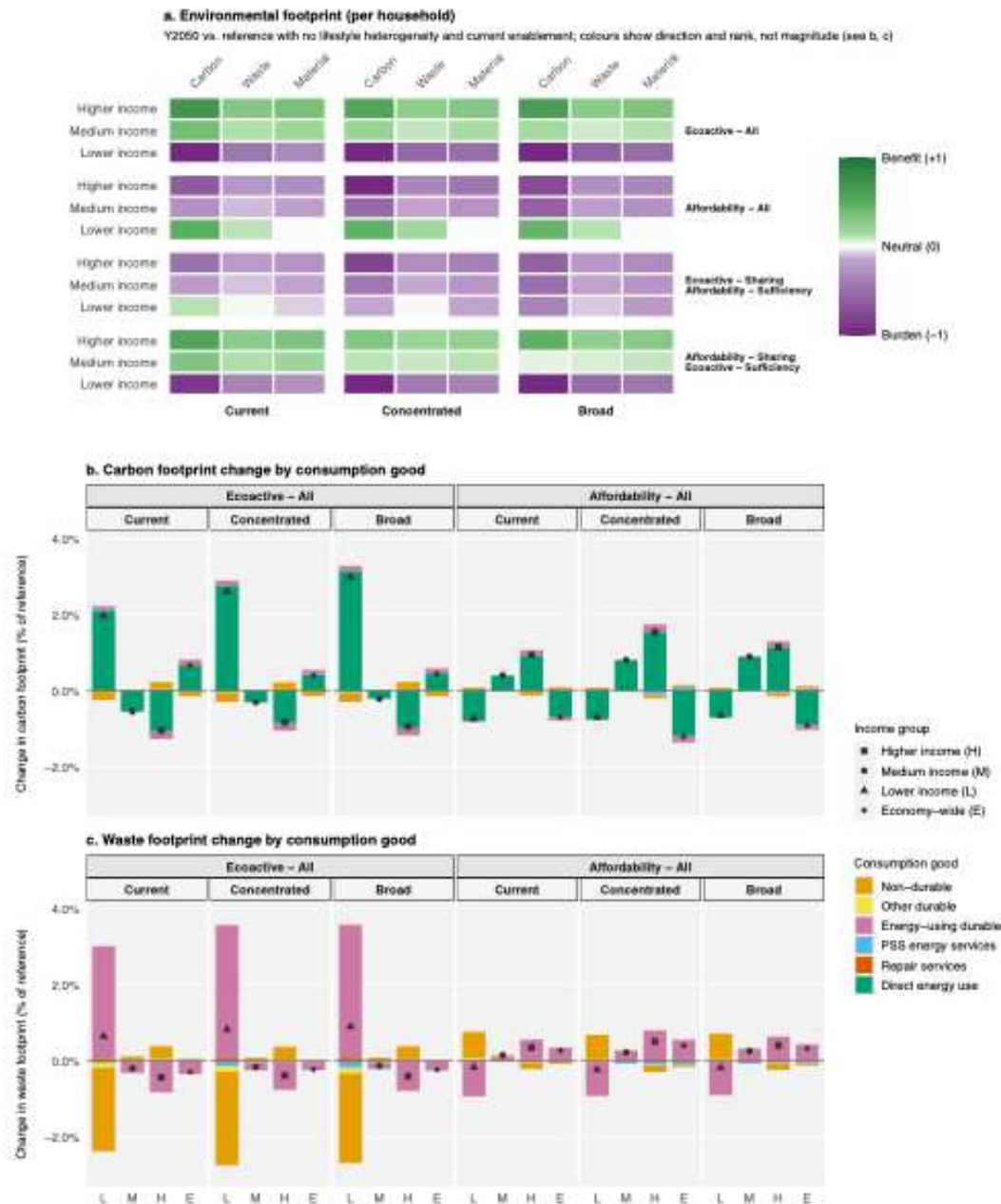


Figure 3 | Environmental footprints across lifestyle groups. (a) shows per-household carbon, waste and material footprints. Reductions are shown as green and increases are shown as purple. Carbon footprints do not include the carbon content of imported goods; they include only the carbon content of domestically produced goods. The footprints are expressed as a percentage change relative to the Reference, and the values are normalised to the 95th percentile of absolute values and bounded to [-1, 1] for the colour scale. (b) shows the change in carbon footprints by consumption good vs. the Reference (per household, 2050). (c) shows the change in waste footprints by consumption good vs. the Reference

(per household, 2050). Results for mixed-driver scenarios are omitted because they are similar to those of Ecoactive-All and Affordability-All (see Supplementary Figure 3). Source: CIRCEE-LIFE runs.

Macro-level environmental gains depend on who reduces consumption.

Whether engagement in sharing is driven by budget constraints or low-carbon cognitions makes little difference to macro-level material flows, waste flows, or cumulative CO₂ emissions. The Ecoactive-sharing/Affordability-sufficiency scenario tracks Affordability-All, and Affordability-sharing/Ecoactive-sufficiency tracks Ecoactive-All (Fig. 4a–c). Instead, environmental outcomes depend on which lifestyle groups practise sufficiency: material and waste flows fall under Ecoactive, when higher- and medium-income groups practise sufficiency, but rise under Affordability, when higher-income groups continue consuming.

The largest behavioural effects in material flows occur for energy-using goods in relative terms, falling by around 3% from the Reference under Ecoactive (Fig. 4a). Capital goods show the largest absolute change, falling by 1.7 Mt under Ecoactive and rising by 1.8 Mt under Affordability, or 0.2% of the respective baseline, following energy-using goods demand. Waste flows decrease for industrial waste and energy-using goods under Ecoactive and increase under Affordability (Fig. 4b). The small economy-wide change in non-durable goods waste also masks different household-level responses: lower-income groups reduce non-durable consumption to finance ownership, whereas higher-income groups show little change.

Cumulative CO₂ emissions are driven primarily by household energy use and only marginally by incineration (Fig. 4c), consistent with the household-level results above. Enabling infrastructure amplifies these existing directions rather than changing them: because the disengaging group responds most strongly to the price signal, more enabling infrastructure moves macro-level environmental outcomes towards higher emissions under both lifestyle drivers. Relative to the Reference, the largest reduction under Ecoactive occurs with the least enabling infrastructure (–96 Mt at Current vs –82 Mt at Broad), whereas under Affordability the increase grows from +102 Mt under Current to +114 Mt under Broad and +133 Mt under Concentrated.

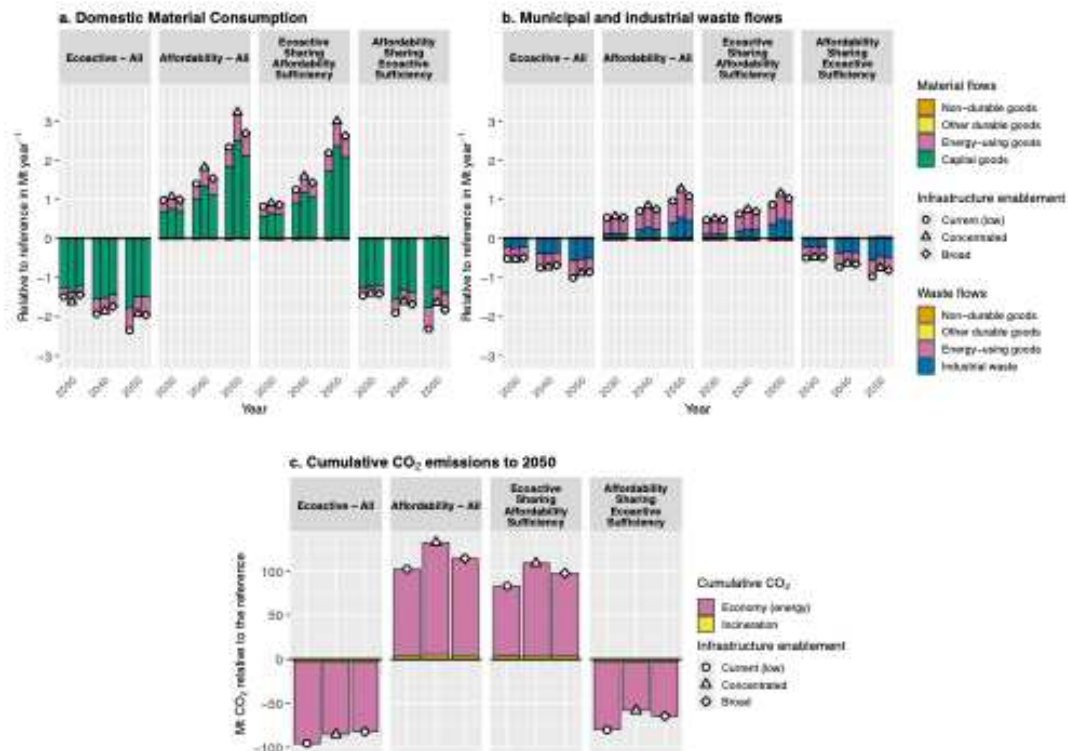


Figure 4 | Economy-wide material flows and cumulative CO₂ emissions relative to the Reference. (a) shows changes in domestic material consumption (DMC). (b) shows changes in municipal and industrial waste flows. (c) shows changes in cumulative CO₂ emissions over 2018–2050. Source: CIRCEE-LIFE runs.

A trilemma emerges between environmental benefits, access equity and welfare equity.

Improved access to energy services does not translate into welfare gains for lower-income groups, because it can require reallocating expenditures away from other consumption goods and services. Under Ecoactive-All, higher-income groups reduce ownership and shift towards market-provided energy services, whereas lower-income groups, whose low-carbon cognitions are weak, expand ownership and use of energy-using goods at home (Supplementary Figure 4). As a result, the low-to-high energy-service consumption gap narrows by 7.8% at Current, as lower-income groups' energy-service access rises by 3.0% and access for the higher-income group falls by 4.5% (Fig. 5a). However, financing this additional ownership reduces lower-income groups' consumption of other goods and services by 2.0% and leads to a 3.2% loss of lifetime welfare (consumption-equivalent variation, CEV), their largest loss in any scenario. Thus, greater access can come at the expense of welfare when it is achieved through ownership.

Under Affordability-All, lower-income groups instead shift to non-ownership models in response to their budget constraints. Their share of energy services provided by the market rises to 6.2%, while the higher-income group's share falls from 5.0% to 4.5%. The energy-service consumption gap widens by 3.4%, their consumption increases by 0.7%, and their welfare improves by 0.75%. Higher-income groups' welfare is not significantly affected (−0.15% to +0.18%; Fig. 5b). Across all scenarios, the energy-service consumption gap and welfare equity can move in different directions.

The limited role of PSS in these shifts reflects its relative cost. In 2018, PSS accounts for 5.8% of all groups' spending on energy services, and in 2050, in the Reference scenario, this is 5.7% for lower-income groups and 5.0% for higher-income ones. Across scenarios, PSS accounts for between 1% and 6% of a group's energy services spending in 2050 (Supplementary Figure 5). Under Ecoactive-All, the lower-income share falls to 4.5% with

Current and under 1% with Broad enablement, as these households substitute towards ownership rather than PSS. Because PSS is labour-intensive (Methods, *equation (12)*), market provision becomes about 19% more expensive relative to home production by 2050. This price effect partly offsets lifestyle-driven shifts towards sharing, leaving PSS provision close to its present share across scenarios. Higher enablement therefore increases households' responsiveness to relative prices rather than their inclination towards PSS.

Taken together, the environmental, welfare and energy-service access objectives cannot all be achieved simultaneously (Fig. 5c). The sufficiency driver determines the direction of the environmental effect: carbon and waste footprints (Supplementary Figure 6) fall by 0.16 to 0.66% and 0.17 to 0.28% when sufficiency is cognition-driven and rise by 0.57 to 1.21% and 0.25 to 0.40% when it is context-driven. These environmental gains, however, coincide with wider welfare differences across lifestyle groups: the welfare spread ranges from 1.8 to 3.2 percentage points in cognition-driven scenarios, compared with 0.2 to 1.2 in context-driven scenarios. Conversely, the closest approach to equality of energy-service access (ratio of 0.99 under Affordability-Sharing with Ecoactive-Sufficiency) comes with a 1.9% lifetime welfare loss for lower-income groups. Ecoactive-All at Current illustrates the trade-off, combining the largest environmental footprint reduction (−0.66%) with the widest welfare spread (3.2 p.p.). Aggregate lifetime welfare falls by 0.52% under Ecoactive-All and rises by 0.18% under Affordability-All, although these aggregate changes mask distributional effects because lower-income groups account for only 13.7% of households in Japan. Sensitivity tests (Methods, *Sensitivity analysis*) preserve the direction of the main environmental and welfare effects, although their magnitude can increase.

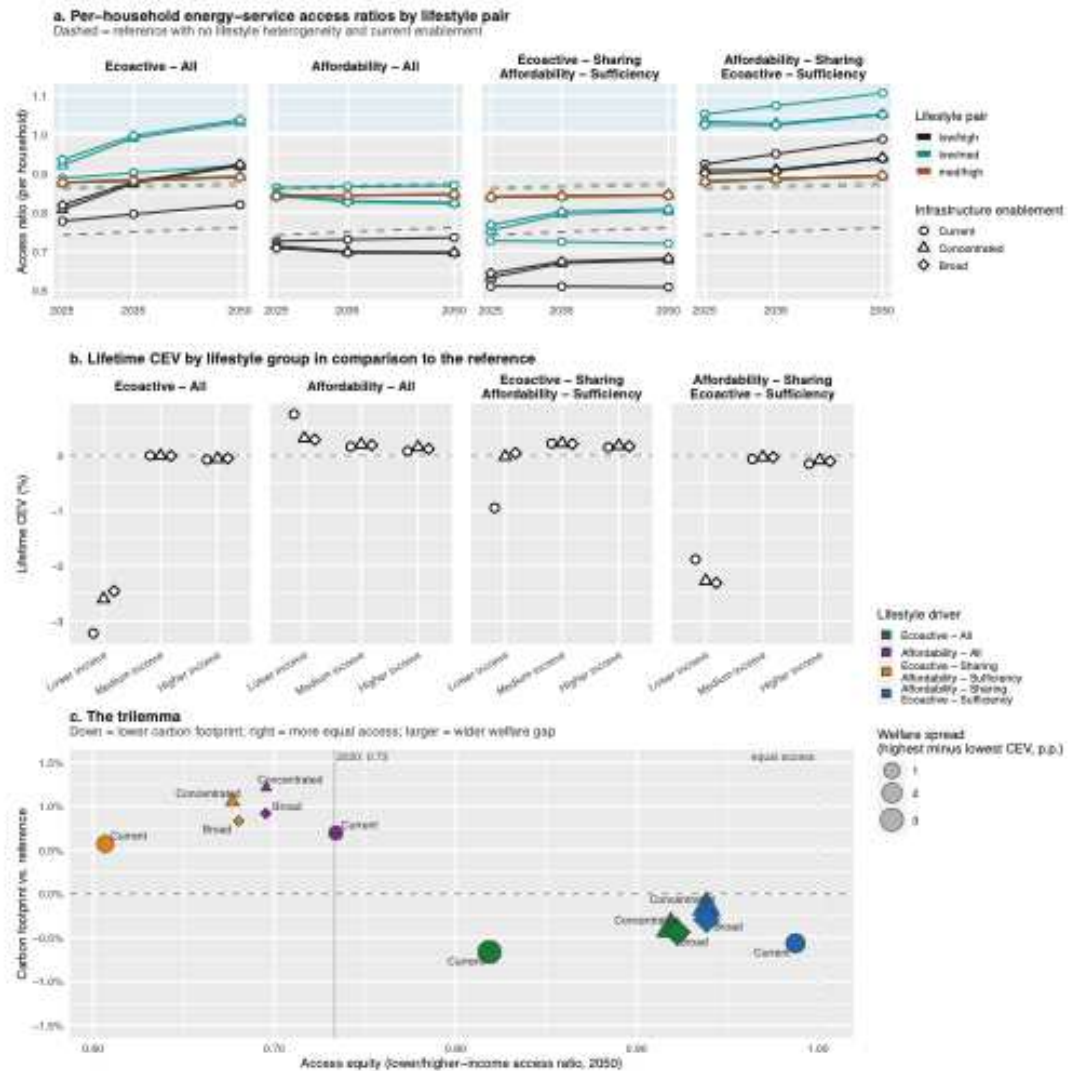


Figure 5 | Welfare and energy-service consumption inequality. (a) shows per-household energy-service consumption gap by group pair (lower-/higher-income, lower-/medium-income, medium-/higher-income). A value of 1 denotes parity between two lifestyle groups. A value below 1 indicates that the first group accesses less than the second. The dashed lines show the Reference, in which the gap between lower- and medium-income groups is higher than that of medium- and higher-income groups. (b) shows lifetime consumption-equivalent variation (CEV, %) by lifestyle group relative to the Reference. (c) shows the trilemma between carbon footprint, the energy-service consumption gap and welfare equity, measured as the welfare spread in lifetime CEV across groups. Each point represents one of the twelve scenarios in 2050. The x-axis represents the ratio of lower-income to higher-income group energy-service consumption, where 1.0 (dotted line) is equal access. The y-axis represents the economy-wide carbon footprint relative to the Reference; points below the dashed line show a reduction in footprint. The point size shows the welfare spread, i.e. the lifetime consumption-equivalent welfare change of the best-off lifestyle group minus that of the worst-off, in percentage points. A larger point means the scenario leaves the lifestyle groups further apart from each other. Colours represent lifestyle drivers, and shapes represent infrastructure enablement. Source: CIRCEE-LIFE runs.

Discussion

Our results show that moving beyond ownership is not a sustainability strategy in itself. Sharing changes how energy services are accessed, whereas environmental benefits depend mainly on which lifestyle group reduces ownership through sufficiency. Across the twelve scenarios, no single scenario simultaneously delivers environmental benefits, equitable energy-

service access and welfare equity. When higher- and medium-income groups adopt sufficiency, energy-service access becomes more equal and cumulative CO₂ emissions decrease, but the welfare gap between lower- and higher-income groups widens because lower-income groups gain access partly by increasing ownership and reallocating consumption away from other goods and services. Conversely, scenarios in which lower-income groups shift towards non-ownership models can improve their welfare while widening the energy-service consumption gap and increasing environmental footprints. These findings connect research on access-based consumption²⁷, demand-side mitigation and well-being²⁸, inequality and low-carbon behaviours⁴¹, and the links between service provision, material cycles and environmental impacts³⁷ by showing that environmental, access and welfare outcomes can move in different directions when lifestyle and economic dynamics interact.

Improving access to energy services therefore does not automatically translate into fairer welfare outcomes for the groups gaining access. Lower-income groups can narrow the consumption gap by purchasing more energy-using goods, but the associated expenditure reduces their consumption of other goods and services and lifetime welfare. In contrast, when budget constraints lead these households towards non-ownership models, their welfare improves but the energy-service consumption gap widens. Access and welfare equity should therefore be treated as distinct distributional outcomes rather than interchangeable measures of equity.

We also show that enabling infrastructure does not determine which lifestyle group moves away from ownership. Instead, it amplifies the behavioural tendencies already associated with each lifestyle group. More enabling infrastructure increases the responsiveness of households to relative prices between ownership and PSS, but the direction of the response remains determined by the lifestyle characteristics. Because energy services provided by the PSS market become relatively more expensive than home production as wages and labour productivity increase, greater responsiveness of households can reinforce a shift towards ownership among disengaging lifestyle groups rather than towards PSS. This cost disadvantage is consistent with the type of service-sector cost dynamics described by Baumol⁴². Within the infrastructure settings tested here, the aggregate level of enablement matters more than its distribution. Infrastructure availability alone therefore does not induce behavioural change: its effectiveness depends on whether households exposed to it are willing and able to change their consumption practices⁴³.

Responses to infrastructure differ across lifestyle groups. Medium-income groups may disengage from both sharing and sufficiency because weaker low-carbon cognitions and lower agency compared with higher-income groups leave them less able to act on their intentions^{21,41}. Higher-income groups can retain ownership despite strong low-carbon cognitions when materialistic orientation influences their choices^{17,18}. Infrastructure therefore does not guarantee spillovers between circular practices. This is consistent with evidence that pro-environmental spillover onto actual behaviour can be weak²⁹. Because ownership carries different status implications across lifestyle groups^{13,14}, access-based consumption does not necessarily facilitate the expected shift from owning to sharing^{7,8}.

These differences are central to the environmental effectiveness of consumer-focused CE strategies. Higher-income groups have larger consumption and environmental footprints, so macro-level environmental outcomes improve when these groups reduce ownership through sufficiency. By contrast, reducing consumption among lower-income groups does not necessarily lower aggregate footprints and can impose welfare costs when households increase ownership to secure energy services. This highlights two gaps in demand-side mitigation. First, lifestyles that do not benefit climate action remain understudied. In our findings, when circular practices are driven by affordability, higher-income groups' continued ownership can offset environmental improvements associated with lower-income groups' adoption of circular practices. Second, lifestyle changes among higher-income groups need more attention because

their larger environmental footprints give their behaviour greater environmental leverage. Progress on reducing material footprints and decoupling resource use from economic activity (SDGs 8.4 and 12.2), reducing waste (SDG 12.5) and advancing climate action (SDG 13) therefore depends on which lifestyle group reduces consumption, and why. This also highlights the need to distinguish energy-service access (SDG 7.1) from welfare and inequality outcomes (SDG 10). These findings support calls for demand-side CE strategies^{3,4} and highlight gaps in understanding lifestyle change²².

These results also distinguish sharing from sufficiency as demand-side consumer CE strategies. Sufficiency acts directly on the number of energy-using goods purchased. Sharing does not necessarily reduce these purchases: households can obtain the same level of energy services through the market while continuing to own energy-using goods. The environmental potential of sharing is further constrained by the relative cost of PSS, whose labour requirement contributes to a cost disadvantage compared with home production as wages and labour productivity increase. Sharing and sufficiency are therefore not environmentally equivalent in our scenarios, consistent with concerns that PSS may not automatically decouple access to value from ownership¹¹ and with previous findings that sharing-economy models can increase rather than reduce consumption^{44,45}. The limited magnitude of these environmental effects indicates that access-based consumption is not equivalent to reducing resource demand and should be understood as complementary to, rather than a substitute for, energy-system decarbonisation and energy efficiency.

Coupling lifestyle and economic dynamics has implications for climate-economy and CE modelling. Models imposing lifestyle change exogenously may miss how lifestyle characteristics affect consumers' consumption habits³⁴. In our scenarios, PSS outcomes depend on infrastructure, the relative costs of ownership and access-based services, low-carbon cognitions among higher-income groups and energy-service access for lower-income groups. Representing feedback between lifestyle dynamics, economic dynamics and material flows makes it possible to assess both environmental effects and their distribution across lifestyle groups. This addresses a broader modelling challenge: social and behavioural processes are often exogenous or studied separately, despite their environmental and distributional implications^{22,34–36,38}.

Our results suggest two broad policy lessons. First, increasing the availability of non-ownership consumption options is unlikely to be enough if their relative cost remains unattractive to consumers. This availability can actually strengthen the pull towards ownership rather than weaken it, for the very lifestyle group the policy is targeting. The mechanisms identified here point to policy levers, including measures that reduce the relative cost of PSS services, such as subsidies, especially for lower-income groups that are motivated by budget constraints, or increase the relative cost of ownership, such as ownership taxes. The effectiveness of such measures will depend on how different lifestyle groups respond to the resulting price changes. Second, policies seeking environmental benefits through sufficiency need to consider which groups consume most and where reductions in consumption occur, rather than assuming all lifestyle groups can engage in sufficiency equally. The results also caution against treating sufficiency as environmentally beneficial independently of distributional outcomes. Asking households that already consume relatively little to reduce consumption further may yield smaller aggregate environmental gains than reducing consumption among higher-income groups, while potentially imposing larger welfare costs on lower-income groups. Policy design should therefore distinguish between expanding access to energy services, improving welfare and reducing carbon- and resource-intensive consumption, rather than assuming moving beyond ownership can achieve all three objectives simultaneously.

There are three main limits to our analysis. We treat PSS as a competitive sector, leaving out network externalities and spatial frictions that would concentrate its benefits in

dense, higher-income areas⁴⁶. The three lifestyle groups aggregate within-group heterogeneity, which can mask distributional dynamics. Finally, the results are conditioned on Japan's high-income, ageing and service-dominated economy: whether the same trilemma arises in other high-income contexts will depend on wage growth, service-sector productivity, household production and informal sharing practices. These and further limits are discussed in Methods.

Methods

Definitions

Product-sharing Product-Service Systems. We define product-sharing PSS as a result-oriented business model in which the energy-service provider retains ownership of energy-using goods and provides services to multiple users, who pay for the outcome delivered rather than owning the goods that deliver an outcome, such as travel from point A to B^{11,39}. The provider controls how goods are used, which can reduce underuse and premature replacement. We focus on result-oriented product-sharing PSS models because provider revenues depend on delivering the function/result of the product rather than transferring ownership of the product itself, which can create stronger incentives for durability and resource efficiency than product- or user-oriented variants^{47,48}. We focus on services provided by energy-using goods, given their lifecycle resource and carbon intensity. Goods are suitable for PSS if they meet certain conditions, such as being long-lasting. While not all energy-using consumer goods are suitable for product-sharing PSS (e.g., refrigerators)⁴⁸, to keep our model traceable and stylised, we consider a single good that aggregates all energy-using goods categories (vehicles, home appliances, personal electronics, dwelling equipment such as heating systems) present in national statistics.

Lifestyles. Lifestyles are defined here as the interplay between cognitions and behaviours within specific material and social contexts²¹ in relation to households' access to non-ownership models. Cognition enhances individuals' motivation to adopt low-carbon behaviours (as in the 'Ecoactive' driver described in the CIRCEE-LIFE coupling section below), context shapes the relationship between motivation and behaviour and can act as an enabler (as in the 'Affordability' driver for the lower-income group described in the CIRCEE-LIFE coupling section below) or as a barrier (as in the 'Ecoactive' driver for the lower-income group), and lifestyle dynamics expand the range of low-carbon and circular consumption activities individuals engage in. We focus on two consumption activities related to non-ownership models: sufficiency and sharing. We frame "sufficiency" as refusing to own energy-using goods by reducing purchases. We frame "sharing" as adopting service-based consumption, where households purchase energy services from a product-sharing PSS market instead of owning the means of producing energy services at home.

These lifestyle groups are empirically derived through hierarchical cluster analysis of national household survey data and represent stylised behavioural archetypes in the model rather than representations of homogeneous populations. Significant heterogeneity may exist within each group. The results therefore reflect the mechanisms associated with the modelled lifestyle characteristics rather than income deciles themselves.

Propensity is the strength of a lifestyle group's engagement in a given low-carbon practice, measured in LIFE as a mean centroid score from 0 (weak) to 1 (strong) across avoid, shift and improve behaviours. Propensity values are homogeneous in LIFE across circular activities: the propensities are a property of the driver, not the behaviour. They indicate the strength of each lifestyle group's Ecoactive or Affordability motivation. A behavioural modifier is the parameter in CIRCEE that shifts a group's preference between two options (e.g., owning vs renting a good) and is calibrated so that the group's engagement in 2020 reproduces the ratio of its propensity to the population mean (refer to *CIRCEE-LIFE coupling* below). It is a multiplicative adjustment to a group's preference for a given practice.

Infrastructure enablement. We define it as the interconnected digital, physical and institutional infrastructure that allows households to access energy services without owning energy-using goods. We represent infrastructure enablement through settings that vary the

elasticity of substitution between energy services produced “at home”, from ownership models, and energy services purchased “at the market”, from non-ownership models, i.e., from a product-sharing PSS firm in our context. In our modelling framework, a highly enabling infrastructure reflects a higher elasticity of substitution between PSS market and home energy services, enabling a switch between ownership and non-ownership models. Conversely, less enabling infrastructure is represented by a lower elasticity of substitution (close to 1), which makes switching between these models more difficult. This representation of infrastructure affects only the ease with which households substitute market-provided energy services for home production. It does not directly impose a shift away from ownership.

Energy-service access represents differences in access across lifestyle groups through their per-group energy-service consumption. Because PSS affects access to market-provided energy services, we assess access as an indicator of material well-being. This choice is motivated by the decent living standards literature⁴⁹, which emphasises access to essential energy services as a dimension of material well-being, although our representation of energy-service access is specific to the model. The energy-service consumption ratio is defined as energy services consumed by the lower-income group relative to the higher-income group; a ratio of 1 indicates equal energy-service consumption between the two groups.

Context

Japan provides an empirical setting where policy ambition for service-provisioning systems exists, consumer awareness and intentions are well established and growing, and infrastructure contexts are in transition. It also provides detailed material-flow accounts, national statistics and consumer surveys (Greendex from National Geographic Society, World Values Survey and other national household surveys) that allow calibration of the model at the required level of aggregation.

Japan’s policy framework provides an institutional basis for sufficiency and sharing behaviours. The 2025 Environment White Paper, METI’s Circular Economy Vision, the Japan Partnership for Circular Economy, and the 2012 Act on Promotion of Consumer Education, which aims to foster sufficiency behaviours and extend product lifespans, together establish the institutional basis for non-ownership models, while the documented diversity of circular business models across automotive and clothing sectors^{30,31} confirms that service-provisioning systems are developing in Japan.

Three features of the Japanese context directly inform our conceptual framework, described hereafter. First, consumer survey evidence reveals a gap between awareness and adoption of sharing (as a non-ownership model) behaviours: PwC Japan⁵⁰ records sharing economy service awareness at 49.9% but actual engagement at only 21.6%, motivating the “Affordability” lifestyle driver in which low-carbon cognitions do not translate into action. Second, surveys by Dentsu⁵¹ show awareness of sharing at 40.7% and sufficiency at 54%, with intentions to incorporate sufficiency into daily life at almost 50%, driven primarily by environmental concerns, which we reflect in the “Ecoactive” lifestyle driver. Third, Japan’s infrastructure presents structural barriers to PSS adoption, including a well-developed public transport network that reduces incentives for mobility PSS, a historically cash-based payment infrastructure, which represents a digital infrastructure barrier to platform-based service provisioning, and a high score on Hofstede’s Uncertainty Avoidance Index (92 out of 100), motivating our sensitivity analysis, in which we vary substitution elasticities across lifestyle groups. Even where access-based services exist for home appliances, consumers often revert to ownership at the end of trial periods⁵², reinforcing the need to test the sensitivity of the model to the infrastructure contexts under which PSS can durably replace ownership. In the automotive sector, a survey by Mitsubishi UFJ Research and Consulting for the Consumer Affairs Agency³² finds that 27.7% of car owners considered abandoning ownership after using non-ownership models, with satisfaction rates among product-sharing car-sharing users approaching 100%, suggesting that barriers to wider adoption may lie beyond users’ experience of service quality, including awareness and infrastructure conditions. The report that 63.7% of people adopted product-sharing car-sharing post-2020 further indicates that infrastructure

contexts are beginning to shift, consistent with the dynamic evolution of substitution elasticity in Broad and Concentrated enablement settings.

Energy-using goods differ in how intensively households use them in Japan. Refrigerators run continuously, while heating and air-conditioning systems are fixed to dwellings. Cars, washing machines and cooking appliances, by contrast, hold 31% of the household stock of energy-using goods and are in use under 4% of the time, against an average of 16% for the whole stock (Supplementary Table 2). We calibrate the PSS sector from data on cars and washing machines, which together hold 14% of the household stock and are the two goods for which business-to-consumer providers report use rates. The Ministry of Economy, Trade and Industry's survey (2020) of the sharing economy identifies them as the principal shared goods in Japan, alongside money and skills⁵³. The model is therefore calibrated on the energy-using goods through which PSS currently operates.

Modelling framework

All the equations presented here are in simplified form for clarity. The detailed model is available in the open-access code.

Model inputs and outputs. CIRCEE-LIFE separates what is calibrated or assumed (the inputs) from what emerges from solving the coupled system. *Inputs* include the behavioural preference parameters (calibrated identically across lifestyle groups), the substitution elasticity between home- and market-provided energy services (calibrated per lifestyle driver, see *Lifestyle drivers and infrastructure enablement*), the SSP2 energy price and efficiency trajectory from WITCH, and household population shares (Supplementary Table 1). *Outputs* include the behavioural modifiers governing the engagement in sharing and sufficiency decisions, which emerge from the iterative LIFE-CIRCEE coupling rather than being imposed directly, all prices, and all downstream quantities reported in Results.

The CIRCEE-LIFE model⁵⁴ is a stylised dynamic general equilibrium model with resource stock and flow consistency designed to assess circular economy strategies. It is coupled with the LIFE model²¹ and has a one-way link to the IAM WITCH³³ (Supplementary Figure 7). CIRCEE-LIFE incorporates microeconomic foundations and consumer lifestyle and income heterogeneity that drive the behaviours of economic agents, as well as industrial ecology concepts. The model's dynamic, forward-looking nature allows consumers to consider current and future costs when deciding whether to own energy-using goods. Although CIRCEE can accommodate different Shared Socioeconomic Pathway (SSP) narratives, CIRCEE-LIFE runs SSP2 only because LIFE is calibrated on SSP2.

Consumption structure. We model how consumers shift from ownership models through lifestyle dynamics. Product-sharing PSS enables households to move away from ownership models through two reinforcing channels: (i) a direct substitution effect (energy services from a PSS market replace ownership) and (ii) an indirect sufficiency effect (less ownership reduces energy-using good expenditures and thus ownership). Both are enabled by infrastructure in place that supports PSS. Lifestyles and income differ among the three lifestyle (household) groups:

- *Higher-income groups* exhibit stronger low-carbon cognitions and more enabling material and social contexts (e.g., supportive social networks) than other lifestyle groups, leading them to intentionally engage in sharing and sufficiency when their low-carbon cognitions are strengthened. They have a younger age profile than other lifestyle groups and interact more strongly with technology and related social systems, which are both necessary to accelerate the transformation towards a low-carbon lifestyle⁵⁵. They correspond to the 'Resourceful' and 'Active' consumer clusters of LIFE²¹.
- *Lower-income groups* exhibit weak low-carbon cognitions, less enabling material and social contexts, and a strong need to save money (material context), which leads them to engage in sharing and sufficiency unintentionally when low-carbon cognitions do not drive the behaviours of households in the model. The literature has shown that lower-income groups benefit from and engage most in the sharing economy⁵⁶. They correspond to the 'Constrained' consumer cluster of LIFE²¹.

- *Medium-income groups* exhibit weaker low-carbon cognitions than higher-income groups but stronger than lower-income groups. They also exhibit higher perceived behavioural control, lower agency and moderate enabling material and social contexts compared to the higher-income group, which makes them less empowered. They have the youngest age profile, have lower levels of education than the higher-income group and have fewer children but reside in slightly larger households (e.g., extended families with elderly dependents or shared professional households) compared to other lifestyle groups. In terms of access/use of digital technologies, they are similar in profile to the higher-income group. They correspond to the ‘Cautious’ consumer cluster of LIFE²¹.

We model the three lifestyle groups as distinct optimising agents, each maximising lifetime utility subject to a budget constraint. Households derive utility from the consumption of energy services, durable goods other than energy-using goods (e.g., furniture and clothing), and non-durable goods (e.g., food and packaging). The heterogeneity in sharing and sufficiency engagement across lifestyle groups is captured by group-specific behavioural propensity modifiers that operate on households’ continuous variable choices.

Utility depends on current consumption relative to a habit stock, the accumulated standard of living from past behaviour, capturing the tendency to maintain consumption patterns over time⁵⁷. In the case of sharing consumption patterns, these habits are dependent on past consumption patterns and on materialism⁴⁰:

$$\begin{aligned} \max_{U_{i,t}} \quad & \sum_{t=2018}^{2050} \beta^t U_{i,t} \quad (1) \\ \text{s.t. } U_{i,t} = \quad & \frac{(C_{i,t} - h_{i,t} C_{i,t-1})^{1 - \frac{1}{\sigma^{ies}}}}{1 - \frac{1}{\sigma^{ies}}} \quad (2) \end{aligned}$$

$$\text{s.t. } Revenues_t = Expenses_t \quad (3)$$

where β^t is the discount factor, $U_{i,t}$ is utility in time t for lifestyle group i , $C_{i,t}$ is the nested consumption aggregator, $h_{i,t}$ is the habit consumption persistence parameter, and σ^{ies} is the intertemporal elasticity of substitution, which is a measure of how willing people are to shift their spending or consumption over time.

The nested consumption aggregator is as follows:

$$C_{i,t} = \left[\alpha^{nes} (NES_{i,t})^{\frac{\sigma^c - 1}{\sigma^c}} + \alpha^{es} (ES_{i,t})^{\frac{\sigma^c - 1}{\sigma^c}} \right]^{\frac{\sigma^c}{\sigma^c - 1}} \quad (4)$$

where $(\alpha^{nes}, \alpha^{es})$ are distribution parameters, σ^c is the elasticity of substitution, $NES_{i,t}$ are non-energy services (non-durable goods and other durable goods), and $ES_{i,t}$ are energy services.

Households choose how much of their energy-service demand to satisfy through home production, $ES_{i,t}^{home}$, by owning energy-using goods and consuming efficient energy, and how much to purchase from a product-sharing PSS market, $ES_{i,t}^{market}$:

$$\begin{aligned}
& ES_{i,t} \\
& = \left\{ \alpha^{home} \left[\overbrace{\left(\alpha^{ed} (u_{i,t}^{lowuse} ED_{i,t}^{lowuse})^{\frac{\sigma^{home}-1}{\sigma^{home}}} + \alpha^{en} (EN_{i,t}^{lowuse})^{\frac{\sigma^{home}-1}{\sigma^{home}}} \right)^{\frac{\sigma^{home}}{\sigma^{home}-1}}}^{ES_{i,t}^{home}} \right]^{\frac{\sigma^{es}-1}{\sigma^{es}}} \right. \\
& \quad \left. + \left((1 - beh_{i,t}^{sharing}) \alpha^{market} \right) [ES_{i,t}^{market}]^{\frac{\sigma^{es}-1}{\sigma^{es}}} \right\}^{\left(\frac{\sigma^{es}}{\sigma^{es}-1} \right)} \quad (5)
\end{aligned}$$

where $(\alpha^{home}, \alpha^{ed}, \alpha^{en}, \alpha^{market})$ are distribution parameters, $(\sigma^{home}, \sigma^{es})$ are substitution parameters between energy-using goods and efficient energy in the home-produced energy-service bundle, and between home- and market-provided energy services in the energy-service bundle, which is the infrastructure measure in CIRCEE-LIFE, $u_{i,t}^{lowuse}$ is the use rate of “low-use” energy-using goods to produce energy services at “home”, $ED_{i,t}^{lowuse}$ is the stock of energy-using goods owned by households, $EN_{i,t}^{lowuse}$ is an energy bundle that aggregates efficient electricity and efficient non-electric energy, $beh_{i,t}^{sharing}$ is the behavioural modifier that increases (negative modifier in the model) or decreases (positive modifier in the model) the engagement in the product-sharing PSS market, $ES_{i,t}^{market}$ are energy services provided by the PSS sector. The behavioural modifier is a preference shift that governs the intratemporal substitution between energy services obtained from ownership and non-ownership models. Infrastructure improvements operate through the substitution elasticity σ^{es} , reducing the non-price frictions associated with accessing product-sharing PSS services independently of market prices.

The demand for PSS market-provided energy services equates marginal utility of market-provided energy services to the all-tax-included final price:

$$\Lambda_{i,t} \alpha^{es} \left(\frac{C_{i,t}}{ES_{i,t}} \right)^{\frac{1}{\sigma^{es}}} (1 - beh_{i,t}^{sharing}) \alpha^{market} \left(\frac{ES_{i,t}}{ES_{i,t}^{market}} \right)^{\frac{1}{\sigma^{es}}} = p_t^{pss} (1 + vat) \quad (6)$$

where $\Lambda_{i,t}$ is the marginal utility of consumption, $(\alpha^{es}, \alpha^{market})$ are distribution parameters, $p_t^{pss} (1 + vat)$ is all-tax-included price of energy services from the PSS market and $p_{i,t}^{home}$ is the all-tax-included price of producing energy services at home, which depends on the user cost and the use rate of energy-using goods, and the price of energy.

The decision to purchase energy-using goods is governed by a user cost equation in which the sufficiency modifier (a negative quantity when households engage in sufficiency and positive otherwise) acts as a perceived price wedge, raising the effective cost of ownership for households with stronger sufficiency lifestyles. This mechanism is similar to a psychological cost of ownership, such as environmental guilt or social norms. It also reflects how sufficiency is measured in the LIFE model: through a decrease in total expenditures. The decision equates the marginal benefit and (user) cost of purchasing one more unit of an energy-using good:

$$\frac{\partial U_{i,t}}{\partial ED_{i,t+1}^{lowuse}} = \frac{q_{i,t}^{new}}{\beta} \frac{p_{t+1}^{nd}}{p_t^{nd}} \frac{\lambda_{i,t}}{\lambda_{i,t+1}} - (q_{i,t+1}^{new} - q_{i,t+1}^{dep} \delta_{i,t+1}^{lowuse}) \quad (7)$$

where $\frac{\partial U_{i,t}}{\partial ED_{i,t+1}^{lowuse}} (= uc_{i,t})$ is the marginal benefit of owning one more unit of a “low-use” energy-using good in period (t+1) decided in period t, $q_{i,t}^{new}$ is the shadow price of an installed unit of a newly purchased energy-using good, $\frac{1}{\beta} \frac{p_{t+1}^{nd}}{p_t^{nd}} \frac{\lambda_{i,t}}{\lambda_{i,t-1}}$ is the household’s inverse stochastic discount factor in real terms, which captures how much additional satisfaction (utility) the household would gain from having one extra unit of income at one point in time, and $q_{i,t+1}^{dep} \delta_{i,t+1}^{lowuse}$ is the value recovered from the fraction of the energy-using good stock that depreciates in (t+1), valued at the shadow price on the depreciated margin. Because depreciated units can be replaced through repair and new purchases, they are valued at $q_{i,t+1}^{dep}$ rather than $q_{i,t+1}^{new}$.

$q_{i,t}^{new}$ equals the effective purchase price net of the sufficiency modifier when investment adjustment costs are zero and exceeds it when investment is rising. $q_{i,t}^{dep}$ is defined analogously. The two shadow prices differ whenever the cost of new purchases and that of repair diverge. $q_{i,t}^{new}$ satisfies the following equation:

$$(1 - beh_{i,t}^{sufficiency}) p_t^{ed} = q_{i,t}^{new} \left[1 - AC_{i,t} - \frac{\partial AC_{i,t}}{\partial Inv_{i,t}^{lowuse}} \right] + \beta \frac{p_t^{nd}}{p_{t+1}^{nd}} \frac{\lambda_{i,t+1}}{\lambda_{i,t}} q_{i,t+1}^{new} \quad (8)$$

where p_t^{ed} is the all-tax-included price of energy-using goods, $AC_{i,t}$ are the adjustment investment costs and $Inv_{i,t}^{lowuse}$ the investments in energy-using goods owned by households.

The depreciation rate is itself endogenous and households trade off using the good more intensively against wearing it out faster as follows:

$$\delta_{i,t}^{lowuse} = \delta_{i,t}^{lowuse} (u_{i,t}^{dep})^{\sigma^{dep}} \quad (9)$$

where $\delta_{i,t}^{lowuse}$ is a scaling factor, $u_{i,t}^{lowuse}$ the endogenous use rate of energy-using goods owned by households and σ^{dep} the sensitivity of the depreciation rate to the use rate. We assume that the depreciation rate of energy-using goods increases non-linearly with the use rate, $u_{i,t}^{lowuse}$, with the sensitivity parameter σ^{dep} . MFA models usually use a depreciation pattern for which physical wear and tear is not proportional to time alone but to intensity of use. They rely on non-linear, probabilistic depreciation profiles, such as Weibull functions⁵⁸⁻⁶⁰. Since we do not track the age distribution of energy-using goods in our model, as in MFA models, we assume that the depreciation rate is a non-linear function of the use rate and a scale parameter $\delta_{i,t}^{lowuse}$. We find that the calibrated value σ^{dep} exceeds unity (Supplementary Table 1), which generates a convex, increasing depreciation rate. Goods that are used more intensively therefore face higher physical wear. This is consistent with the increasing hazard regime of a Weibull distribution. The use rate of energy-using goods is determined endogenously by equating the marginal benefit of additional use against its marginal cost (the shadow value of the depreciation that use causes), which rises non-linearly with the use rate because physical wear accelerates with intensity of use:

$$uc_{i,t-1} = (1 - beh_{i,t}^{sufficiency}) p_{i,t}^{ed} \delta_{i,t}^{lowuse} \sigma^{dep} (u_{i,t}^{lowuse})^{\sigma^{dep}-1} \quad (10)$$

where $uc_{i,t-1}$ is the user cost of owned energy-using goods, $p_{i,t}^{ed}$ is the total cost (including all taxes) of “low-use” energy-using goods, multiplied by the depreciation of those goods caused by each additional unit of use time, $\delta_{i,t}^{lowuse} \sigma^{dep} (u_{i,t}^{lowuse})^{\sigma^{dep}-1}$. As a negative quantity, the sufficiency modifier lowers the shadow cost of the depreciation caused by use. Households practising sufficiency therefore use the goods they already own more intensively rather than replacing them. Sufficiency thus reduces new purchases while increasing use of the existing stock. The two margins work in opposite directions on end-of-life flows, and the net effect on disposal is a model outcome rather than an assumption.

Product-sharing PSS structure. We model the long-run dynamics of product-sharing PSS markets, where frictions, such as matching inefficiencies and transaction costs, have dissipated thanks to competition⁶¹. We model the energy-using goods stock used by product-

sharing PSS providers as perfectly and costlessly divisible: the benefits to providers depend on the total stock of energy-using goods they make available through the market, irrespective of whether that stock is rented in large or small units of time. Perfect divisibility is a stronger assumption for some goods than others: it is a reasonable approximation for washing machines, where service units are discrete and cleaning between uses is minimal, but involves more abstraction for cars. We include a per-unit maintenance cost parameter, which enters the service provider's optimisation and affects the equilibrium use rate and rental price. This cost is calibrated based on reports and literature on the share of maintenance and cleaning costs in total costs (Supplementary Table 1). The use rate evolves endogenously over time with relative prices and the depreciation schedule. It does not necessarily reach full utilisation. These assumptions are consistent with our focus on aggregate environmental and distributional outcomes rather than platform design or contract structure.

The product-sharing PSS sector combines labour, energy-using goods stock, and efficient energy to produce market energy services (Supplementary Figure 8):

$$Y_t^{pss} = \left\{ \alpha^l (A_t L_t^{pss})^{\frac{\sigma^{pss}-1}{\sigma^{pss}}} + \alpha^{es,pss} \left[\left(\alpha^{ed,pss} (u_t^{highuse} E D_t^{highuse})^{\frac{\sigma^{es,pss}-1}{\sigma^{es,pss}}} + \alpha^{en,pss} (E N_t^{highuse})^{\frac{\sigma^{es,pss}-1}{\sigma^{es,pss}}} \right)^{\frac{\sigma^{es,pss}}{\sigma^{es,pss}-1}} \right]^{\frac{\sigma^{pss}-1}{\sigma^{pss}}} \right\} \quad (11)$$

where $A_t L_t^{pss}$ is productive labour, $(\alpha^l, \alpha^{es,pss})$ are distribution parameters for labour and energy-service inputs, $(\alpha^{ed,pss}, \alpha^{en,pss})$ are distribution parameters for energy-using goods and efficient energy, $u_t^{highuse}$ is the use rate of “high-use” energy-using goods of the product-sharing PSS sector, $E D_t^{highuse}$ is the stock of “high-use” energy-using goods used by the product-sharing PSS sector, $E N_t^{highuse}$ is the volume of efficient energy used to produce energy services, and $(\sigma^{pss}, \sigma^{es,pss})$ are the substitution parameters between labour and energy-service inputs, and between energy-using goods and volume of efficient energy respectively.

The final price of market energy services provided by the PSS sector evolves endogenously according to:

$$p_t^{pss} = [(\alpha^l)^{\sigma^{pss}} (w_t)^{1-\sigma^{pss}} + (\alpha^{es,pss})^{\sigma^{pss}} ((\alpha^{en,pss})^{\sigma^{es,pss}} (p_t^{e,pss})^{1-\sigma^{es,pss}} + (\alpha^{ed,pss})^{\sigma^{es,pss}} (r_t^{ed})^{1-\sigma^{es,pss}})^{\frac{1}{1-\sigma^{es,pss}}}]^{\frac{1}{1-\sigma^{pss}}} \quad (12)$$

where $(\alpha^l, \alpha^{es,pss}, \alpha^{en,pss}, \alpha^{ed,pss})$ are distribution parameters, $(\sigma^{pss}, \sigma^{es,pss})$ are substitution parameters, w_t is the wage per efficient unit of labour where the wage per worker is $w_t A_t$, $p_t^{e,pss}$ is the aggregate price of energy and r_t^{ed} is the rental rate of energy-using goods used by the PSS sector. Since labour enters directly into the price of market energy services, that price inherits wage growth in a way that the price of home energy services does not, which is the Baumol mechanism highlighted in Results.

The user cost (rental price) of the energy-using goods stock used by the product-sharing energy-service provider, which determines the price of market-provided energy services along

with the total cost of energy and wages, equates the marginal benefits and marginal costs of renting one more unit of these energy-using goods:

$$p_t^{pss} \frac{\partial Y_t^{pss}}{\partial ED_t^{highuse}} = \frac{\left\{ \frac{q_{t-1}^{ed}}{\beta} \frac{\lambda_t}{\lambda_{t-1}} - [q_t^{ed}(1 - \delta_t^{highuse}) - p_t^{maintenance} u_t^{highuse}] \right\}}{u_t^{highuse}(1 - tax)} \quad (13)$$

where $p_t^{pss} \frac{\partial Y_t^{pss}}{\partial ED_t^{highuse}}$ is the marginal benefit of renting one more unit of the energy-using good, $\frac{q_{t-1}^{ed}}{\beta} \frac{\lambda_t}{\lambda_{t-1}}$ is the intertemporal replacement cost of the energy-using good stock multiplied by the intertemporal marginal utility of income, $q_t^{ed}(1 - \delta_t^{highuse})$ is the resale value of the energy-using good after accounting for depreciation, $p_t^{maintenance}$ is the maintenance cost per unit of energy-using good, $u_t^{highuse}$ is the use rate of energy-using goods, and tax is the taxation of revenues from renting energy-using goods.

Maintenance costs enter the model as a shadow cost that affects energy-using good asset valuation and use rate decisions through the Euler equation rather than as an explicit cash outflow. This treatment is analogous to that of physical depreciation, which similarly affects investment decisions without appearing as a cash outflow. The user cost of high-use durable goods is determined endogenously to cover both the marginal depreciation cost and the maintenance cost of deploying energy-using goods through the product-sharing PSS platform, following standard asset pricing in dynamic general equilibrium models.

The product-sharing PSS sector sets the use rate at the point where the return from one additional unit of use covers its marginal cost, i.e. the depreciation it induces on the energy-using good stock plus the per-use maintenance expenditure. Since depreciation rises non-linearly with the use rate, the model generates an upper bound on use that prevents the product-sharing PSS sector from fully depleting the stock, linking use intensity to waste flows:

$$r_t^{highuse} = q_t^{ed} \delta^{highuse} \sigma^{dep} (u_t^{highuse})^{\sigma^{dep}-1} + p^{maintenance} \quad (14)$$

where $r_t^{highuse}$ is the rental rate of energy-using goods, q_t^{ed} is the intertemporal replacement cost of the energy-using good stock, i.e. the present discounted value of future investment costs required to replace one unit of energy-using goods, σ^{dep} is the sensitivity parameter of the depreciation rate to the use rate of energy-using goods (Supplementary Table 1, parameters *sigma_dep_lowuse* and *sigma_dep_highuse*).

CIRCEE-LIFE is calibrated to a deterministic steady state in 2018 and reproduces that base year by construction; parameters and data sources are in Supplementary Tables 1 and 2. The LIFE model begins in 2020, so behavioural modifiers are calibrated to 2020 targets and their evolution through time follows the dynamics of LIFE from 2020 to 2060. They enter the model in 2019 at that calibrated level to avoid abrupt changes in 2020 and evolve along the LIFE trajectories from 2020. Infrastructure enablement is held at its current level in all scenarios until 2024, after which, following Japanese PSS policy frameworks, Broad and Concentrated diverge towards their respective 2050 values.

Software. The model uses the open-source Dynare software⁶² and runs in MATLAB.

CIRCEE-LIFE coupling

The LIFE-CE model. The original LIFE model²¹ has been modified to align the low-carbon behaviours it measures empirically with the CE consumption activities represented in CIRCEE: sufficiency and sharing. Low-carbon behaviours are categorised according to the Avoid-Shift-Improve (A-S-I) framework²⁸. In the revised LIFE-CE model, ‘Avoid’ modifiers measure lifestyle heterogeneity across activities that reduce expenditure on durable goods (sufficiency); ‘Shift’ modifiers measure heterogeneity across uptake of public and shared transport (sharing); and ‘Improve’ modifiers measure heterogeneity across repair activities (repair).

CIRCEE and LIFE-CE model coupling. The heterogeneity in sharing and sufficiency engagement across lifestyle groups is captured by modifiers that enter households’ first-order

conditions and CES nest weights (Eqs. 5, 6, 8 and 10), enabling an endogenous and dynamic representation of lifestyles. The modifiers, represented as negative quantities in CIRCEE, target the propensities of LIFE-CE to adjust continuous choice variables in CIRCEE, that is, the underlying attitude towards a behaviour before it translates into observed frequency (reduced expenditures on owned energy-using goods and increased PSS market energy-service consumption). They are recalibrated to the scale and context of CIRCEE using a bisection search nested inside a fixed-point iteration (Fig. 1b). Each modifier is solved by bisection: bracketing it between values that overshoot and undershoot its target, then halving the interval. Because the three lifestyle groups share an economy and the behavioural margins overlap, each modifier is calibrated with the others held at their current values, and the procedure is repeated until all modifiers stabilise (the fixed-point outer loop). The fixed-point outer loop is required because the three lifestyle group modifiers affect CIRCEE's prices and quantities, so each group's calibration target depends on the modifiers applied to the other groups. The resulting modifiers reproduce the observed 2020 engagement levels of LIFE conditionally, each given the others, rather than as the solution to a single simultaneous system. Calibrating against a common zero-modifier baseline was tested and rejected: for the lower-income group, it implies a change in engagement of around 40% in 2020, for which the model fails to converge. Their dynamic evolution is then governed by the iterative coupling between CIRCEE and LIFE-CE, which feeds (frequency) changes in market-provided energy services and in expenditures of owned/low-use energy-using goods back into LIFE-CE to re-estimate cognition and behaviour inputs until convergence.

Propensity values in LIFE, represented by the behavioural modifiers in CIRCEE, are measured in LIFE as universal across circular practices: the same Ecoactive or Affordability propensity value applies jointly to sharing and sufficiency in LIFE, rather than being estimated separately for each practice. By allowing sharing and sufficiency to respond to either the same or different lifestyle drivers, the framework represents conditions for aligned or divergent engagement without imposing direct behavioural spillovers across scenarios. This choice isolates lifestyle-group heterogeneity in engagement in circular practices from heterogeneity arising from how individual behaviours are measured. Thus, differences in sharing and sufficiency uptake across lifestyle groups are attributed to lifestyle heterogeneity rather than to behaviour-specific propensities. These universal propensities feed into the calibration ratios used in the iterative LIFE-CIRCEE coupling (see above), through which behaviour-specific modifiers are obtained. Changing the propensity basis therefore changes the calibration ratios and the resulting behavioural modifiers, while leaving the structure of the coupling unchanged.

Lifestyle drivers and infrastructure enablement

Building on the main barriers to the adoption of product-sharing PSS identified in the literature, we explore different lifestyle drivers (Fig. 1a) and test the sensitivity of these drivers to the substitution elasticity between home- and PSS market-provided energy services.

Lifestyle drivers shape the motivation of consumers to move away from ownership models through engagement in sharing and sufficiency. We distinguish between three drivers:

(i) No lifestyle heterogeneity: in the absence of behavioural heterogeneity, engagement in sharing and sufficiency is driven solely by relative prices and budget constraints as in standard general equilibrium and climate-economy models³⁴. This defines the Reference.

(ii) Ecoactive: low-carbon cognitions translate into behaviour. The driver captures consumers who actively translate their low-carbon cognitions into behaviour.

(iii) Affordability: behaviours driven by the need to save money (material context). The driver includes the consumers who may hold low-carbon cognitions but do not translate intentions into behaviour.

These three drivers map directly onto the consumer typology defined previously. The "Ecoactive" driver applies to higher- and medium-income groups, whose behaviour is driven by low-carbon cognitions and who therefore engage relatively more in sharing and sufficiency when the driver is activated. For this lifestyle driver, we do not strengthen the low-carbon

cognitions of lower-income groups; thus, they engage relatively less in sufficiency and sharing. This is driven by different factors such as the pursuit of status, but also the socioeconomic inequalities that restrict their own capacity and opportunity to engage in these behaviours⁴¹. This highlights that higher-income groups are better positioned than lower-income groups to adopt low-carbon behaviours, though there is a need to address behavioural change across lifestyle groups. The “Affordability” driver applies to lower-income groups, whose engagement in non-ownership models is driven by budget constraints rather than environmental awareness and who engage relatively more in sharing and sufficiency when the driver is activated; and the no lifestyle heterogeneity driver serves as the Reference against which lifestyle-driven deviations are measured.

Distinguishing between the different motivations to engage in a circular consumption activity acknowledges two dimensions:

- Structural dimension: The drivers of low-carbon lifestyles differ between higher-income groups, for whom choice is purposeful and intentional, and lower-income groups, whose consumption practices are more constrained by affordability, education, and access to infrastructure and services^{41,63}. Contextual barriers to engaging in low-carbon lifestyles, such as the digital divide, education, and lack of access to ICTs and other enabling infrastructure, translate for the “Ecoactive” driver into lower-income groups engaging relatively less in low-carbon activities^{24,41}.
- Cognitive dimension: The “Affordability” driver represents consumer groups with stronger low-carbon cognitions that do not translate into action, reflecting the gap between intentions and behaviour documented in the literature^{21,24} and consumer surveys in Japan^{50,51}. This cognitive orientation supports policy measures and related narratives emphasising ‘green identity’ and ‘social benefit’²¹. The “Ecoactive” driver strengthens low-carbon cognitions of higher-income groups to the point where they overcome these motivational and social barriers.

As illustrated in Fig. 1a, we combine these lifestyle drivers across sharing and sufficiency: (1) both Ecoactive-driven, (2) both Affordability-driven, (3) Ecoactive-driven sharing and Affordability-driven sufficiency, (4) Affordability-driven sharing and Ecoactive-driven sufficiency. The Reference has no lifestyle-specific drivers. These combinations allow us to explore potential behavioural spillovers between sharing and sufficiency. A meta-analysis of pro-environmental behaviour spillovers²⁹ shows that positive spillovers are more likely when behaviours share intrinsic motivation and are perceived as similar. Both sharing and sufficiency involve moving away from ownership, so scenarios with a common driver represent favourable conditions for aligned engagement and potential positive spillovers. However, the CIRCEE-LIFE coupling allows engagement in both practices to evolve endogenously through lifestyle and economic dynamics, without imposing direct behavioural spillovers between them. Sharing can increase through infrastructure and relative-price changes without inducing sufficiency, while households may reduce ownership without shifting towards PSS. Mixed-driver scenarios also allow engagement to diverge because the two practices respond to different motivations and socioeconomic constraints⁴¹. The framework therefore represents conditions under which engagement in sharing and sufficiency may reinforce one another without assuming that positive spillovers necessarily occur.

Infrastructure shapes the availability of supportive infrastructure and regulations for adopting non-ownership models. We test different levels of enablement through the substitution elasticity in equation (5) and the corresponding inequalities in access to enabling infrastructure. A higher elasticity means that home- and market-provided energy services become better substitutes at any given relative price, reflecting a context in which infrastructure lowers the non-price frictions associated with accessing product-sharing PSS, without directly affecting the market price of PSS services. Due to limited empirical evidence on the elasticity, we calibrate the bounds using the heterogeneity in observed adoption patterns across lifestyle

groups. The lowest value considered of 1.1 reflects very weak substitutability where consumers remain locked into ownership; the highest of 4.0 reflects fully enabling infrastructure beyond which further increases yield diminishing returns to lifestyle change (Supplementary Figure 9), suggesting less behavioural effort is needed for lifestyle changes.

We test three infrastructure settings (Fig. 1a) that vary in two dimensions: whether lifestyle groups face equal or unequal access to service-provisioning systems, and the level of enablement of infrastructure. One setting is static and serves as the analytical benchmark: Current, in which all lifestyle groups face differentiated but constrained infrastructure for the full horizon. We assume that the current state of infrastructure is unevenly distributed among lifestyle groups by being more enabling towards higher-income groups who live in denser urban areas with better physical and digital infrastructure. This provides the reference point against which the distributional consequences of infrastructure settings can be isolated and measured. Two settings are dynamic: in each, the substitution elasticity evolves gradually towards its respective 2050 value. Consistent with the path-dependent nature of structural change documented in the literature^{64,65}, the gradual evolution of the substitution elasticity reflects the slow pace at which structural change becomes effective. Existing infrastructure cannot change abruptly because there exist lock-in mechanisms related to sunk investments, infrastructure, and regulations, making transitions inherently slow and path-dependent^{65,66}. At the country level, major net-zero milestones, including Japan's NDC, the GX 2040 Vision, and the 7th Strategic Energy Plan, place the inflection point of structural change in 2040, motivating the trajectory of infrastructure improvement modelled between 2020 and 2050. The substitution elasticity reaches its final value in 2050, coinciding with Japan's carbon neutrality target.

Current enablement reflects Japan's still developing PSS market³⁰⁻³². In 2018, households spend about US\$5,200 a year on energy services in the calibration, between the US\$2,000 they spend on fuel, light and water and the US\$6,900 they spend on these combined with transport, communication and household goods⁶⁷. Of this, about US\$300 goes to PSS: 5.8% of spending on energy services, or US\$17 billion nationally and 0.34% of GDP, consistent with METI's estimate of 0.4% for the sharing economy and with the US\$21.8 billion (0.44% of GDP) reported for 2021 by the Japan Sharing Economy Association. With Current, we calibrate income-group differences in substitution elasticity to documented differences in PSS access^{30-32,50-52}: higher-income groups are assumed better positioned to access developing PSS markets, reflecting their concentration in high-density urban areas, where PSS uptake is higher, and their digital technology skills, following LIFE's behavioural assumptions. We test sensitivity to this calibration directly in Supplementary Figure 9, where we vary the substitution elasticity across its full plausible range.

In the real world, infrastructure enablement has physical, digital and institutional components. Physically, it is the distance to the nearest car-sharing station or laundry service, which determines whether renting is a good alternative to owning. Digitally, it is the access to smartphones, platform coverage and cashless payment options that booking an energy service provided by the market requires. Japan's historically cash-based payment system has been a barrier here. Institutionally, it is the insurance, parking and liability rules under which shared vehicles and appliances operate. Each is unevenly distributed among household groups. Car-sharing stations cluster in dense urban areas, where demand is highest, and digital skills are lower among older and lower-income households²¹. Under Current, these conditions hold at today's level. Under Concentrated, expansion follows existing demand, so infrastructure reaches the urban, higher-income neighbourhoods that already have it. Under Broad, expansion extends to suburban and rural areas and to households with less digital access, so lower-income groups gain most. The infrastructure settings are structured around two research questions. First, does the overall level of infrastructure enablement matter for lifestyle changes? Comparing Current enablement with the two dynamic scenarios addresses this question. Second, does distributional policy design matter even when the overall infrastructure is highly

enabling? Broad and Concentrated address this but with opposite distributional settings. The wider gap in infrastructure access between lifestyle groups in Concentrated captures how infrastructure development tends to concentrate benefits among those already best positioned to capture them. Broad enablement reflects a highly enabling infrastructure in which policy ensures that even lower-income groups reach full enablement. Concentrated enablement reflects a trajectory in which a highly enabling infrastructure coexists with adoption barriers for lower-income groups, such as the digital divide and (physical and social) geographic barriers. The conceptual framework allows the model to isolate the independent contributions of substitution level and distributional design to CE, environmental, and equity outcomes (Fig. 1).

Although calibrated to Japan, the qualitative mechanism—the environmental benefits depend on which lifestyle group adopts sufficiency—is not specific to Japan: it follows from the income-share structure of consumption and the labour intensity of PSS, both of which characterise middle- and high-income economies more broadly. Our results establish the conditions under which the mechanism operates; whether the specific elasticity thresholds and price trajectories obtain elsewhere depends on income distribution and labour cost dynamics specific to each context. Our conceptual framework maps onto the broader policy challenge facing middle- and higher-income countries where digital infrastructure, urban morphology, and regulatory frameworks are changing but unevenly across lifestyle groups and geographies⁴¹. In lower-income countries, where the overall infrastructure remains limited, the Current enablement setting is more directly relevant, capturing the lock-in structural dynamics and distributional barriers that prevent service-provisioning systems from scaling.

A natural concern is whether the findings above are a design artefact: if the Ecoactive scenario is designed to strengthen the low-carbon cognitions of higher-income groups, it may seem unsurprising that their engagement determines environmental footprints at the macro level given their consumption share. The behavioural modifiers of lifestyle groups are not free parameters: their values are fixed by the calibration described above, which requires each lifestyle group's simulated engagement to reproduce LIFE's propensity. The coupling fixes the behavioural response, but not what follows from it. How that response propagates through the general equilibrium and material flow analysis is determined by solving the system, not by any single input to it. This is where the magnitude and channel of the environmental footprint outcomes arise, along with the divergence between energy-service access and economic welfare, the amplifying effect of enabling infrastructure, and the dominance of sufficiency in aggregate outcomes.

Outcome indicators

To assess how product-sharing PSS adoption affects household living standards and their distribution across lifestyle groups, we compute welfare, distributional, and energy-service indicators for each lifestyle-driver × infrastructure scenario and lifestyle group.

Welfare equity. Welfare equity is measured as the spread in lifetime consumption-equivalent variation (CEV) across lifestyle groups. The CEV is based on the utility function and answers how much consumption would need to change, as a percentage, to make a lifestyle group indifferent between each scenario and the reference run.

Energy-service consumption equity/gap. Because product-sharing PSS adoption affects access to market-provided energy services, we assess changes in energy-service consumption as an indicator of material well-being, drawing on the emphasis on access to energy services in the decent living standards literature⁴⁹. The energy-service consumption gap is defined as the ratio of energy-service consumption of the lower-income group to that of the higher-income group. A ratio below 1 indicates that lower-income groups consume fewer energy services than higher-income groups. This detects where expenditure inequality falls while energy-service inequality rises, a pattern that would occur if lower-income groups adopted non-ownership

models, through sufficiency for example, without gaining proportionate access to service provisioning systems.

Environment and material indicators. Environmental footprints by lifestyle group are computed across the five product categories present in CIRCEE (e.g., nondurables, other durables, owned energy-using goods, product-sharing PSS services, and repair services) and three lifecycle phases. This allows one to identify whether patterns of material/carbon/waste footprints among lifestyle groups diverge. At the micro-level, carbon footprints are expressed in tonnes of CO₂ per household per year; waste and material footprints are expressed in tonnes per household per year. At the macro-level, carbon footprints are expressed in MtCO₂ per year and material and waste footprints in Mt.

The **production-phase carbon footprint** covers the CO₂ emissions from the production of goods and the economy-wide CO₂ emissions net of households' CO₂ emissions from own energy use. Footprints are attributed to total energy use across producing sectors, from the processing of materials to manufacturing. The CO₂ emissions from the production of capital goods are further allocated to the final consumption goods in proportion to the capital use to produce each one of them, capturing the emissions embodied in the machinery and infrastructure. The resulting production-phase footprints for consumption goods are then attributed to each lifestyle group by its expenditure share in that consumption good category, adjusted for the domestic content of consumption, excluding exports and including the material content of imports.

The **end-of-life carbon footprint** covers the CO₂ emissions from the incineration of municipal waste arising from the retirement of goods. For nondurable and other durable goods, the allocation follows lifestyle group expenditures and stock shares respectively. For owned energy-using goods, the attribution follows each group's contribution to disposal, which depends on the use rate and repair intensity: a lifestyle group that repairs more contributes proportionally less to disposal and thus carries a lower end-of-life carbon footprint. The end-of-life carbon footprint from the retirement of energy-using goods used by the product-sharing PSS sector is attributed across lifestyle groups in proportion to their share of market-provided energy services consumed. The disposal of energy-using goods of the product-sharing PSS sector is governed by the use and depreciation rates.

The **industrial waste carbon footprint** captures the CO₂ emissions from the incineration of waste generated during manufacturing (material loss) attributed to each lifestyle group through the same expenditure allocation logic as the production phase carbon footprint. Together, the three lifecycle phases sum to a total lifecycle carbon footprint for each lifestyle group that additionally includes the direct CO₂ emissions from energy use.

The **waste footprint** covers the end-of-life municipal, industrial and capital-allocation waste of the consumption basket of each lifestyle group.

The **material footprint** captures the mass of virgin and secondary materials embedded in final goods consumed by each lifestyle group, after accounting for material losses during production. It covers both domestic material content and the material embodied in imports (via the material intensity of imported goods). The material content of the capital inputs used to produce consumption goods is also accounted for in the material footprint of the consumption basket. Also, the footprint separates the energy-using goods owned by lifestyle groups for own use and energy-using goods used by the product-sharing PSS sector, attributing material use proportionally to each lifestyle group's new acquisitions of energy-using goods and PSS market energy-service consumption respectively. This separation identifies cases where product-sharing PSS reduces material demand associated with ownership but increases material demand associated with non-ownership consumption.

Limitations

There are six limits to our analysis. First, CIRCEE does not include CO₂ emissions from imports, so absolute levels can be underestimated. Since imports barely change (less than 2%), our comparisons between lifestyle drivers and infrastructure settings are more reliable than the absolute levels. Second, we group all energy-using goods together and leave out specific green product design features; a more detailed product assessment would require life-cycle assessment. Also, we assume homogeneous energy-using goods produced by a single firm, omitting the dynamics of similar goods with varying energy, material, and CO₂ profiles across production and use. Third, we treat the PSS sector as a competitive firm, not accounting for non-business sharing platform structures. Network externalities can generate increasing returns⁴⁶, while spatial frictions can reduce them; both can concentrate benefits in dense, higher-income areas and constrain peripheral, lower-income groups' access. We also collapse platform availability, digital infrastructure, and regulations into a single substitution elasticity (i.e. infrastructure). These could improve independently, requiring a richer representation of supportive infrastructure than the stylised model provides, and could also affect the costs of PSS. Fourth, the model's three lifestyle-income groups, calibrated to Pettifor et al.'s empirically derived lifestyle typology²¹, aggregate within-group heterogeneity that can mask some distributional dynamics. Extending the framework to the whole income distribution would require re-deriving behavioural propensities at improved scales. Fifth, our results also depend on the SSP2 energy price and efficiency path extracted from the WITCH model (Supplementary Figure 1); different pathways would change the absolute levels but not the direction of the effects or the comparison between lifestyle drivers, since the main cost disadvantage of energy services produced from the market comes from labour intensity, not energy prices. Finally, our results are conditioned on Japan's high-income, ageing and service-dominated economy. The direction of the trilemma should carry to other high-income settings, because it follows from the labour intensity of service provision rather than from Japan-specific parameters, but its magnitude will differ where wage growth, service-sector productivity or informal sharing practices differ substantially. The relative-cost mechanism would be weaker if productivity growth in PSS provision reduced its labour requirement. A further extension would capture the opportunity cost of household time in producing energy services at home, and how this cost would further shape the relative cost dynamics.

Data sources

To ensure accurate simulations, it is essential to replicate the historical macroeconomic data of Japan's economy. The model is calibrated to 2018 as its initial steady state. In the Dynare software implementation, CIRCEE-LIFE is initialised at a steady state, a balanced growth path at which all endogenous variables grow at constant rates and agents' optimality conditions hold exactly, before the simulation begins over the 2018–2050 horizon. The choice of 2018 as the base year is justified on two grounds. Technically, 2018 is the year for which the full set of calibration data is available at sufficient disaggregation across national accounts, material flow accounts, and consumer surveys. Empirically, 2018 corresponds to a period of low cyclical activity in Japan: the output gap stood at 1.86% according to Bank of Japan data, indicating that the Japanese economy was close to its potential output and therefore a reasonable approximation of the balanced growth path that the steady state initialisation requires. Together, these conditions ensure that the model's initial conditions reflect structural rather than cyclical features of the Japanese economy.

The model parameters and exogenous variables follow the latest calibration of CIRCEE-LIFE⁵⁴ using mainly Japanese national statistics (E-stat and the Agency of Natural Resources and Energy), the Japan Industrial Productivity Database 2021 from RIETI, OECD.stat database for fiscal data, SSP Scenario Explorer 3.2.0 for SSP2. The calibration of depreciation rates, waste flows and material stocks and flows has been refined since earlier versions of CIRCEE thanks to special data extracts from the Mat-stocks database^{68,69}. We focus

on SSP2 for demographic and economic growth data from the IIASA database, and for the evolution of each lifestyle group in total population in the LIFE-CE model.

Parameters and exogenous variables related to materials and waste are calibrated on the model's first-order conditions (FOCs) and on data from the Mat_stocks database (MISO2) and the Ministry of the Environment's White Papers on the Sound Material Cycle society and reports on industrial and municipal waste, RIETI's input-output tables and the Ministry of the Environment's Sankey diagrams (waste generation and management). Prices of raw, virgin and secondary materials were computed from FOCs, data from RIETI's IO table (nominal expenses data), material flows from MISO2^{68,69} and waste reports from the Ministry of the Environment (quantity data).

Sensitivity analysis

The model's sensitivity to key parameters is documented in Corbier et al.^{54,70}. We also tested robustness to a parameter central to behavioural dynamics: the elasticity of substitution between home- and market-provided energy services (equation (5); see Supplementary Figure 9). We do not additionally vary the SSP2 labour-productivity path because LIFE is only calibrated on SSP2 and this path is an exogenous scenario input rather than a calibrated parameter. We also do not vary the behavioural propensity modifiers directly, since the four lifestyle drivers already span the relevant range of behavioural heterogeneity by construction. The magnitude of the environmental and behavioural responses is sensitive to the substitution elasticity between home- and market-provided energy services, consistent with its key role in the Baumol mechanism. Also, we explored two more infrastructure settings in the model beyond those reported. Both additional settings produced qualitatively similar dynamics, with no substantial differences in the magnitudes of the main outcomes ('Dystopian' and 'Utopian' settings are available at the GitHub link below).

Finally, we tested robustness to the habit persistence parameter (equation (2)) and the elasticity of substitution between energy services and other consumption (equation (4)), as they are important parameters in households' consumption decisions. The habit persistence parameter is tested at 0.45 and 0.65, compared with the value of 0.55 used in the twelve scenarios. The elasticity of substitution between energy services and other consumption is tested at values of 1.3 and 1.6, compared to a value of 0.98 used in the twelve scenarios. Values below 0.98 for the substitution elasticity imply a stronger complementarity between energy services and other consumption, which we do not regard as a plausible representation of household preferences in the context of the paper. In scenarios where households reduce their consumption of energy services, a value below 0.98 would imply they also want less of everything else at the margin, i.e., they would reduce the consumption of energy services and other consumption. Each parameter sensitivity value is reported for Ecoactive-All and Affordability-All under Current enablement with the full coupling between CIRCEE and LIFE (Supplementary Figures 10–13).

The direction of the main environmental and welfare effects is preserved across all sensitivity values. Ecoactive-All reduces the macro-level DMC, waste generation and CO₂ emissions and Affordability-All increases them. Cumulative CO₂ emissions change by -0.33% to -0.54% under Ecoactive-All and by +0.33% to +0.54% under Affordability-All. Domestic material consumption changes by -0.30% to -0.26% under Ecoactive-All and by +0.28% to +0.29% under Affordability-All, while waste changes by approximately -0.16% under Ecoactive-All and +0.15 to +0.16%, under Affordability-All. The lower-to-higher-income energy-service consumption ratio ranges from 0.818 to 0.827 under Ecoactive-All, compared with 0.819 in the calibrated run, and from 0.715 to 0.736 under Affordability-All, compared with 0.734 in the calibrated run. The welfare spread across lifestyle groups ranges from 2.38 to 3.68 percentage points under Ecoactive-All, compared with 3.23 percentage points in the calibrated run, and from 0.47 to 0.67 percentage points under Affordability-All, compared with 0.67 percentage points in the calibrated run. The welfare gap between higher- and lower-income groups remains positive under Ecoactive-All (2.28–3.60 percentage points) and negative under Affordability-All (-0.67 to -0.47 percentage points). The ordering between the two lifestyle drivers therefore holds. Overall, habit persistence has little effect, whereas the substitution

elasticity matters more, particularly for cumulative CO₂ emissions and the magnitude of the welfare differences.

Increasing the elasticity between energy services and other consumption from 0.98 to 1.6 increases the magnitude of the environmental response under both lifestyle drivers, so the contrast between Ecoactive-All and Affordability-All widens rather than narrows.

Data Availability

All data supporting the findings of this study are available from publicly accessible sources and mentioned in the References section. The input data were derived from the public databases detailed in the Methods section and Supplementary Information (SI). The compiled datasets used to generate the figures in this study are provided at the following [Google Drive link](https://drive.google.com/drive/folders/1uD9UOoQWqMv_RCItdqmtssEBefyTTuj?usp=sharing) [https://drive.google.com/drive/folders/1uD9UOoQWqMv_RCItdqmtssEBefyTTuj?usp=sharing].

Code Availability

This study uses the CIRCEE model, which is an open-source model. The source code is publicly available at <https://github.com/witch-team/circeemodel.git>. The data and scripts used to generate the main-text and supplementary figures, together with machine-readable versions of Supplementary Tables 1 and 2, are available in the `post/` directory of the same repository.

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Author information

Ethics declarations

Competing Interests

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