



Net0 Pathways through improved IAMs across Sectors, Dimensions, and Scales

Open-Source lifestyle change model and IAM linkage source code

The LIFE model: empirical foundations, generic coupling process, demonstration case studies, and linkage source code.

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Executive Summary

Significant lifestyle changes are essential for reducing future energy consumption and emissions to meet the goals of the Paris Climate Agreement. Demand-based mitigation strategies can reduce global CO₂ emissions by 40-70% across all end-use sectors by 2050. Integrated Assessment Models (IAMs) play a crucial role in exploring climate change mitigation strategies. However, they do not directly model behaviour nor its cognitive drivers and are therefore limited in representing the mitigation potential of lifestyle changes. Expanding IAMs to endogenously represent lifestyle changes enables exploring a broader range of transformative solutions towards low-carbon futures.

The LIFE Model. The LIFE (Lifestyle, Cognitions, Behaviour, and Context) model captures the interplay between cognitions (mental processes guiding behaviour), behaviours (actions avoiding or reducing energy use), and context (material and social environments). It uses cluster analysis of large-scale social survey data from the UK, China, USA, and Australia to identify four lifestyle types: Resourceful, Active, Constrained, and Cautious. These types are characterized by different levels of low-carbon behaviours and cognitions. Soft-coupling the LIFE model representation of lifestyle heterogeneity and lifestyle change mechanisms with the demand modules of global IAMs enables endogenous simulation of lifestyle change as part of broader mitigation pathways analysis.

Generic Soft-Coupling Approach. The LIFE model employs a generic soft-coupling approach with global IAMs to simulate low-carbon lifestyle changes. This involves iterative information exchange between the LIFE model and IAMs, allowing for the dynamic simulation of lifestyle changes. The approach includes several steps. First, the LIFE model characterizes lifestyle types with empirical data. Then, low-carbon behavioural propensities are applied to IAM equations implicitly representing behavioural parameters. The modified IAM equations generate behavioural outcomes to reflect lifestyle-driven behaviours, that are fed back to the LIFE model. The LIFE model equations are subsequently applied to predict lifestyle changes. The outputs of the LIFE model are finally fed back to the IAM equation. Iterating through these steps can simulate lifestyle changes over time.

Application to the Buildings Sector Using MESSAGEix-Buildings and open-source coupling code. The methodology is demonstrated using the MESSAGEix-Buildings model, a bottom-up building stock model with global and regional resolution. The LIFE model introduces lifestyle heterogeneity at the global level, with behavioural propensities influencing energy efficiency improvements via advanced renovations and new constructions and set-point temperature reductions in residential buildings. This coupling allows for the simulation of aggregated behavioural changes and their impact on energy demand for residential space heating at the global level under different climate policy scenarios. Based on the coupling approach between the LIFE and MESSAGEix-Buildings models, we developed an open-source lifestyle changes

model and code for coupling with IAMs and end-use sector models. The coupling code and example workflow and data are available in a public repository and can support broader application of the coupling with the LIFE model.

Application to the Circular Economy Using CIRCEE. The LIFE model is applied to the circular economy using the CIRCular Energy-Economy model (CIRCEE). This is a dynamic general equilibrium model with resource/stock flow consistency. The LIFE model introduces lifestyle heterogeneity at the country level, with behavioural propensities influencing the unnecessary consumption of durable goods that avoid energy and material use. The coupling allows for simulation of the socio-economic impact of increasing Extended Producer and Responsibility (EPR) fees as they impact sufficiency behaviours for durable goods. Soft-coupling with the LIFE model also enables endogenous simulation of lifestyle and lifestyle change as part of broader analysis of the potential of circular economy and new business models for climate change mitigation.

Multi-Domain Application Using IMACLIM-R. The LIFE model is applied across multiple domains using the IMACLIM-R model. Imacim-R is a computable general equilibrium model. It formalises the explicit description of the evolution of technical and non-technical parameters including investments, and commodity prices (notably energy) across different sectors of the economy (notably transport, industry, residential, and electricity). The LIFE model introduces heterogeneity simultaneously at the global, domain level across home energy and transport with behavioural propensities influencing the choice of building performance level at the time of purchase or renovation, the choice of heating system, the intensity of carpooling practice and the choice of motorization for light-duty vehicles. The coupling allows for the simulation of combined actions across home energy and transport and their impact on carbon emissions.

Conclusions. The integration of lifestyle changes into IAMs represents a significant advancement in climate change mitigation modelling. The LIFE model's coupling approach provides a robust framework for simulating the dynamic interplay between cognitions, behaviours, and context, enabling a more comprehensive understanding of lifestyle-driven mitigation strategies. This approach supports policymakers in considering both technological and behavioural solutions to achieve climate goals.

Key Findings

- The LIFE model effectively captures lifestyle heterogeneity and mechanisms of change.
- Soft-coupling with IAMs allows for dynamic simulation of lifestyle changes in global change scenarios.
- The approach is adaptable to different domains, including individual end-use sectors, the circular economy and multi-domain scenarios.
- The integration of lifestyle changes into IAMs enhances the scope and effectiveness of climate policy analysis.



- The open-source model and coupling code in this deliverable provides a tool to support broader application of the coupling approach.



1. Introduction (University of Oxford)

Significant lifestyle change is required to reduce future energy and emission outcomes consistent with Paris Climate Agreement goals to limit global warming to well below 2°C [1-3]. The Sixth Assessment Report of the IPCC suggests that by 2050, global CO₂ emissions could be reduced 40-70% across all end-use sectors with demand-based mitigation strategies [4, 5].

Global IAMs are used to explore strategies for climate change mitigation to inform decision makers. Strategies include improved energy efficiency, changes in energy supply (e.g., greater use of green energy), and technological changes (e.g., shift to electric vehicles, low-energy appliances, adoption of renewables). They are becoming increasingly important and influential in informing climate policy debate and setting research priorities [6, 7]. Extending these strategies into the realms of lifestyle could expand the range of transformative solutions modelled, enabling policy makers to consider the influence of both intentions and impact [8].

To adequately model lifestyle, IAMs need to capture both the impact of lifestyles and the mechanisms of lifestyle change [9, 10]. Lifestyle is a universal, integrative concept. It involves the interplay between three elements: cognitions, behaviours and context [3, 11-13]. Lifestyle heterogeneity can be captured across and within these three elements, as well as across domains of behaviour (e.g., homes, mobility, food), and geographically across countries and cultures [14-18]. Integrative frameworks provide a lens through which to synthesise consistencies between disciplines (e.g., health and low-carbon) as well as behavioural domains.

In low-carbon research, behaviours are observable as physical actions which avoid energy use (e.g., switching off lights), physical activities which shift behaviours (e.g., using a bike rather than a car), and improved consumption (e.g., using energy efficient technology) [14, 19, 20]. These three types of low-carbon behavioural changes are captured by the Avoid-Shift-Improve framework [5]. Although low-carbon lifestyles are observable through these behaviours, they are not synonymous with behaviour. Behaviours are discrete actions associated with specific personal and contextual influences. In contrast, lifestyles are made up of constellations of actions linked with some degree of consistency to broadly defined cognitions and contexts [21, 22].

Cognitions are mental processes which guide and direct low-carbon behaviour [23]. They can be seen as distinctive, complimentary pathways to low-carbon behaviour. Cognitions include perceived behavioural control ("beliefs that personal actions will lead to desired goals") [2, 24-26]; value orientation ("guiding principles which reflect how people live their lives") [17, 27]; health orientation ("feelings related to well-being, health and life satisfaction") [13, 28, 29] and environmental beliefs ("saliency of the need to act to the benefit of the environment") [11, 30].

Context creates an enabling or constraining environment for a low-carbon lifestyle [3, 11-13]. Context is material (e.g., access to enabling infrastructure) as well as social (e.g., family capital and social cohesion). As an example, provision of safe cycling infrastructure (material) that reinforces norms and routines of cycle commuting (social) interact to enable low-carbon behaviour (mode shifting from car to bicycle) [31].

These three elements of lifestyle are interconnected processes that create affordances, individual learning and habituation, and cognitive responses which shape behaviour [32]. Each element can be viewed as a distinctive mechanism or driver of lifestyle change [33-35].

1. Lifestyle change is *contextually-driven* - lifestyles shift as context becomes more enabling or constraining. Changes relate to physical and social environments that sustain or undermine lifestyle change [36-38] and include affordability, accessibility of infrastructure, digitalisation, social support, access to bike lanes [39, 40]. This mechanism of lifestyle change relates to *opportunity*.
2. Lifestyle change is *cognitively-driven* - lifestyles reflect self-expression, personal ideology, and a sense of identity [19, 41]. Changes in lifestyle relate to individual empowerment, self-management and efficacy [39, 42], shifts in values [41], beliefs [40, 43], and attitudes towards health and wellbeing [44]. This mechanism of lifestyle change relates to *identity*.
3. Lifestyle change is *behaviourally-driven* - lifestyles also shift in response to familiarity with behaviours (and technologies), social learning and/or a striving for self-consistency [45]. This mechanism of lifestyle change relates to *experience*.

IAMs do not directly model behaviour nor its cognitive drivers which presents a unique challenge to endogenizing low-carbon lifestyles [46, 47]. Exogenous 'work-arounds' use qualitative scenario narratives of lifestyle change translated into exogenously-imposed quantitative changes in energy service demands (activity levels like passenger kilometres of mobility) or other demand-related parameters within the IAM [8, 34]. Exogenous modelling studies have explored contextually-driven lifestyle change through large-scale societal and economic transformation such as in technology, urban design, societal virtualisation, and the digital economy [48, 49]. Changes in cognitive drivers are largely assumed as the motivation for changes in behaviour, but these are not explicitly modelled [10, 34, 49]. Exogenous approaches cannot capture the dynamic effects of lifestyle change and its interactions with other techno-economic and infrastructural change dynamics represented in the IAM. A major research challenge is how to shift IAM implementation approaches from their exogenous representation of lifestyle change in scenario narratives to endogenous generation of lifestyle change dynamics within the models [8, 9].

Lifestyle is defined as '*the interplay between cognitions and behaviour in specific material and social contexts*' [50]. Lifestyle is a unifying concept, that directs behaviour across multiple domains. It consists of three interacting elements: cognitions, behaviour and contexts. Cognitions direct and motivate behaviour. Context shapes how the interplay between behaviours and cognitions constitutes lifestyle.

2. The LIFE Model (University of Oxford)

2.1 Conceptual and Empirical Foundations.

To measure low-carbon lifestyle heterogeneity the LIFE model draws on a cluster analysis of large-scale social survey data in four countries (UK, China, USA and Australia) [51-54]. This distinguishes four lifestyle types heterogeneous across low-carbon behaviours and low-carbon cognitions. Low-carbon behaviours are captured 'universally' i.e., distinctive domain related behaviour is measured within three key domains: mobility; food; homes and aggregated. Cognitions are measured within four distinctive but complimentary pathways which measure perceived behavioural control, values, health and wellbeing, and environmental beliefs, and are similarly aggregated. Context is exogenous. It captures material and social constraints, and enablers to low-carbon lifestyle. It moderates the size of clusters and explains their unique characteristics.

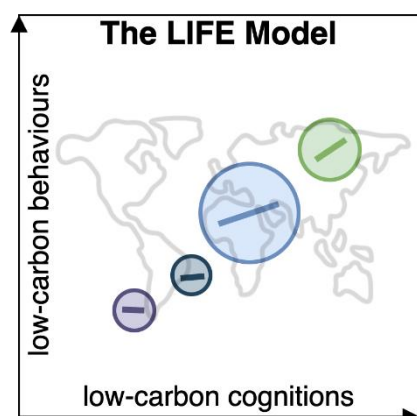


Figure 1 – The LIFE Model Schematic (1)

Key to schematic

Green and blue circles denote engaged types whose behaviour is strongly driven by cognitions; grey and purple circles denote disengaged types whose behaviour is weakly driven by cognitions.

The size of circles denotes the proportional size of clusters across lifestyle types.

The line in each circle denotes strength of the linear relationship between outcome (behaviour) and predictor (cognitions).

Low-carbon cognitions and low-carbon behaviour are measured on a scale of 0 to 1 (where 0=low and 1=high).

Figure 1 is a schematic representing the relative positioning of the four lifestyle types within a 2x2 space defined by strength of low-carbon cognitions and related participation in low-carbon behaviours. Each type has a characteristic cluster size (% of population) which reflects contextual enablers or constraints (the third element of lifestyle). 'Resourceful' types are highly enabled by their social and material contexts. 'Active' types are goal driven and seek healthier outcomes in life. 'Constrained' types face strong barriers to low-carbon lifestyle. 'Cautious' types have the means but not the motivation to engage in low-carbon behaviour.

2.2 Extrapolation of Lifestyle Heterogeneity to Countries Globally.

Lifestyle groups are heterogeneous within a country, and lifestyle changes develop differently in each group. Empirical evidence for this heterogeneity is only available in some countries based on data analysed to date, but global IAMs require global coverage. We extrapolate the key characteristics of each lifestyle type to other global datasets. The main output of this process is a set of parameters that measure lifestyle heterogeneity globally, regionally, and within or across three domains (mobility, food, homes).

2.3 Representation of Different Mechanisms of Lifestyle Change

There is a dynamic relationship between the three key elements of low-carbon lifestyle which explain lifestyle change. We use our empirical data to identify and measure three distinct mechanisms or drivers of lifestyle change over time (see Figure 2).

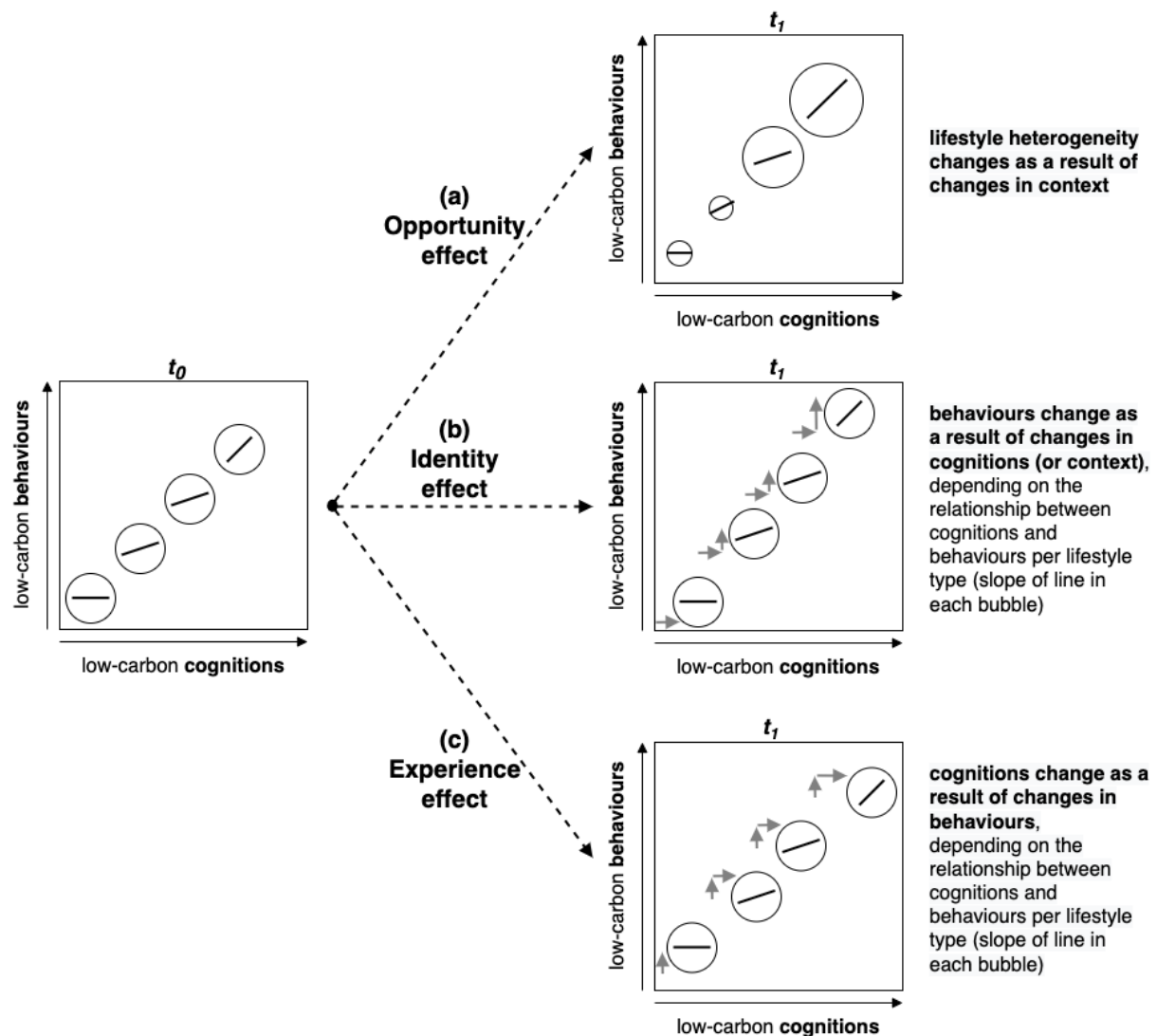


Figure 2 – The LIFE Model Schematic (2): Drivers of Low-Carbon Lifestyle Change. Upper-panel (a) shows the ‘opportunity effect’, driven by change in context. Middle panel (b) shows the ‘identity effect’, driven by change in

cognitions. Lower panel (c) shows the ‘experience effect’, driven by change in behaviours. From time T_1 the process iterates.

key to schematic

(a) size of bubble depicts the proportional size of clusters across lifestyle types
(b) slope of line in each bubble depicts the strength of the linear relationship between outcome (behaviour) and predictor (cognitions)
(c) slope of the line depicts the strength of the linear relationship between outcome (cognitions) and predictor (behaviour)

The ‘opportunity effect’ describes how the prevalence of different low-carbon lifestyle types change as a result of contextual shifts in either enablers or constraints of low-carbon behaviours. For example, as incomes rise and skills are learnt, low-carbon behaviours and cognitions may become more easy, likely, normal, or accepted. As a result, people within a population may move from a more ‘Cautious’ or disengaged low-carbon lifestyle type to a more ‘Resourceful’ or engaged lifestyle type. This is shown in Figure 2(a) with the bubbles towards the upper right increasing proportionally in size (% of the population). Based on our empirical findings, this effect is modelled in the LIFE model, and formally captured using a multinomial logistic regression equation for which the simple, empirical equation takes the following form:

$$Pr_g(t) = f(\text{Age}(t), \text{Income}(t), \text{Education}(t)) \text{ [Equation 1]}$$

In which Pr_g = cluster size of group (1-4)

‘The identity effect’ describes how the propensity of each lifestyle type towards low-carbon behaviours changes as values, beliefs, and intentions change. For example, a strengthening of perceived self-efficacy (ability to act), coupled with increased awareness of climate risk, stimulates low-carbon behaviours as people intentionally strive for consistent self-identities (i.e., alignment between cognitions and behaviours). This is shown in Figure 2(b) with the bubbles shifting rightwards to stronger low-carbon cognitions and then upwards towards stronger low-carbon behaviours. The magnitude of the upward shift depends on the responsiveness of each lifestyle type to strengthening cognitions, shown by the line within each bubble. In the LIFE model, this is formally captured in ordinary least squares bivariate regression equations that take the form:

$$Beh_g(t+1) = \alpha_g + \beta_g(\text{Cog}(t)) \text{ [Equation 2]}$$

in which Beh = low-carbon behaviours, Cog = low-carbon cognitions, g = lifestyle types

‘The experience effect’ describes how low-carbon cognitions change as people become familiar with and learn more widely about behaviours that have changed. The opportunity and identity effects outlined above show how changes in personal context (e.g., income, skills) or external context (e.g., prices, infrastructure) may shift the relative influence of enabling and constraining factors shaping behaviour. Resulting changes in behaviour generate learning, familiarity, or experience. Dissonance reduction mechanisms then align cognitions with these new experiences. In the example of active travel, if cycling infrastructure provision leads to

more active travel, people may start to see low-carbon mobility as a part of their identity as someone contributing to efforts to tackle climate change. This is shown in Figure 2(c) as an upward movement of each lifestyle type to stronger low-carbon behaviours and then rightwards towards stronger low-carbon cognitions, depending on the characteristic relationship between behaviours and cognitions for each lifestyle type. In the LIFE model, this is captured in the form:

$$Cog_g(t) = \alpha_g + \beta_g(Beh(t)) \text{ [Equation 3]}$$

in which Beh = low-carbon behaviours, Cog = low-carbon cognitions, g = lifestyle types, t=time

The time lag (t) identified in Equation [2] and Equation [3] is derived from change in the constant term (α) over time.

3. Generic soft-coupling approach with global IAM (University of Oxford and IIASA)

3.1 Endogenous Modelling of Low-Carbon Lifestyle Change in a Global IAM

Soft-coupling the LIFE model representation of lifestyle heterogeneity and lifestyle change mechanisms with the demand module(s) of a global IAM enables endogenous simulation of lifestyle change as part of broader mitigation pathways analysis. This generic coupling approach that iteratively exchanges information between the LIFE model and a global IAM introduces four low-carbon lifestyle types, and explicitly represents three distinctive drivers of low-carbon lifestyle change. The approach is represented in Figure 3 and distinguishes a number of steps (shown in black bubbles).

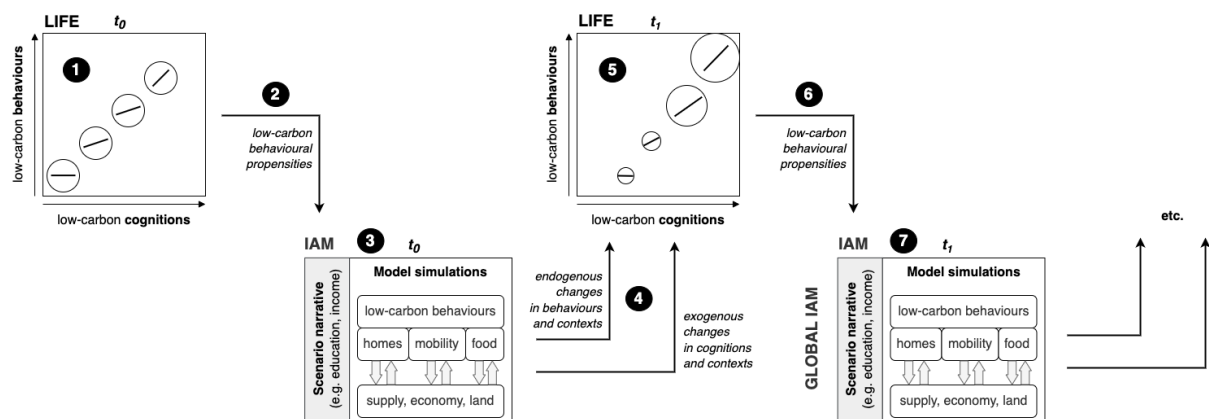


Figure 31 The LIFE Model Schematic (3): Generic Soft-Coupling with Global IAM

Step 1. Using empirical data from national social surveys extrapolated to all countries globally, the LIFE model characterises four lifestyle types with distinct sizes (% of population) and propensities towards low-carbon behaviours¹.

Step 2. The low-carbon behavioural propensities are applied to equations implicitly representing behavioural parameters or behavioural outcomes in the IAM. For demand-side modules within IAM frameworks, inputs such as technology options, costs, constraints, and

¹ Propensities measure the probability of engaging in low-carbon behaviour for each lifestyle type. They apply to the inputs side of the equation in the IAM. For the purposes of calibration and/or compatibility with discrete outcomes in IAM equations the behavioural propensities can also be converted into behavioural frequencies (see Sections 4.3.3 and 5.2.2 for examples of the calibration and coupling approach)). These measure the uptake/adoption behaviour as a proportion (%) of the total and apply to the outputs side of the equation in the IAM. Depending on the research question and model set up, these behavioural propensities and/or frequencies can be universal (applicable to all behaviours), specific to a class of behaviour (e.g., avoid, shift, improve), specific to a domain of behaviours (e.g., homes, mobility, food), or specific to a single behaviour (e.g., energy efficient retrofits). In principle the LIFE model is flexible to different IAM input requirements.

discount rates are turned into outputs such as energy service demands (activities), modes or forms of service provision, technology-fuel combinations, energy efficiencies or intensities. These outputs implicitly represent behaviours such as retrofitting, mode shifting, or installing a heat pump.

Step 3. The IAM equations, modified by behavioural propensities from the LIFE model, generate behavioural outcomes (e.g., energy retrofit rates), as well as changes in context relevant to low-carbon behaviours (e.g., income growth). This step does not affect other scenario assumptions and input parameters used in the IAM.

Step 4. Changes in relevant IAM outputs are passed back to the LIFE model. The LIFE model can interpret IAM outputs which are consistent with its empirical foundations. At the global, universal level this relates to changes in energy consumption/demand. For domain specific coupling disaggregated IAM output consistent with the Avoid-Shift-Improve framework could also be interpreted. For example, in the homes domain changes in final energy intensities for space heating and cooling could be fed into equations in LIFE driving avoidance behaviours (lowering thermostat settings).

Step 5. The LIFE model applies these to equations predicting cognitively driven lifestyle change [equation 2] and behaviourally driven lifestyle change [equation 3]. The LIFE model uses the exogenous scenario narratives to predict contextually driven lifestyle change [equation 1].

Step 6-7. The revised low-carbon behavioural propensities are fed back to the IAM, and then modified IAM equations re-estimate behavioural outcomes, in a repeat of Steps 2-3, and so on, through the timesteps of the full IAM simulation (e.g., to 2050, or to 2100).

These iterative feedbacks between the LIFE model and the global IAM translate the static characterisation of lifestyle heterogeneity and lifestyle change mechanisms in the LIFE model into a dynamic simulation of lifestyle change in the global IAM.

4. Application to the buildings sector using MESSAGEix-Buildings and open-source coupling code (IIASA and University of Oxford)

4.1 Coupling approach

We demonstrate here the endogenous coupling methodology using a single-sector demand-based global model, MESSAGEix-Buildings. This is a bottom-up building stock model with regional spatial resolution (11 model regions), and a 5-year temporal resolution [55]. MESSAGEix-Buildings can be run on a standalone basis or as a demand module within the MESSAGEix IAM framework coupled to the main MESSAGE energy system model and MACRO macroeconomic model.

Using the LIFE model coupling, we introduce lifestyle heterogeneity across four low-carbon lifestyle types. In this demonstration approach, behavioural heterogeneity is introduced at the global level, universal level (i.e., without regional, or domain specificity). This approach is purposely simplified to enhance clarity of results. At the global, universal level the LIFE model coupling is based on a universal set of behavioural propensities (which apply to input equations in MESSAGE). To couple with discrete outcomes in MESSAGE we use two sets of modifiers ('I' and 'A'). The 'I' modifiers relate to 'Improve' behaviours which apply to the uptake of advanced renovations in MESSAGE. The 'A' modifiers relate to 'Avoid' behaviours which apply to average set point temperatures in MESSAGE. Contextually driven lifestyle change is driven exogenously and observable as an independent effect from this coupling process, hence parameters for contextually driven lifestyle change include regional disaggregation.

The basic steps of this demonstration coupling, shown in Figure 3, are as follows:

Step 1. The LIFE model generates four lifestyle types each with a size (% of total) and behavioural propensity modifiers ('I' and 'A').

Step 2. The MESSAGEix-Buildings model uses the 'I' modifiers to amplify or reduce the intangible cost term in equations estimating efficiency improvements. It uses the 'A' modifiers as an additional term in equations estimating reductions in set-point temperatures.

Step 3. The MESSAGEix-Buildings model reports change in total energy demand for space heating (EJ) at each time step as a proxy for aggregated behavioural change. Comparison of final energy intensities with- and without- behavioural propensity modifiers, shows the secondary effect of low-carbon lifestyle change.

Step 4. Final energy intensities for each lifestyle type are passed back to the LIFE model.

Step 5. The LIFE model uses aggregated behavioural changes from MESSAGEix-Buildings to re-estimate input assumptions on low-carbon behaviours. The LIFE model also uses demographic changes from the scenario narrative - income, age, and national level statistics

measuring educational attainment/technology access [56] to re-estimate relative size of lifestyle type. This feedback step into the LIFE model recognises that lifestyle types change because (a) behaviours have changed (b) external context has changed, and these (c) also cause cognitions to change – see ‘opportunity effect’, ‘identity effect’, and ‘experience effect’ (see Section 2.3).

Step 6. The revised low-carbon behavioural propensities are fed back to the IAM.

Step 7. Modified IAM equations re-estimate behavioural outcomes. Return to step (1) for the next timestep. Note that both LIFE and MESSAGEix-Buildings run over a default 5-year timestep, so are aligned over time periods of change in the empirical data (LIFE) and future simulations (MESSAGEix-Buildings).

4.2 Results

Using the specific approach for coupling LIFE with MESSAGEix-Buildings, we run four scenarios that demonstrate the value of endogenously simulating low-carbon lifestyle change. All scenarios use the Shared Socioeconomic Pathway SSP2 set up which describes a “middle of the road” scenario in which “the world follows a path in which social, economic and technological trends do not shift markedly from historical patterns” [57]

First, the baseline SSP2 scenario introduces the LIFE model coupling to MESSAGEix-Buildings to evaluate the effect of endogenizing heterogeneous low-carbon lifestyles and distinct mechanisms of lifestyle change. We assume continuation of current national policies without stringent climate change mitigation policies.

Second, the SSP2+Values scenario compares the effects of endogenizing low-carbon lifestyle and heterogeneous lifestyle change with and without enhanced cognitively-driven lifestyle change (‘Identity’ effect). In this second scenario we simulate rapid change in the uptake of energy efficient activities due to a widespread strengthening of low-carbon values and norms over the period 2025 to 2050. Equations measuring lifestyle change effects are artificially forced by randomising the slope coefficients (β) in equation [2] for each lifestyle type at each time period. Rates of change vary between lifestyle types, reflecting varying responsiveness to cognitive drivers.

Third, we run two additional scenarios, SSP2_1.5C and SSP2_1.5C+Values, to assess the heterogeneous lifestyle changes in the previous two scenarios, SSP2 and SSP2+Values respectively, under high energy prices in a climate change mitigation scenario aligned with 1.5°C targets.

SSP2+Values enables us to evaluate the sensitivity and flexibility of the coupling parameters to modelling strengthened drivers of low-carbon lifestyle change. We show this by comparing SSP2 with the SSP+Values results. Specifically, we are interested in how stronger low-carbon

cognitions directly act via the 'Identity' effect to strengthen low-carbon behaviours which in turn have a feedback effect to strengthen low-carbon cognitions via the 'Experience' effect. We make no additional assumptions with respect to exogenous contextual shifts such as changes in material infrastructures (e.g., urban form) or changes in social structures (demographics) so we can clearly isolate the effect of exogenously forcing the LIFE model as a novel scenario storyline element. With the climate mitigation scenarios SSP2_1.5C and SSP2_1.5C+Values we can evaluate the effect of higher energy prices on low carbon lifestyle changes of heterogeneous household groups. By comparing these two scenarios with the baseline SSP2 and SSP2+Values we can assess the effect of different price signals.

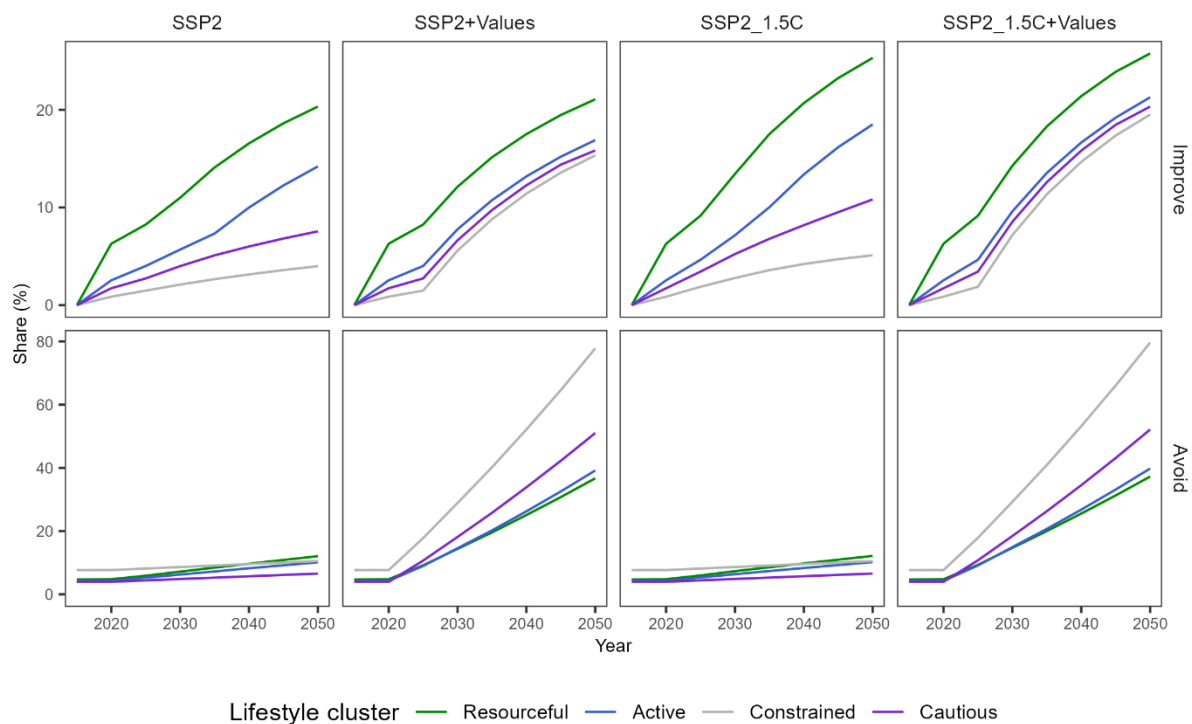


Figure 4 Share of Advanced Renovations (Improve activities) and Reduced Setpoint Temperatures (Avoid activities) among Four Different Lifestyle Types in different scenarios.

Coupling with the LIFE model introduces heterogeneous uptake of advanced renovations in buildings (Improve activities) across the four lifestyle types in MESSAGEix-Buildings (Figure 4). This variation is driven by the different levels of intangible costs that moderate the uptake of energy efficient renovation within these different lifestyle types. In the SSP2 scenario, the 'Resourceful' and 'Active' types experience faster and higher rates of growth due to the strong influence of the two drivers of lifestyle change in these groups. In contrast, the 'Constrained' and 'Cautious' types have slower rates of growth. Lifestyle change dynamics lead to an increasing activity gap between the engaged and disengaged lifestyle types by 2050. The SSP2+Values scenario introduces the additional effect of strengthening of low-carbon cognitions (e.g., values, norms). This accelerates the uptake of advanced renovations between 2025 and 2050, closing the activity gap between the 'engaged' and 'disengaged' types.

In the SSP2_1.5C scenario, the higher energy prices drive higher levels of divergences in Improve activities across the four lifestyle groups. On one hand, the 'Resourceful' and 'Active' type accelerate the uptake of advanced renovation due to the combined effects of higher behavioural propensity and shorter payback of energy efficiency improvements that can reduce energy expenses under high energy prices. On the other hand, higher energy prices only have limited effects on the uptake of renovation actions for the 'Constrained' and 'Cautious' types that have lower behavioural propensity towards these actions. In the SSP2_1.5C+Values scenario, all lifestyle groups increase the share of "Improve" actions, including the 'Cautious' and 'Constraints' due to improved cognition.

The relative influence of the drivers of lifestyle change, are noticeably different across the 'Avoid' dimension, reflecting differing levels of activity responsiveness across the lifestyle types. Under SSP2, 'Constrained' and 'Cautious' types, characterised by lower incomes, are more highly responsive to energy saving 'Avoid' behaviours. Under SSP2+Values shares of 'Avoid' behaviour increase more rapidly and are higher in the disengaged types. Effects of the mitigation scenarios on "Avoid" actions are relatively smaller as the model only partially accounts for the elasticity of demand changes relative to energy prices.

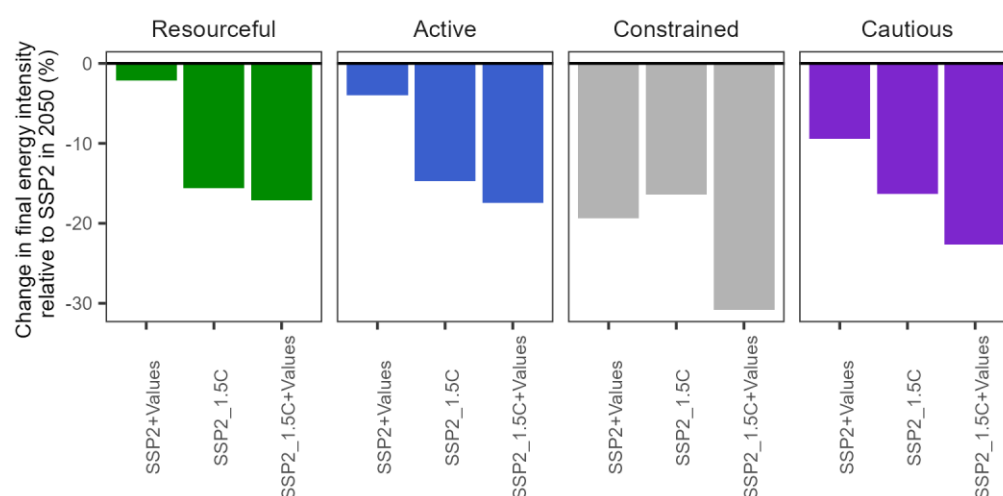
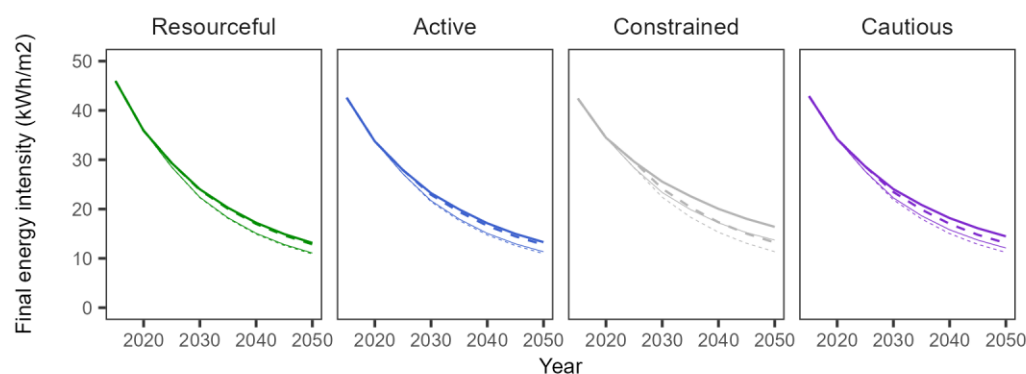


Figure 52 Final energy intensity for space heating by lifestyle type in different scenarios (top panel) and percentage change relative to the SSP2 scenario in 2050 (bottom panel).

The introduction of lifestyle heterogeneity across ‘Avoid,’ and ‘Improve’ behaviours is reflected in differing energy intensities across groups (Figure 5). The enabled ‘Resourceful’ and ‘Active’ types, responsive to both ‘Avoid’ and ‘Improve’ activities, experience faster reductions in energy intensity between 2020 and 2050. Under SSP2+Values the sensitivity and flexibility of the coupling parameters to modelling strengthened drivers of low-carbon lifestyle change is confirmed. Our simulation of rapid change in intentions towards ‘Avoid’ and ‘Improve’ actions in the less responsive ‘Constrained’ and ‘Cautious’ types is reflected by accelerated reductions in final energy intensity, compared to SSP2. The increased level of ‘Improve’ activities under the mitigation scenarios SSP2_1.5C and SSP2_1.5C+Values enables additional energy intensity reductions across all four lifestyle groups.

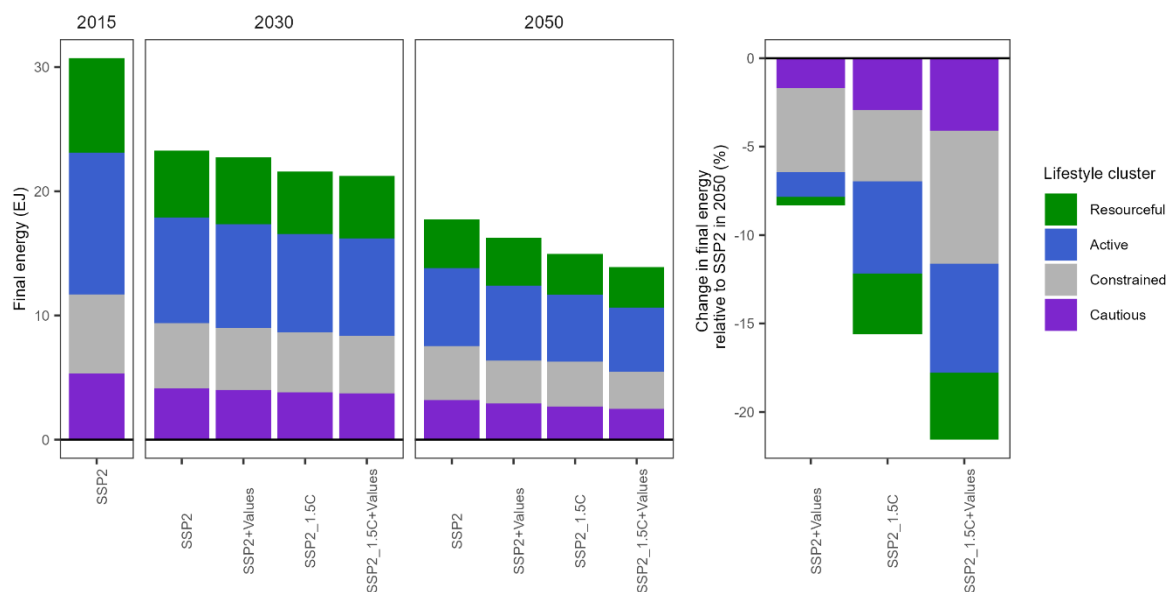


Figure 63 Projections of total final energy demand for space heating by lifestyle type in different scenarios, contrasting 2015, 2030 and 2050 (left panel) and changes in final energy for space heating relative to SSP2 in 2050 (right panel).

The results of our demonstration coupling shows that including behavioural propensity modifiers enables total energy consumption to be apportioned among the lifestyle groups and each contribution evaluated separately. Combined energy intensities differentiated by group and cluster size result in differentiated reductions in total final energy demand for space heating (Figure 6). In the SSP2+Values scenarios, increased activity across the disengaged types reduces final energy demand by between 2030 and 2050 relative to baseline SSP2 by about 8%, with the largest reduction attributable to the ‘Constrained’ group. In the mitigation scenario SSP2_1.5C, larger energy demand reductions are driven mostly by the engaged lifestyle groups, in particular the ‘Active’ group, supported by higher behavioural propensities. In the SSP2_1.5C+Values, improved cognition pushes energy demands further down, with increasing contribution of the disengaged ‘Constrained’ and ‘Cautious’ groups.

4.3 Coupling code

Based on the coupling approach between the LIFE and MESSAGEix-Buildings models, we developed an open-source lifestyle changes model and coupling code for coupling with IAMs and end-use sector models. In line with the implementation for the MESSAGEix-Buildings model, the code includes the coupling routines for two key dimensions, namely Improve “I” and Avoid “A”, using specific sets of modifiers.

In the “I” dimension, the share of low-carbon actions – advanced new constructions and renovations in MESSAGEix-Buildings – is an output of the model and depends on a set of other parameters. An intermediary parameter should therefore be used to make the link with the propensities in the LIFE model, and some correspondence should be established between the household propensities and expected behaviours in output of the model through the intermediary parameter. This requires a calibration routine to estimate the relationship between modifications in the intermediary parameter and changes in the output parameter in the end-use sector model. In MESSAGEix-Buildings, we use the intangible costs as intermediary parameters influencing the share of new construction and renovations.

In the “A” dimension, the modifiers apply to the share of households adopting low-carbon behaviours, corresponding to reduced set-point temperature for heating in the MESSAGEix-Buildings. This applies to a model parameter representing an input to the model calculations. The routines for the “I” and “A” dimensions in the coupling code can be generically used for running a feedback loop between the LIFE model and any other end-use sector model and IAM (referred to as “coupled IAM” from here on), provided that a consistent mapping between the relevant model dimensions and parameters is given.

The coupling code consists of three main components: 1) a set of functions representing the core equations in the LIFE model; 2) a function to estimate the relationship between the intermediary parameter and share of actions in the coupled IAM for the “I” dimension; 3) a coupling function and routine to link the LIFE model in component 1) and the coupled IAM. The code is provided as a set of scripts in R [58] that is possible to run using the RStudio integrated development environment [59]. The following sections describe the structure of the repository, the three main components, and key input and output data.

4.3.1 Repository structure

The repository containing the coupling code and an example workflow and data is available at the following address:

https://github.com/iiasa/message-ix-buildings/tree/main/message_ix_buildings/life_coupling

The overall repository structure is shown in Figure 4. The *coupling_code.R* file contains the core functions of the life model, calibration routine, and model coupling. The *_init.R* file provides an example workflow, using the setup from the coupling with the MESSAGEix-Buildings model. The related sample input and output data are in the folder “input” and “output” respectively. Input data are divided into inputs from the LIFE model (“LIFE” sub-folder) and inputs from the coupled IAM model (“IAM” sub-folder).

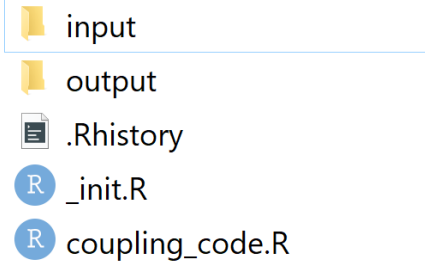


Figure 4 Repository structure.

4.3.2 Coupling functions

The *coupling_code.R* file contains all functions required for coupling the LIFE model to an IAM or sectoral model, including core functions of the LIFE model, calibration process, and model coupling. Three R functions represent the core equations for the coupling with the LIFE model. The function *fun_ls1_d_beh_prop* converts the changes in behaviour frequency d_{beh} to changes in behavioural propensity d_{prop} for a given timestep i , driven by the observed changes in energy demand from the coupled model in the previous timestep $i-1$, by using a fixed equalizing ratio f_{beh_prop} :

$$d_{prop} = f_{beh_prop} \cdot d_{beh}$$

The function *fun_ls2_d_cog* subsequently predicts the changes in low-carbon cognition d_{cog} to calculate the “experience effect” (behaviour-driven lifestyle change) based on the changes in behavioural propensities within each lifestyle, based on the changes in propensities d_{prop} calculated above and a set of time-dependent random intercepts h_{cog} of low-carbon cognitions and random slope values f_{prop} :

$$d_{cog} = h_{cog} + f_{prop} \cdot d_{prop}$$

The function *fun_ls3_d_prop* predicts a new set of behavioural propensity modifiers d_{prop} for calculating the “identity effect” (cognitively-driven lifestyle change) within each lifestyle group for each dimension, based on the changes in cognitions d_{cog} calculated above and a set of time-dependent random intercepts h_{prop} and random slope values f_{cog} :

$$d_{prop} = h_{prop} + f_{cog} \cdot d_{cog}$$

This function is applied separately to different dimensions, namely “Improve” and “Avoid” in the coupling with the MESSAGEix-Buildings model. Finally, the new set of behavioural propensities are converted to behavioural frequencies using “Improve” and “Avoid”-specific ratios ($ratio_{beh_I, prop}$, $ratio_{beh_A, prop}$). In the case of the “Improve” dimension, behavioural frequencies are further converted to a set of modifiers for the specific model parameter in the coupled model, corresponding to intangible costs in the case of MESSAGEix-Buildings, using the regression model generated in the calibration process.

A calibration process is necessary to ensure that the expected changes in behavioural frequency estimated by the LIFE model are correctly reproduced in the coupled model, via the set of updated propensity modifiers in output of the coupling routine. For the calibration

process, a regression is fit based on the results of a set of sensitivity runs for the coupled model to establish a relationship between propensity modifiers and changes in behaviour. The regression used to fit such relationship with intangible costs in the case of MESSAGEix-Buildings model is based on spline curves of the second order, using the function *fun_life_calib* in the coupling code. The inputs to the calibration process are contained in the file "life_sens_mod_beh_I.csv", including the set of modifiers "s_int_mod" and associated changes in behaviour "beh_I_diff".

The calibration process needs to be run only one time before starting the scenario runs.

The function *fun_life_coupling* can be used to run the actual coupling with the LIFE model at every timestep in the scenario runs and is built upon the functions described above. The function takes as inputs the basic parameters required for the LIFE model and the percentage difference in activity levels of the coupled model between two subsequent timesteps, based on the difference in energy demands. The outputs of this function include the updated behavioural propensity modifiers and behaviours to be fed back into the coupled model to run the subsequent time step. Comprehensive lists of data inputs and outputs are provided Tables 1-2 here below. The input and output parameters are provided for every timestep in the model runs ("year" column, 5-year timesteps from 2020 to 2050 in MESSAGEix-Buildings,) for the different lifestyle groups ("hh_group" column with the following groups: "g1" = active, "g2" = resourceful, "g3" = constrained, "g4" = cautious, "univ" = universal with no lifestyle differentiation).

Table 1 Data inputs for the coupling code.

Variable	Model parameter name	Description	Dimensions	Data source	Model functions using this parameter
d _{beh}	d_beh	Change in behaviour ²	hh_group	Coupled IAM model	fun_ls1_d_beh_prop, fun_life_coupling
f _{beh_prop}	f_beh_prop	Equalizing ratio	hh_group	LIFE model	fun_ls1_d_beh_prop, fun_life_coupling
h _{cog}	h_cog	Random intercepts of low-carbon cognitions	hh_group, year	LIFE model	fun_ls2_d_cog, fun_life_coupling
f _{prop}	f_prop	Random slopes applied to behavioural propensities	hh_group, year	LIFE model	fun_ls2_d_cog, fun_life_coupling
h _{prop}	h_prop	Random intercepts of behavioural propensities	hh_group, year	LIFE model	fun_ls3_d_prop, fun_life_coupling

² Note that changes in behaviour with positive sign denote shifts towards low-carbon behaviours. In the application with MESSAGEix-Buildings, the sign of changes in energy demand was inverted for consistency with this convention.

f_{cog}	f_{cog_I}	Random slopes applied to low-carbon cognitions ("Improve" dimension)	hh_group, year	LIFE model	fun_ls3_d_prop, fun_life_coupling
f_{cog}	f_{cog_A}	Random slopes applied to low-carbon cognitions ("Avoid" dimension)	hh_group, year	LIFE model	fun_ls3_d_prop, fun_life_coupling
$\text{ratio}_{\text{beh}_I, \text{prop}}$	$\text{ratio}_{\text{beh}_I \text{prop}}$	Ratio between behavioural propensities and "Improve" behaviour frequencies	hh_group, year	LIFE model	fun_life_coupling
$\text{ratio}_{\text{beh}_A, \text{prop}}$	$\text{ratio}_{\text{beh}_A \text{prop}}$	Ratio between behavioural propensities and "Avoid" behaviour frequencies	hh_group, year	LIFE model	fun_life_coupling
$\text{beh}_{I, \text{base}}$	$\text{beh}_I \text{base}$	Frequency of "Improve" behaviours in the base year	hh_group	LIFE model	fun_life_coupling

Note: year = model timestep; hh_group = lifestyles household group: g1 = active, g2 = resourceful, g3 = constrained, g4 = cautious, univ = universal.

Table 2 Data outputs from the coupling code.

Variable	Model parameter name	Description
d_{beh_I}	beh_I_diff	Change in "Improve" behaviour frequencies (%)
mod_I	mod_I	Modifiers to "Improve" model parameter
beh_A	beh_A	Frequency of "Avoid" low carbon behaviours

4.3.3 Example workflow

The *_init.R* code provides an example workflow, exemplifying the use of the code to soft-couple the LIFE model with an IAM or end-use sector model. In order to make the coupling code easily applicable to other models, we provide sample inputs and outputs as csv files that can be replicated and adapted in the coupling with other models. To make the coupling operational

and running with external models, a workflow can be established to automate the data exchange between the models on a timestep. Here, we illustrate the workflow with “static” timeseries data from previous scenario runs from the coupling of the LIFE model with the MESSAGEix-Buildings model for the global residential sector, as described in the sections above.

The workflow in the coupling code contains the following steps:

- Step 1: Basic settings for the runs, including importing required R-packages, setting up working directory and path to relevant data and files, set up of the timeseries for the the scenario runs.
- Step 2: Import functions from the *coupling_code.R* file.
- Step 3: Load and process basic input data
- Step 4: Run calibration process
- Step 4: Run coupling loop over a series of model time steps, including loading of input data from the (external) coupled model, coupling code runs, reporting of the results and export as csv files for each time step.

The relevant input data for running this workflow are available in the “input” folder, divided into inputs from the LIFE model (“LIFE” sub-folder) and inputs from the coupled IAM model (“IAM” sub-folder). Sample results are stored in the “output” folder for every time step.

5. Application to the circular economy using CIRCEE (CMCC and University of Oxford)

5.1 Coupling Approach

In this second case study we demonstrate the application of the endogenous coupling methodology to investigate the effectiveness of Japan's consumer-side circular economy strategies, specifically the Extended Producer Responsibility schemes, under the presence of circular markets and lifestyle heterogeneity. Despite the EPR schemes' signals to foster sustainable consumption practices, their impact is limited, as the fees are often too low to trigger significant changes in consumer behaviour. Through coupling with the LIFE model, we explore the potential effects of increasing EPR fees on Japanese households' consumption patterns.

The shift towards a circular economy depends on policy support [60], behavioural changes and corresponding lifestyle changes [61-63], breakthrough innovations, and new business models, including sharing and digitalization [64]. Circular economy (CE) strategies can modify the consumption habits of households. Assessing the full potential of a CE requires a macro-level and integrated assessment approach that addresses the complex inter-dependencies and trade-offs between environmental, social, and economic objectives.

The CIRCUlar Energy-Economy model (CIRCEE) is a dynamic general equilibrium model with resource/stock flow consistency. The model includes microeconomic foundations, key industrial ecology concepts and household heterogeneity (Figure 7). Soft-coupling with the LIFE model enables endogenous simulation of lifestyle and lifestyle change as part of broader analysis of the potential of circular economy and new business models for climate change mitigation.

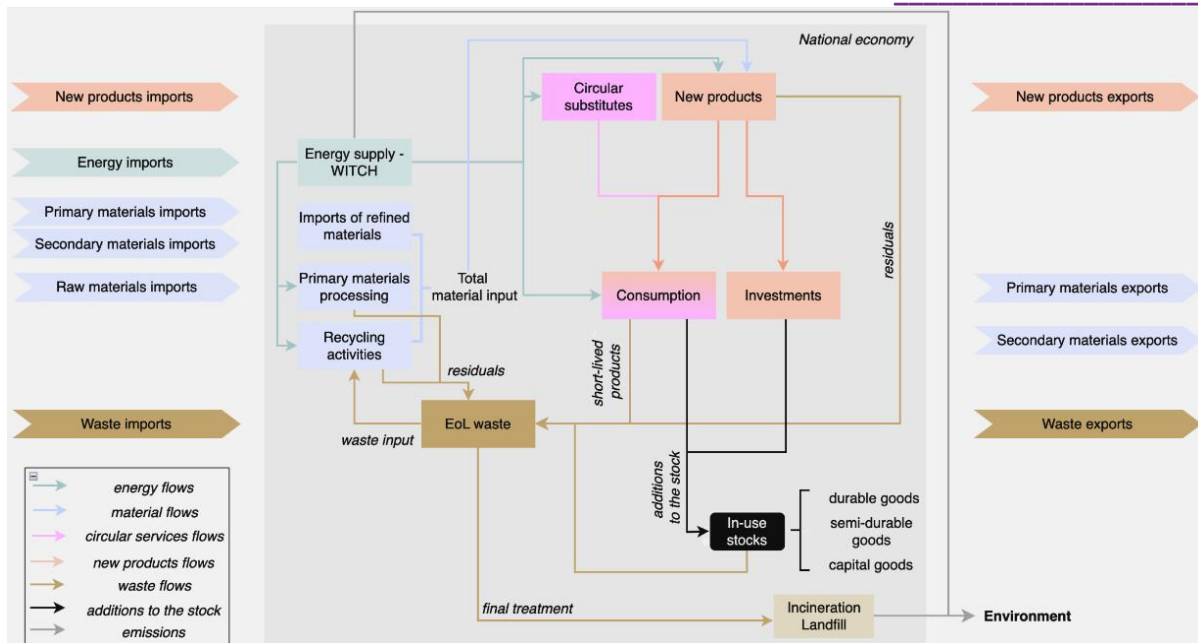


Figure 7. CIRCEE graphical representation

Coupling the LIFE model to a new sector (CE), and single country (Japan) requires some modification to the original framing in Section 2.1. To align the LIFE model with circular economy behaviour (CE) we re-map Avoid-Shift-Improve behaviours onto Sufficiency-Sharing-Repair behaviours, captured in equations in the CIRCEE model (see Figure 8). Mapping between LIFE and CIRCEE draws on both original variables in the empirical data (e.g., car-sharing) and new variables (repairing goods, lowering costs). In this revised mapping 'A' modifiers measure lifestyle heterogeneity across activities which lower expenditure on durable and non-durable goods (sufficiency), 'S' modifiers measure heterogeneity across the uptake of public/shared modes of transport (Sharing), 'I' modifiers measure heterogeneity across maintenance and improvement activities (Repair) (see Figure 8).

Behaviour Type
AVOID excess use and inefficient, unsustainable consumption activities (SUFFICIENCY)
SHIFT from ownership to use (SHARE)
IMPROVE by maintenance or repair (REPAIR)

Figure 8. – LIFE Model mapping across circular economy behaviours (sufficiency, sharing, repair)

In the CIRCEE model 'A' modifiers are applied to mitigation options that reduce unnecessary consumption of goods and avoid energy and material use, 'S' modifiers are applied to mitigation options that substitute for existing alternative options and service-providing systems, 'I' modifiers are applied to all mitigation options that improve the efficiency of existing technologies and end-uses (see Figure 9).

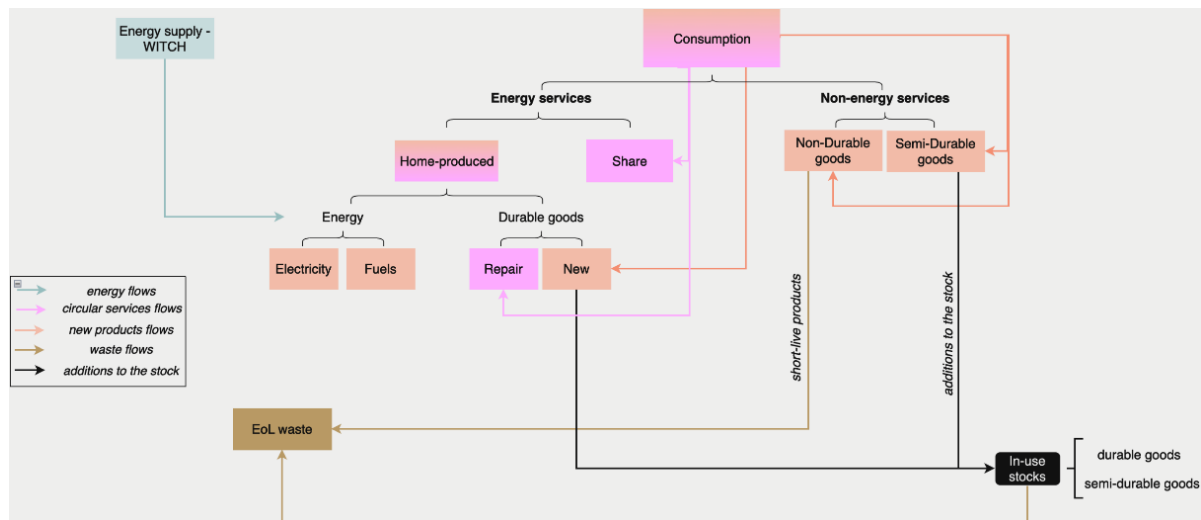


Figure 9. Consumption decisions in CIRCEE. Households consume energy services, semi-durable goods (e.g. furniture and clothing) and non-durable goods (e.g. food and packaging). Energy services are provided either by a sharing market or produced at home. Households produce at home energy services by owning durable goods and consuming energy. Also, households can decide to repair a part of their durable good stock instead of buying conventional new durable goods to replace the old ones.

In a final modification we map the four-lifestyle typology onto the three-household architecture of the CIRCEE model. The revised three-lifestyle typology consists of 'Low-carbon', 'Cautious' and 'Constrained' types. 'Low-carbon' types are an aggregation of the 'Resourceful' and 'Active' groups. Characteristically A-S-I behaviour in this group is purposeful and intentional. 'Cautious' types are disengaged, with low motivation towards A-S-I behaviour. 'Constrained' types face many barriers but are more likely to engage in 'Avoid' behaviours where this is motivated by the need to save money.

The generic coupling approach is applied iteratively, exchanging information between the LIFE model and the CIRCEE model for the three low-carbon lifestyle types. The coupling approach follows the generic 7 step approach (Figure 3)

- Step 1. The LIFE model characterises three lifestyle types with distinct sizes (% of population) and behavioural propensity modifiers.
- Step 2. The modifiers are applied to behavioural equations in the CIRCEE model measuring durable and semi-durable goods expenditures, repair of durable goods, and sharing energy services. These implicitly map onto behaviours including sufficiency, sharing and repair.
- Step 3. CIRCEE model equations, modified by behavioural propensities from the LIFE model, generate behavioural outcomes (e.g., expenditures in durable and semi-durable goods), as well as changes in context relevant to low-carbon behaviours (e.g., income

growth). This step does not affect other scenario assumptions and input parameters used in CIRCEE.

- Step 4. Changes in relevant CIRCEE model outputs are passed back to the LIFE model. These relate to changes in durable goods repair demand, sharing energy services demand, and durable goods and semi-durable goods demand.
- Step 5. The LIFE model applies these to equations predicting cognitively driven lifestyle change [equation 2] and behaviourally driven lifestyle change [equation 3]. The LIFE model uses the exogenous scenario narratives to predict contextually driven lifestyle change [equation 1].
- Step 6-7. The revised low-carbon behavioural propensities are fed back into the CIRCEE model, and then modified CIRCEE equations re-estimate behavioural outcomes, in a repeat of Steps 2-3, and so on, through the timesteps of the full CIRCEE model simulation (e.g., to 2060).

In this next section (and related results) we demonstrate the coupling between the CIRCEE model and the LIFE model focusing on the socio-economic-climatic impact of increasing Extended Producer Responsibility (EPR) fees with sufficiency behaviours for durable goods. The basic steps of this demonstration coupling for sufficiency are as follows:

Step 1. The LIFE model generates three lifestyle types each with a size (% of total) and behavioural propensity modifiers ('I' and 'A'). The 'A' and 'I' modifiers are framed and measured in the LIFE model as both voluntary and intentional and in-voluntary, driven by a lack of opportunity. This important distinction acknowledges heterogeneity in the drivers of lifestyle between enabled households for whom choice is purposeful and intentional and households for whom consumption activity is driven by inequalities across affordability, health, education, and access to infrastructure and services [32, 65-67].

Step 2. The CIRCEE model uses the modifiers to amplify (positive modifier) or reduce (negative modifier) the expenses in durable goods in demand equations and budget constraints.

Step 3. The CIRCEE model reports change in total demand for durable goods at each time step as a proxy for aggregated behavioural change. Comparison of the demand with- and without-behavioural propensity modifiers, shows the secondary effect of low-carbon lifestyle change.

Step 4. Changes in total demand for durable goods for each lifestyle type are passed back to the LIFE model.

Step 5. The LIFE model uses aggregated behavioural changes from the CIRCEE model to re-estimate input assumptions on low-carbon behaviours. The LIFE model also uses demographic changes from the scenario narrative - income, age, and national level statistics

measuring educational attainment/technology access to re-estimate relative size of lifestyle type.

Step 6. The revised low-carbon behavioural propensities are fed back into the CIRCEE model.

Step 7. Modified CIRCEE equations re-estimate behavioural outcomes. Return to step (1) for the next timestep.

5.2 Results and discussion

5.2.1 Scenarios

We assess the effects of increasing EPR fees on energy-using durable goods on diverse lifestyle groups under the presence of new business models, e.g. the sharing economy. More specifically we evaluate the socio-economic-climatic consequences of elevated EPR fees for energy-consuming non-durables in Japan, considering lifestyle changes.

A significant portion of municipal solid waste is composed of semi-durable and durable goods. EPR fees in Japan for household appliances range from 4,400 JPY for a washing machine to 20,000 JPY for a car [68, 69]. Implementing eco-modulation or increasing EPR fees is essential for fueling green product design and conscious consumption [70-74]. The French Circular Economy Law (2020) permits an increase in EPR eco-modulation mechanisms rates beyond 100\% of the EPR fee, up to 20\% of the product's selling price. We assume two scenarios for the evolution of the EPR fee:

- one current policy scenario with no EPR fee increase, labeled 'currentpol';
- one policy scenario, labeled '20%', with EPR fee increase from 4.1% to 20% (annual increase of 6.55%) of the energy-using durable goods' final price as suggested by [71, 74]. 4.1% is the weighted average of recycling and transportation fees for cars and home appliances in total energy-using durable goods, factored into the average selling price of each good in Japan for the base year 2018.

Finally, we implement three lifestyle variants for each scenario and timing structure. Households can adopt various lifestyles to practice sufficiency/minimalism. Japan's Act on Promotion of Consumer Education includes education programs and awareness campaigns aimed at reducing unnecessary goods purchases to promote sustainable consumption:

- The 'Universal' variant assumes no lifestyle heterogeneity among households. Lifestyles are homogeneous.
- The 'Avoid' variant assumes that sufficiency/minimalism behaviours are contextually-driven and associated with materially challenged lifestyles as an unintentional activity. In this variant 'Constrained' households engage in "Avoid" behaviour to save money. Behaviour modifiers for the three lifestyle types are predicted from the 'A' dimension in the LIFE model.
- The 'Improve' variant assumes that sufficiency/minimalism behaviours are

cognitively-driven and in contrast with the 'Avoid' variant an intentional activity. 'Lowcarbon' households participate intentionally in sufficiency behaviours, driven by their environmental beliefs and health orientation. For this variant behaviour modifiers for the three lifestyle types are predicted from the 'I' dimension in the LIFE model.

'Improve' and 'Avoid' variants allow us to model sufficiency behaviour as both a cognitively-driven process and as a contextually-driven process. In this application, the sufficiency modifier is applied only to energy-using durable goods.

5.2.2 Results

Implementing Extended Producer Responsibility (EPR) fees—whether charged at the time of disposal or at the time of purchase of energy-using durable goods—proves to be effective in reducing long-run demand for these goods (refer to Figure 10). When the EPR fee is incorporated into the acquisition price in the CIRCEE model rather than charged at disposal, it has a more significant impact on reducing overall demand for durable goods in the long run. In the long run, the acquisition of durable goods decreases in the acquisition version but increases in the disposal version due to growth effects. Households prefer present consumption and are more sensitive to current income losses than future potential losses. This preference results in a more significant reduction in durable goods acquisitions under the acquisition fee version in the long run. Additionally, the disposal fee version sees higher durable goods acquisitions as households consider selling part of their goods before disposal to avoid the fee. Also, one other reason for the higher acquisition of durable goods in the disposal version is that households consider the possibility of selling part of their durable goods in future periods before the date of disposal, i.e. before paying the EPR fee at disposal. Taking this possibility into account, they increase relatively more their acquisition of durable goods compared to the acquisition version in the long run where the EPR fee cannot be recouped from selling the durable goods in the future.

In the short to medium run, up to 2035, durable goods acquisitions are higher in the acquisition version than the disposal version for two main reasons:

- Energy Efficiency Gains: Most energy efficiency gains are realized before 2035³, reducing the overall user cost of durable goods and incentivizing households to buy more efficient durable goods. However, after 2035, the price effect of the fee at purchase overshadows the energy efficiency effect, leading to an increase in user costs and a decrease of durable goods acquisitions.

³ Energy efficiency gains are calibrated from WITCH data on the evolution of electricity and non-electricity energy for Japan from 2018 to 2050. The scenario considered for the evolution of energy is the one with no climate target implemented under current policies.

- **Timing of Fees:** A disposal fee affects both current and future durable goods, including those purchased before the policy's implementation. In contrast, an EPR fee incorporated into the acquisition price only impacts current and future purchases. Thus, an increase in disposal fees negatively affects the user cost of durable goods currently in use that will soon be disposed of, impacting current income as households must pay an unforeseen fee on previously purchased goods.

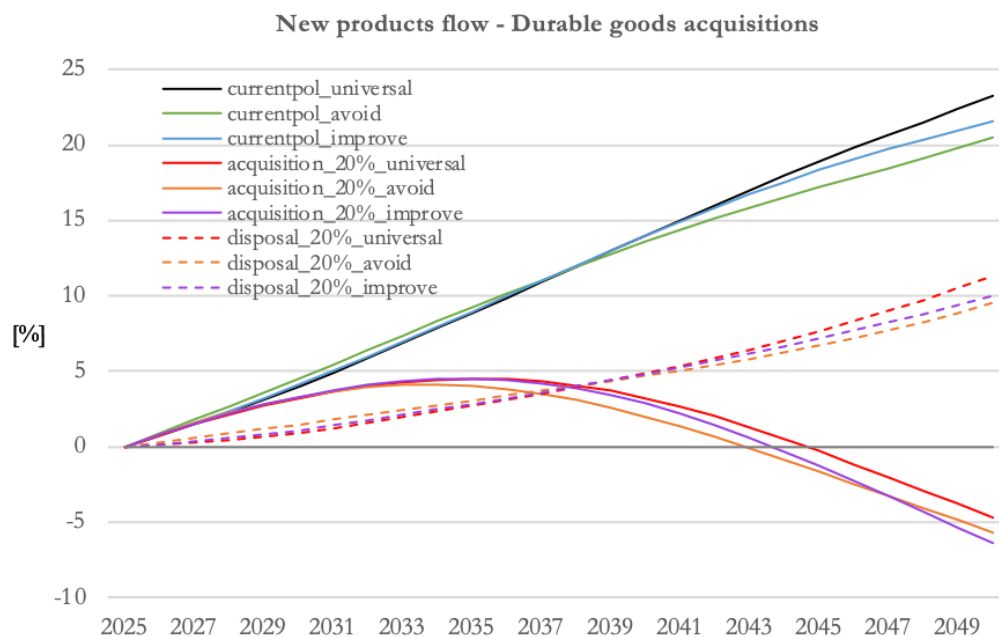


Figure 10. Evolution of total new durable goods acquisitions in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

Focusing on lifestyle variants, the 'Improve' variant yields the best outcomes across all policy scenarios, driven by the behaviour of 'Lowcarbon' households, who represent more than 60% of the population (refer to Figures 10 and 11). In the 'Improve' variant, sufficiency behaviours are intentional and driven by low-carbon cognitions, leading 'Cautious' and 'Constrained' households to engage less in sufficiency behaviour compared to the 'Universal' variant (refer to Figure 11). In the 'Avoid' variant, sufficiency behaviours are driven by the need to save money, resulting in 'Constrained' households reducing their durable goods acquisitions more than in the 'Universal' variant. Additionally, 'Cautious' households tend to avoid certain things in the 'Avoid' variant, leading to fewer energy-using durable goods acquisitions. Overall, lifestyle changes enhance the positive outcomes of EPR fees, whether at disposal or acquisition.

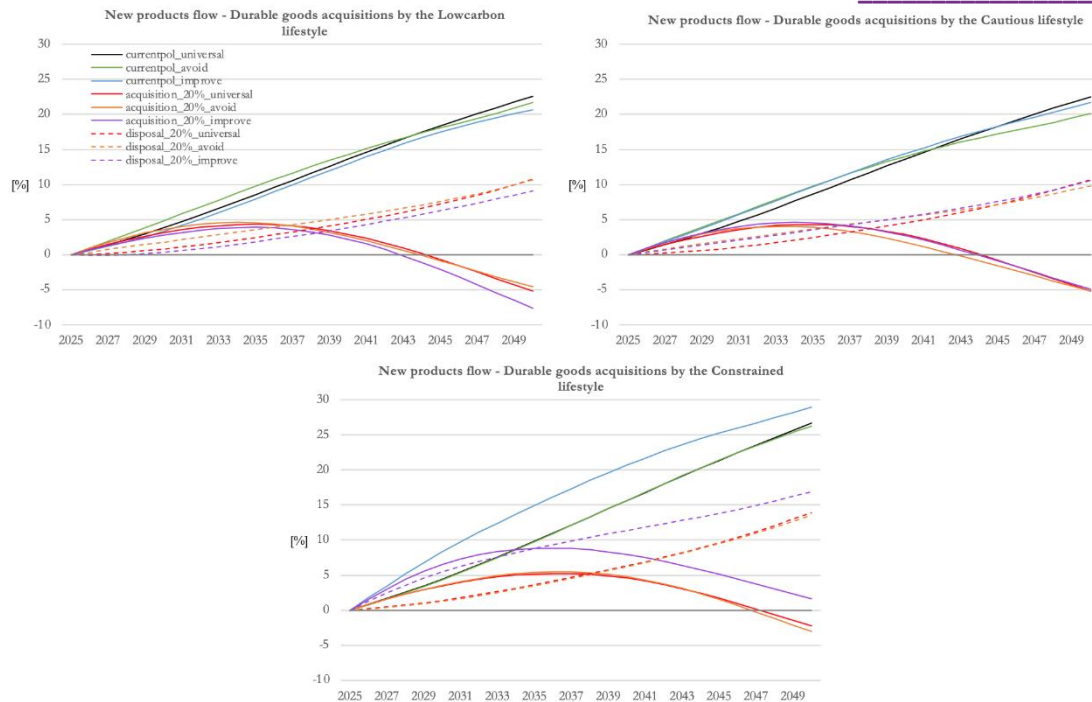


Figure 11. Evolution of new durable goods acquisitions per lifestyle type in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

Implementing higher EPR fees induces a greater shift toward the circular economy (refer to Figure 12). Households face a trade-off between repairing their old durable goods, engaging in the sharing economy, and acquiring new durable goods. Compared to the current policy scenario, households substitute new acquisitions with repairing durable goods and using shared energy services instead of home-produced ones. The decrease in shared energy services in the short-medium run for the acquisition version is driven by higher acquisitions of new durable goods due to the energy efficiency effect outweighing the price effect. In the disposal version, the repairing economy is not fostered compared to the acquisition version as repairing extends the lifespan of goods, delaying disposal and the payment of the EPR fee. In ulterior periods, because of a higher EPR fee, households do not have the incentive to dispose durable goods if they can dispose them in earlier periods for a lower EPR fee at disposal.

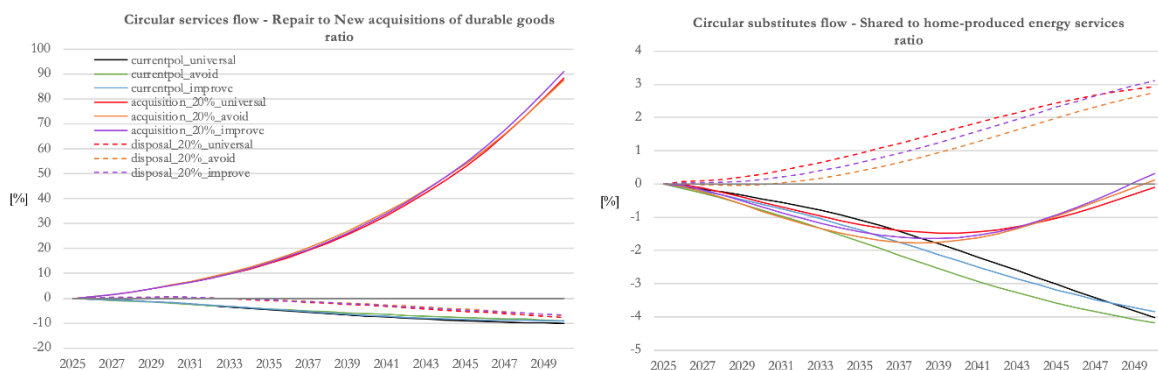


Figure 12. Evolution of total repair durable goods relative to new durable goods and total shared energy services to home-produced energy services in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three scenarios for lifestyle changes. Source: CIRCEE_LIFE simulations

In the long run, higher EPR fees lead households to consume relatively more non-energy services (non-durable goods and semi-durable goods) compared to energy services (see Figure 13). The substitution to non-energy services is driven by a lower acquisition of durable goods, prompting households to re-balance their consumption baskets in favor of circular products and non-energy services in the policy scenario compared to the current policy scenario.

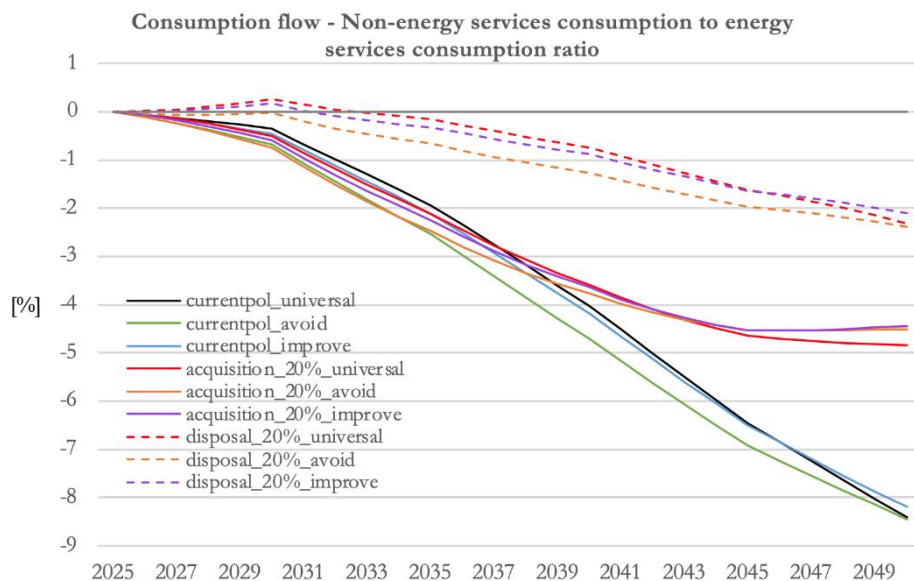


Figure 13. Evolution of total non-energy services consumption compared to energy services in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

Focusing on lifestyle variants, in all policy variants and EPR fee versions, the 'Improve' variant shows the best outcomes with higher repaired durable goods and increased shared energy services, driven by the motivation of 'Lowcarbon' households to engage in sufficiency behaviour by relying less on new acquisitions of durable goods (refer to Figure 14). 'Constrained' households also show higher repair durable goods compared to new acquisitions of durable goods, driven by a higher consumption of home-produced energy services compared to shared ones. 'Cautious' households repair their durable goods more in the 'Avoid' and 'Improve' variants compared to the 'Universal' variant due to higher energy service needs, although differences are not significant. The sharing economy is more fostered in the 'Improve' variant due to 'Lowcarbon' households. 'Constrained' households consume more shared energy services in the 'Avoid' variant for all policy scenarios, driven by the need to save money and to avoid certain things. These (unintentionally) decreases relatively more their acquisition of durable goods to produce energy services at home compared to the

'Universal' variant. 'Cautious' households consume relatively more sharing energy services in the long run compared to home-produced energy services in the 'Avoid' variant for the disposal fee version.

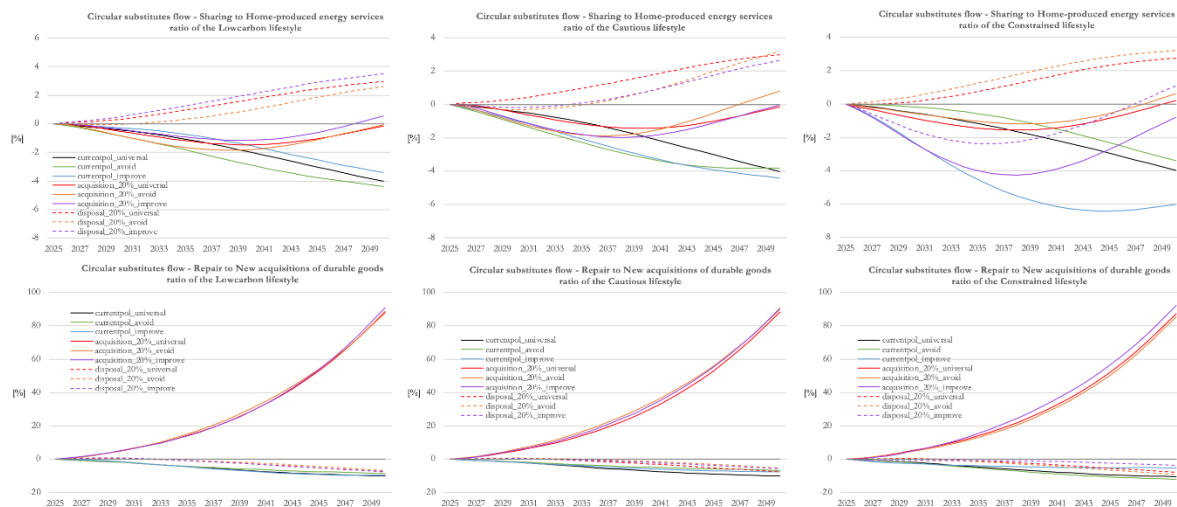


Figure 14. Evolution of repaired durable goods compared to new acquisitions of durable goods, and shared energy services compared to home-produced energy services in deviation from year 2025 per type of lifestyle. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

The lower acquisition of durable goods in the 'Improve' variant for 'Lowcarbon' households, and in the 'Avoid' variant for 'Constrained' and 'Cautious' households, leads to a substitution towards non-durable and semi-durable goods in the long run compared to the current policy scenario (refer to Figure 15). 'Constrained' households react more to policy changes due to liquidity constraints, whereas 'Lowcarbon' and 'Cautious' households can adjust their asset portfolios in response to policy changes and have "smoother" consumption changes.

Overall, 'Constrained' households, driven by contextual factors, exhibit unintentional behaviour in the 'Avoid' variant, leading to higher engagement in circular services but lower engagement in the 'Improve' variant. 'Lowcarbon' households, motivated by their low-carbon cognitions, show intentional behaviour in the 'Improve' variant, resulting in higher engagement in circular services but lower engagement in the 'Avoid' variant. 'Cautious' households, due to their tendency to avoid certain things in the 'Avoid' variant, acquire relatively fewer energy-using durable goods and engage more in the sharing market as an unintentional behaviour. These lifestyle changes support the success of EPR policies at the aggregate level, particularly in the 'Improve' variant, driven by the proactive behaviour of 'Lowcarbon' households.

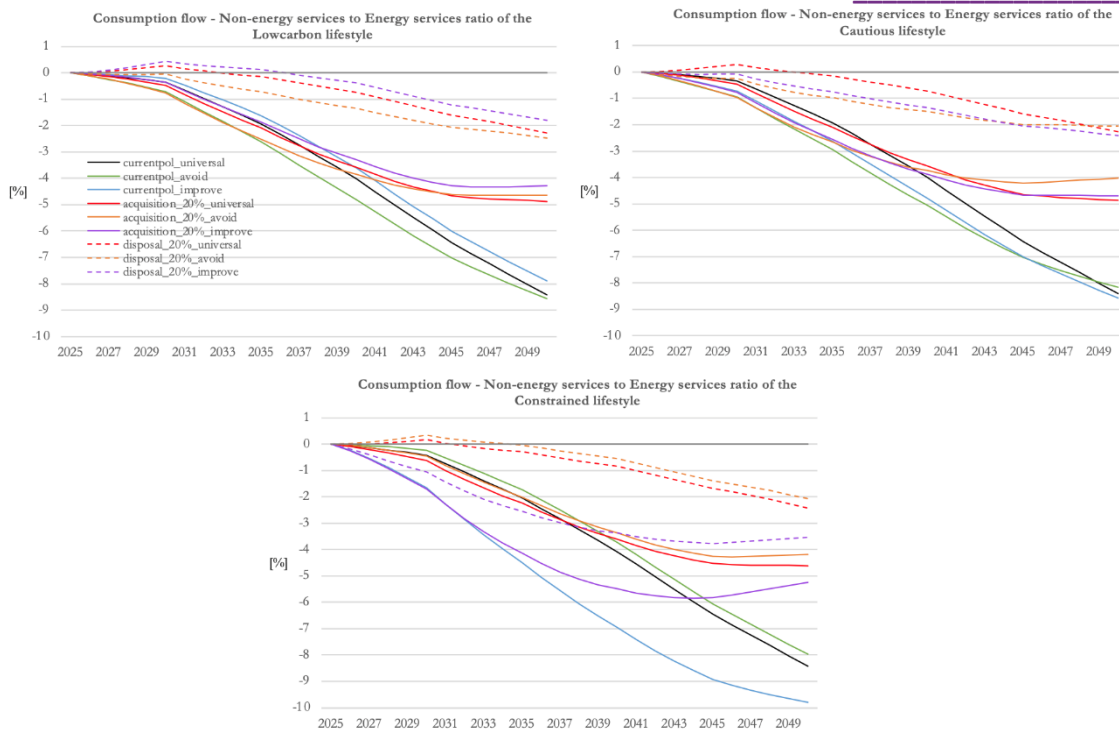


Figure 15. Evolution of non-energy services consumption compared to energy services in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

The dynamics of the in-use stock of durable goods follow those of durable goods acquisitions (refer to Figures 10 and 16). The EPR fee at purchase yields the best outcomes in terms of material needs reductions, especially when coupled with the 'Improve' scenario. Material imports and gross additions to in-use stocks are lower due to reduced material needs for durable goods production. In the disposal version, higher material needs and in-use stocks result from higher durable goods acquisitions and a greater shift towards non-energy services. The 'Avoid' variant has less beneficial outcomes due to higher material needs from the substitution towards non-energy services⁴, higher capital investments, and increased durable goods acquisitions compared to the 'Improve' variant. Also, the primary deficit of the government is lower in the disposal version thanks to higher fiscal revenues from higher V.A.T revenues. This lower primary deficit in the 'Avoid' variant is a positive income shock to the materially-endowed agents who own the government debt⁵, driving up the consumption of goods (refer to Figure 17). Overall, resource security improves across the policy scenarios.

⁴ Non-durable goods and semi-durable goods represent approximately 85% of material needs to produce consumption goods in Japan.

⁵ In CIRCEE, only domestic agents own the public debt because in Japan most of the debt is owned by domestic investors

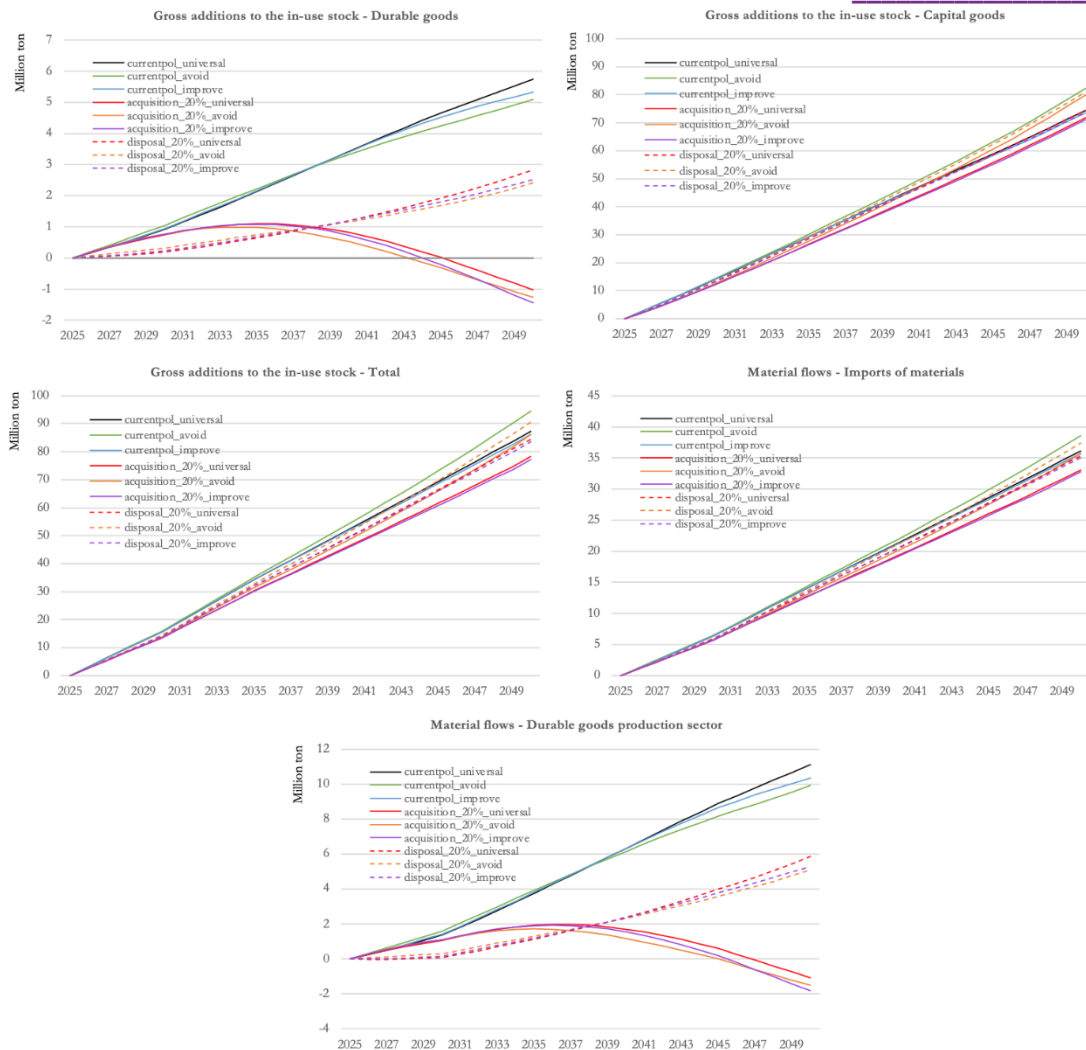


Figure 16. Evolution of material in-use stock and flows, waste flows and material imports in Million ton in deviation from year 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

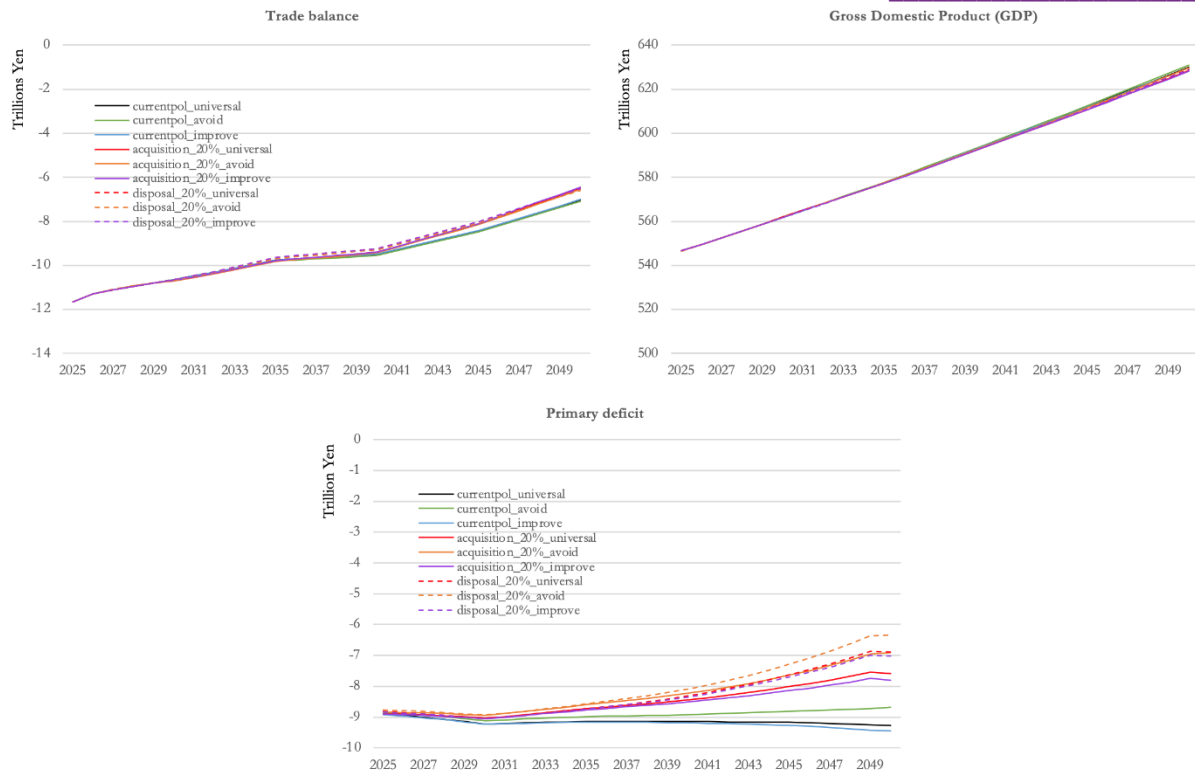


Figure 17. Evolution of the primary deficit, trade balance and GDP in Trillions of Yen. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

Municipal waste flows decrease across all policy scenarios (refer to Figure 18). By 2050, municipal waste generation is 3 million tons lower than the current policy scenario in the acquisition version and 2 million tons lower in the disposal version. The 'Improve' and 'Avoid' variants yield similar outcomes in the long run, reducing more municipal waste compared to the 'Universal' variant. In the short to medium run, waste generation is higher in the 'Avoid' variant. However, in the 'Improve' variant, the re-balancing of the consumption basket in favour of non-energy services by the 'Lowcarbon' lifestyle offsets the initial reduction in municipal waste from lower durable goods disposal. Industrial waste flows are lower in the policy scenarios, with the 'Improve' variant showing the greatest reduction due to lower consumption goods production and material losses during production.

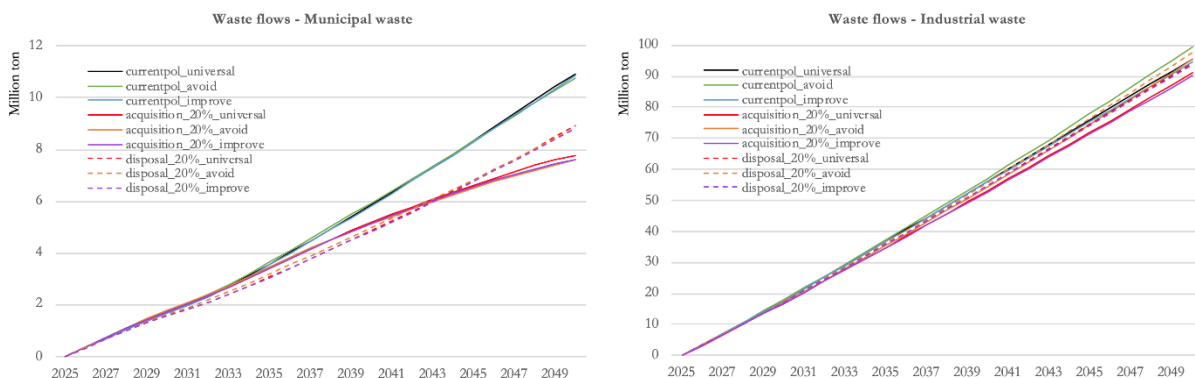


Figure 18. Evolution of waste flows in Million tons compared to 2025. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

In the policy scenarios, household energy use is lower by only 0.1 EJ in 2050 compared to 2025 in the acquisition version (refer to Figure 19). While households reduce their purchases of new durable goods, they do not necessarily decrease their consumption of energy services in response to higher EPR fees. In fact, to maintain their energy service consumption, they increase their use of circular goods and services. The greatest reduction in households' energy use in the disposal version is driven by higher consumption of shared energy services compared to home-produced ones, a substitution towards non-energy services, and a lower energy efficiency. The higher energy efficiency in the disposal version is due to a lower share of less energy efficient (repaired) durable goods in the total stock of energy-using durable goods compared to the acquisition version. The overall impact on energy use is not significant due to higher energy needs for sectors producing non-durable goods and shared services, which counterbalance the initial decrease in household and durable goods sector energy use. Also, the durable good producing sector represents only 1\% of the total energy use of all production sectors. The overall long-term decrease in final energy use is driven by energy efficiency gains from the WITCH model.

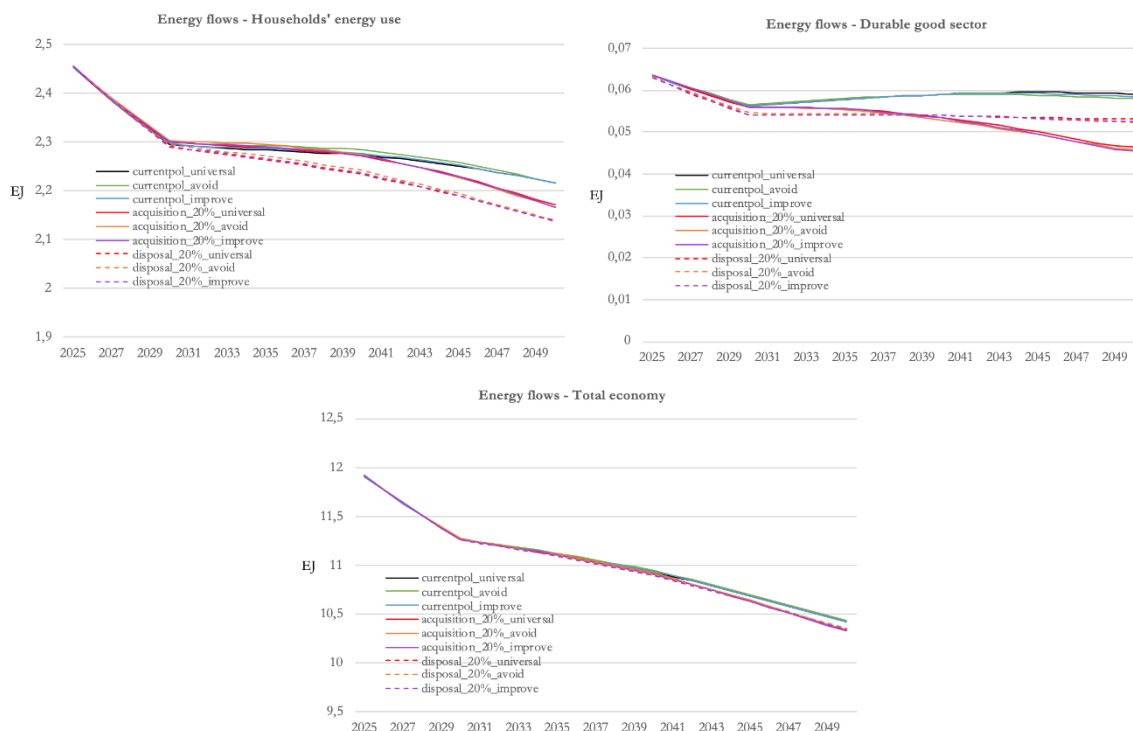


Figure 19. Evolution of energy use in EJ. 'currentpol' and '20%' are two policy scenarios. 'acquisition' and 'disposal' are two versions for the model for the implementation of the EPR fee. 'universal', 'avoid' and 'improve' are three variants for lifestyle changes. Source: CIRCEE_LIFE simulations

5.2.3 Discussion and further research

To conclude, according to the model's results, EPR fees on energy-using durable goods can encourage households to engage in circular consumption choices. The effectiveness of EPR fees is significantly enhanced by the behavioural responses of consumers. The model shows that these fees will increase the saliency of environmental consumption, making consumers more aware of the consequences of their choices. As a result, the higher prices for durable goods lead households to substitute circular services, reducing the material and energy requirements for producing these goods.

In addition, the model suggests an important insight regarding policy design. The timing of the EPR fee imposition (at purchase versus disposal) plays a crucial role in determining its effectiveness. Imposing the fee at the point of purchase creates an immediate financial incentive for consumers to opt for circular products and services, thereby reducing waste disposal reducing material needs in the long run, more effectively than a fee imposed at disposal.

When adopting such policies, it is essential to consider consumer-driven substitution mechanisms that may influence the intended benefits for resource use, waste production, and greenhouse gas emissions. Although the policy may help slow the resource loop for certain products, its effect on GHGs emissions may be limited. Although an increase in EPR fees leads to a reduction in net additions to durable goods in-use stocks, their impact on waste generation can be mitigated by adapting consumption practices. In response to the policy, households may shift their consumption towards goods that consume more materials and energy during production, such as non-durable goods. This shift undermines the initial positive effects of fees on reducing total waste generation and energy consumption. Additionally, a move towards sharing services increases the energy needed to produce these services, which partially offsets the reduction in household energy consumption due to the policy.

Additionally, the success of EPR fees is also influenced by household lifestyles. Households with a strong low-carbon cognitions are more likely to respond positively to EPR fees, reinforcing the need for complementary policies that promote environmental awareness and education. Particularly, households driven by low-carbon cognitions will be crucial for the success of the circular economy, as seen in the 'Improve' variant, in high-income countries. Meanwhile, contextually driven households, which represent a larger share of the population in low-income countries, also play a significant role in fostering circular economy strategies, as seen in the 'Avoid' variant, in these regions. Therefore, there exists potential synergies between economic and behavioural instruments.

It is important to acknowledge that EPR schemes also exist for other categories of goods, such as semi-durable and non-durable items, including packaging and furniture. If the model were to simultaneously incorporate EPR schemes across these various categories, the resulting consumer behaviour changes could lead a broader shift in consumption patterns,

potentially leading to a reduction in consumption levels and energy levels at the aggregate level. This suggests that an integrated approach to EPR implementation could play a significant role in driving sustainable consumer choices.

The outcomes are contingent on the specific structure and parameters of the model. In the case of CIRCEE, on the consumer side, the most influential parameters are the substitution elasticities which, as with all macroeconomic models, drive the model's dynamics. Consumption choices depend on the range values of these elasticities. There is a need for more comprehensive data on the sharing economy and repair activities to accurately estimate the substitution elasticities that influence consumption behaviours. Moreover, many countries either do not track or only partially track sharing economy data, which remains challenging to quantify and define. Until such data are widely accessible, models must rely on arbitrary range values for these crucial parameters.

The current version of CIRCEE does not account for endogenous green product design, so whether the EPR fee provides incentives to producers to engage in green product design is not considered. While behavioural plasticities can enable many CE strategies, they rely on design technology aimed at extending product lifespans. Additionally, studying firms' pricing strategies related to green product design would be interesting. Model results show that higher EPR fees can modify consumer habits towards increased repair and longevity of durable goods. Producers, recognizing potential decreases in turnover and the presence of a sharing market, might design more durable products with a premium to incentivize new purchases. EPR fee reductions could be offered to consumers who buy durable goods that are more durable thanks to green product design. A detailed life-cycle assessment for specific products, requiring extensive research and data collection on new green design technologies and cost implications, is necessary. This would necessitate a disaggregated product representation in CIRCEE, focusing on reparability and durability, and could involve linking product-focused industrial ecology models with CIRCEE.

In addition, while the local impact on GHGs emissions may be limited in Japan, reducing material needs—most of which are imported into Japan—could have a broader global impact. This reduction could decrease material production in resource-rich countries, leading to less energy use to produce the materials and, consequently, lower GHGs emissions globally.

The advancement of CIRCEE depends on open access to datasets and sufficient funding to study CE's multifaceted aspects, from micro-level green product design specifics to macro-level resource efficiency and economic growth implications. Securing dedicated funding is critical for extensive data collection. As an open-source model, CIRCEE can benefit from research community support, fostering collaborative development through shared knowledge and resources. Such a model would provide policymakers with valuable insights, enabling well-informed decisions that balance the synergies and trade-offs of CE strategies.

6. Multi-domain application using IMACLIM-R (CIRED, Oxford)

6.1 Coupling Approach

An important distinction in low-carbon lifestyles research is between domain-specific lifestyles and ‘general’ lifestyles across domains. Do we have a single lifestyle? Or a lifestyle specific to food, leisure, travel, homes, or energy use? In social science literatures lifestyle is seen as a universal concept. People that lead a low-carbon lifestyle are characterised by strong environmental intentions, and a desire for a greener, self-identity [45, 75]. In low-carbon research lifestyles are commonly viewed as both ‘domain-specific’ or ‘generalisable’ across domains [2, 76]. The disadvantage of the latter point is that lifestyle becomes closer in meaning to behaviour and does not account for underlying social processes that drive lifestyle consistency [45]. In this demonstration using Imacim-R, we couple the LIFE model simultaneously across two different domains of consumption use: home energy and transport. In all simulations lifestyle change for each lifestyle type are driven by combined actions across home energy and transport (behaviour-driven lifestyle change), cross-situational motivations (cognitive-driven lifestyle change) and social and material context (context-driven lifestyle change). Interactions between these three drivers are important to understanding spillover effects [75].

The Imacim-R model is primarily grounded in macroeconomic theory and draws inspiration from the Arrow-Debreu model by basing its representation of the economy on equilibria in both value and physical flows, through an exercise in harmonising energy balances and national accounting data. As such, it falls into the category of computable general equilibrium models, but distinguishes itself with this dual accounting approach aimed at representing the technical and thermodynamic constraints linked to energy processes. Unlike most IAMs, the Imacim-R model features a multisectoral macroeconomic structure that takes into account sectoral interdependencies in price formation, competitiveness, and production levels. Another distinctive aspect of its formalism is the explicit description of the evolution of technical and non-technical parameters over time (Figure 20), investments, and commodity prices (notably energy) across different sectors of the economy (notably transport, industry, residential, and electricity). The evolution of these parameters is concretely described in nexuses.

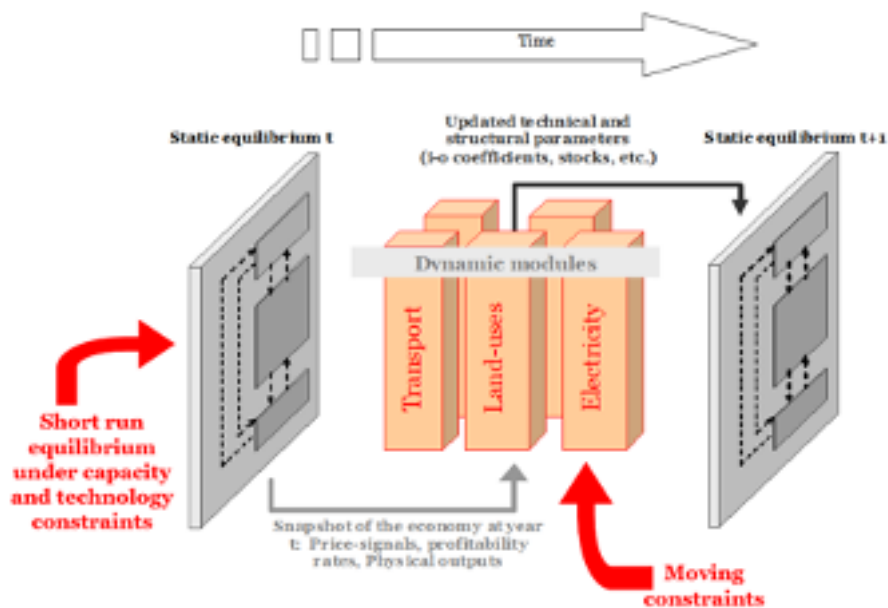


Figure 20 : Representation of the recursive structure of Imaclim-R

The steps for coupling are fundamentally identical to those for coupling to a single domain (e.g., MESSAGEix-Buildings). The main variation is that parameters estimated from the LIFE model are measured at the global, domain level (compared to global, universal level for the MESSAGEix-Buildings model)⁶. In the coupling process we focus on 'I' (improve) and 'S' (shift) behaviours.

The basic steps of demonstration coupling with the Imaclim-R model is as follows:

Step 1. The LIFE model generates four lifestyle types each with a size (% of total) and behavioural propensity modifiers ('I' and 'S' homes and 'I' and 'S' transport).

Step 2. In the homes domain the Imaclim_R model applies the 'I' modifiers to equations influencing the choice of building performance level at the time of purchase or renovation. It applies the 'S' modifiers to equations representing the choice of heating system (especially when it is replaced). In the transport domain the Imaclim-R model applies the 'I' modifiers to equations influencing the intensity of carpooling practice and the 'S' modifiers to equations influencing the choice of motorization for light-duty vehicles.

Step 3/4. The Imaclim-R model reports change in the intensity of adoption of low-carbon behaviours for 'I' and 'S' behaviours within both domains for each lifestyle type which are passed back to the LIFE model. These changes are monitored at an aggregate level, based on the carbon footprint of the cumulated behaviours concerned (see details below).

Step 5. The LIFE model uses aggregated behavioural changes from the Imaclim-R model to re-estimate input assumptions on low-carbon behaviours for each domain. The LIFE model also

⁶ The life model can introduce behavioural heterogeneity at the global level (i.e., without disaggregating to regions), universal level (i.e., without disaggregating to domains such as homes, travel, or food), or domain level

uses demographic changes from the scenario narrative - income, age, and national level statistics measuring educational attainment/technology access to re-estimate relative size of lifestyle type.

Step 6. The revised low-carbon behavioural propensities are fed back to the Imaclim-R model.

Step 7. Modified Imaclim-R equations re-estimate behavioural outcomes. Return to step (1) for the next timestep.

Operationally, the coupling involves the internalization of the LIFE dynamics into the Imaclim framework. This is concretely achieved through:

- The addition of a LIFE nexus representing the evolution of the population and its characteristics as described by the LIFE model. Each year, this nexus describes the evolution of the proportion of different household types, as well as the evolution of characteristic variables: cognitions, behaviour propensities, etc.;
- The adaptation of the "buildings" and "cars" nexuses, which respectively describe the dynamics of the residential building stock and the light-duty vehicle fleet. This adaptation firstly involves disaggregating the description of certain individual choice processes described in the nexuses to distinguish between different household types. Thus, we move from representing behaviours of a representative household to those of 4 representative households. Secondly, it involves modifying certain choice processes to account for differences between household types. The principle adopted is that of different valuations of positive and negative externalities of various options in the choice function. For example, in the logit function that governs the choice of heating system technology for homes, the modified LIFE variable will allow the representation of additional costs linked to negative externalities (for fossil-based systems) that households will consider to varying degrees based on their propensity to adopt low-carbon behaviours.

The variable produced by the IMACCLIM model, representative of the intensity of adoption of low-carbon behaviours across the two domains, which is then used by the LIFE model to calculate annual changes in cognitions, is the average carbon footprint of each household type for the "car use" and "residential" sectors. This indicator allows for the aggregation of sensitivity to the four tested behaviours. It thereby enables the representation of the spillover effects that the adoption of certain low-carbon behaviours may have on behaviours in other domains.

6.2 Results

In this first coupling experiment, we tested two scenarios: a baseline scenario (NPI), and a scenario making it possible to reach a target of limiting global warming to 2°C. The changes that occur in the second scenario are mainly driven by a trajectory of growth in the price of carbon, which induces changes in the investment or consumption behaviour of businesses, households and governments.



Through this coupling, we distinguish four types of households: the 'Resourceful', the 'Active', the 'Constrained' and the 'Cautious', which have different initial cognitions and behaviours, and different behavioural dynamics (Equations [2] and [3]). The consequences of these differences on the carbon impact of individuals' decisions over the period 2025-2050 can be observed at an aggregate level through the individual household carbon footprint (Figure 21). This footprint is calculated solely on emissions linked to car use and the use of residential buildings. We observe a decreasing footprint for all household types in both scenarios, but with a very different rate of reduction. The 'Constrained' are the slowest to reduce, the 'Resourceful' and 'Active' are the fastest (very close to each other), and the 'Cautious' are in an intermediate position.

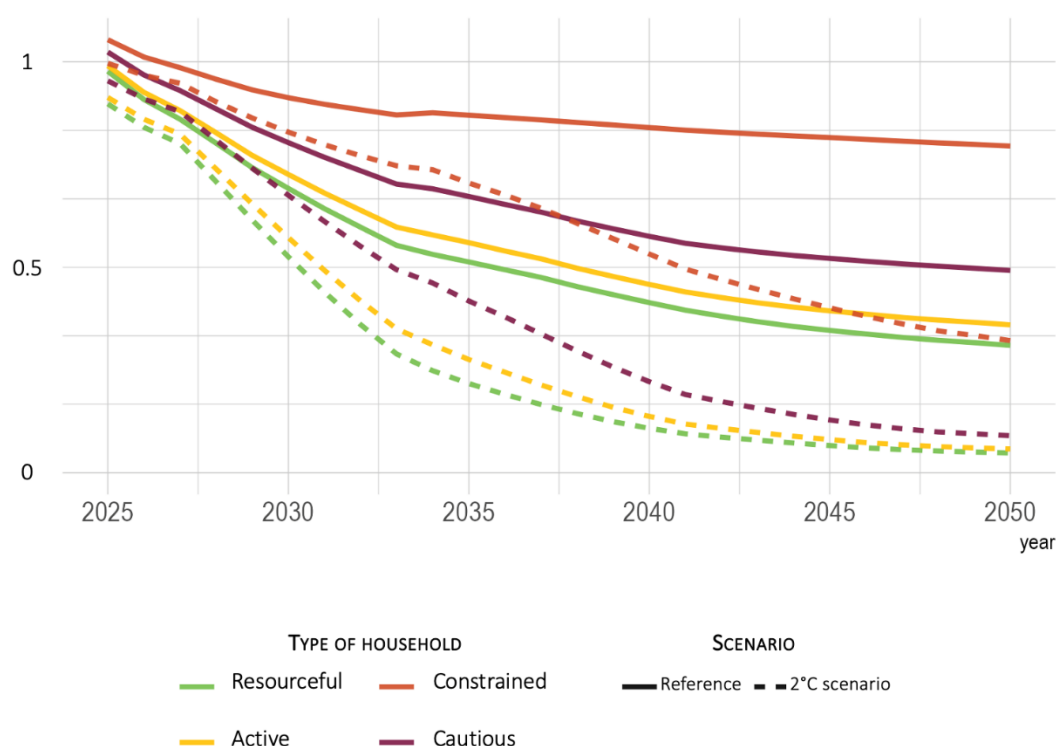


Figure 21 Individual carbon footprint for car mobility and residential use per type of household ('y' axis measuring tonnes of CO₂ equivalent per year per capita, 1=value in 2020)

Analyses of behaviour on a more granular scale provides a better understanding of these results. In the area of mobility, there are two cases in point. For the choice of vehicle engine (electric or Internal Combustion Engine), the differences between household types are significant at the outset, and increase over time. For car-pooling behaviour, the difference is significant at the outset, but only increases slightly because this is a behaviour that has a high degree of inertia and in the model. This is also a potential 'replacement' behaviour for vehicle ownership. In the residential sector, the choice of heating system tends to follow the first case. The sensitivity of this choice is also relatively high. As for the choice of building type, the differences between household types are significant, but remain overall within a relatively low

range (<15%), particularly in the Southern Global countries. The additional costs of the low-energy buildings considered in the model are in fact relatively high.

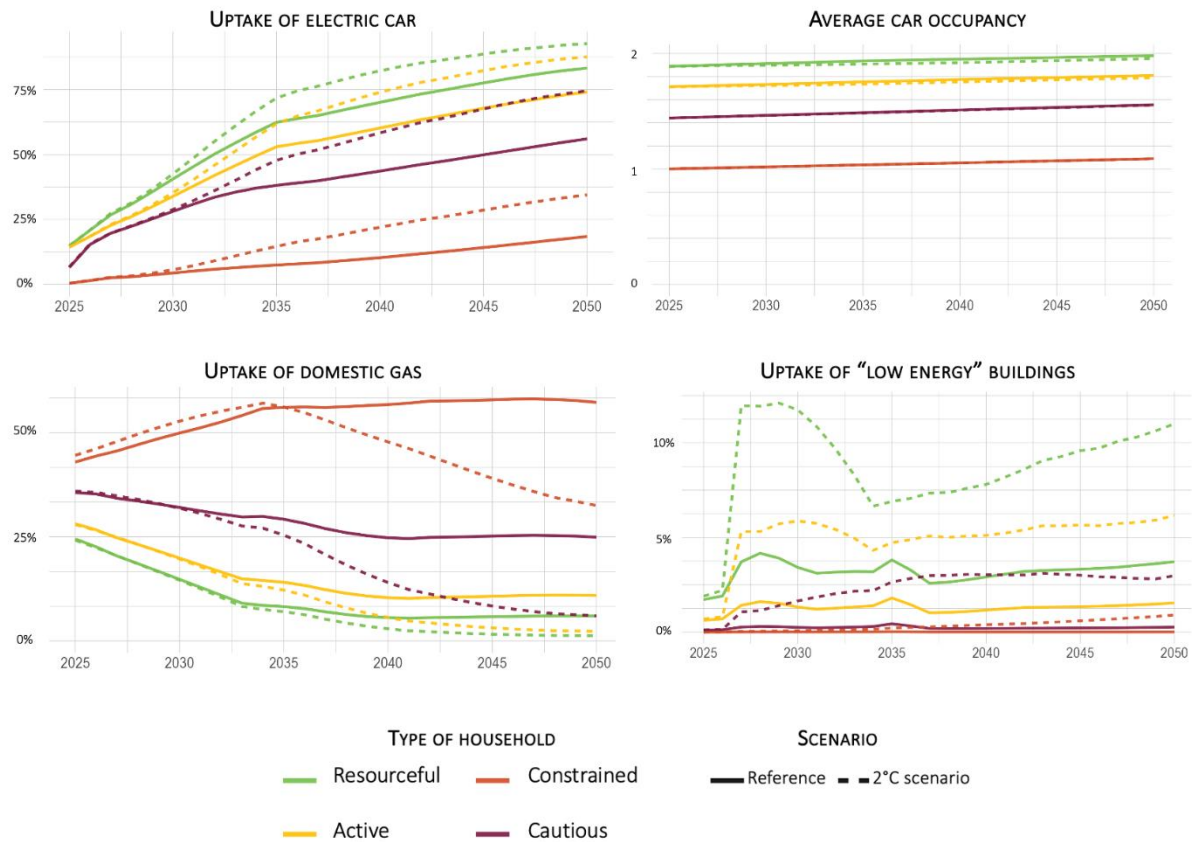


Figure 22. Representation of behavioural changes for different types of households across the four targeted behaviours. The representation is not exhaustive for the residential sector, as there are five possible choices of heating systems (coal, domestic fuel, domestic gas, electric heater, and heat pump), as well as three types of buildings (standard, low carbon, and very low carbon). Here, we have depicted one of the significant behaviours.

6.3 Discussion

This first experiment serves primarily as a demonstrator and is intended to test the consistency and plausibility of the changes introduced by the cross-domain coupling. In this version, only the effects of differences in cognition and the feedback loop from cross-domain behaviour to cognition are considered. However, we would like to use this coupling to explore other issues. The first relates to equity issues associated with the climate transition. To do this we will need to introduce - at least - heterogeneity in the incomes of different types of households. In this way, over and above the external costs considered and the effects of preferences, differences in the ability of households to make low-carbon choices would also be considered, which is a factor of the first order. Following on from this we could potentially simulate the impact of domain specific monetary policy incentives intended as a 'catalyst behaviour' for encouraging 'spillover effects' [75]. In the wider literature evidence for 'spill-over' effects is limited, particularly in understanding when and how cross-situational motivations (e.g., pro-environmental identity) may predict behaviour and when contextual factors (affordability, skills, technology) are more important.

Further developments on this point are thus envisaged in the remainder of the project, potentially requiring the mobilisation of new data sets, before exploring alternative scenarios.

7. Conclusions

Coupling with the LIFE model enables global IAMs to simulate dynamic interactions between distinct mechanisms of low-carbon lifestyle change and the techno-economic processes endogenous to global IAMs. The LIFE model distinguishes contextually, cognitively, and behaviourally-driven lifestyle change mechanisms respectively, referred to as 'Opportunity', 'Identity', and 'Experience effects. It advances conceptual reasoning and methodological practice beyond the conventional approach to lifestyle change in global IAMs that maps scenario narratives into exogenous and static assumptions on behaviour and activity in discrete end-use sectors (homes, mobility, food).

The novel implementation of the globally-applicable lifestyle change model (LIFE) to the integrated assessment frameworks described and demonstrated in this report makes several important contributions.

Coupling the LIFE model to the MESSAGEix-Buildings model (Case Study 1) we demonstrate the impact of the lifestyle change mechanisms as they apply to final energy demand for space heating in global residential buildings. We illustrate how the cognitively-driven lifestyle change mechanism can be aligned to a distinctive lifestyle change scenario narrative (widespread shift in values) to reduce the activity gap between lifestyle types under different climate policy scenarios. Currently global IAMs model a limited range of transformative solutions towards lifestyle change [8, 10]. Encapsulating and integrating the three key elements of low-carbon lifestyle; behaviour, cognitions and context, the LIFE model widens the potential 'toolkit' of IAMs towards modelling social processes and the mechanisms of socially oriented change [9]. We provide an open-source lifestyle change model and code to support further linkages to external IAMs and end-use sector models.

Coupling the LIFE model to the CIRcular Energy-Economy model (CIRCEE)) (Case Study 2) we demonstrate the versatility and adaptability of the LIFE model. The LIFE model can measure behaviours at the global, regional or country level. In the application to the CIRCEE model we shift emphasis from a global representation (in MESSAGEix-Buildings) to a single country (Japan). The LIFE model notionally frames behaviours across the A-S-I framework. Drawing on the strong empirical foundations of the LIFE model, we map A-S-I behaviours onto circular economy behaviours (CE). We also reduce the lifestyle types to three groups and re-estimate the unique drivers of lifestyle change (contextual, cognitive, and behaviour) from a revised but similarly robust empirical model.

Coupling the LIFE model to the Imaclim-R model we further demonstrate the versatility of the LIFE model by coupling simultaneously across two key domains of practice. Although this work is still in the earlier stages of coupling development it has potential to test unique scenarios, particularly related to spill-over effects [75].

We are planning further work testing lifestyle-related scenarios that draw on both endogenous and exogenous mechanisms of lifestyle change. A natural evolution of the exogenous mechanism (context-driven lifestyle change) is to test pathways involving more stringent

socio-economic challenges (such as SSP3 'A Rocky Road' a World in which economic development is slow, consumption is material intensive, inequalities persist or worsen over time). In terms of new context-driven scenarios it is possible to align the LIFE model with other important contextual drivers such as digitalization trends (widening access to technology and related skills), cultural trends (threats to community and social cohesion), and household trends (urban/rural, household size, life-cycle).

Work is also underway to develop the endogenous coupling by differentiating the lifestyle types by property type (MESSAGEix-Buildings), and income (MESSAGEix-Buildings and Imaclim-R). This will enable us to introduce the endogenous lifestyle change mechanisms more deeply into the cost and pricing-based architecture of the models.



8. Appendices

CIRCEE-LIFE Coupling, and Calibration

The raw values for behavioural frequencies/modifiers from the LIFE_CE model are appropriately recalibrated to the scale and context of the macroeconomic model CIRCEE. Essentially, the recalibration routine compares lifestyle type variation in the LIFE_CE world with lifestyle type variation in the CIRCEE world; it adjusts the behavioural propensities accordingly so that the two are in correspondence.

The recalibration methods must ensure smooth integration and avoid unrealistic step changes in behaviour modeling. In the context of CIRCEE, changes in lifestyle types need to be captured dynamically because the model has a dynamic structure. To find the best value for modifiers in CIRCEE, we choose the bisection search method.

The algorithm used consists of a loop in which the lifestyle modifiers are tuned successively. When a modifier is tuned for a specific “circular” activity, the other modifiers are fixed. This loop is necessary because a lifestyle modifier change may slightly impact the behaviour of other lifestyles. The loop stops when we reach a fixed point and the lifestyle modifiers do not evolve after a new iteration. In the current version, lifestyles affecting different circular activities cannot be carried out at the same time, as it could cause infeasibility. CIRCEE can only be run for specific A-S-I behaviours, such as sharing, repairing, and sufficiency, individually. In the future, users will be able to run different A-S-I behaviours simultaneously. Sufficiency relates to the decrease of expenditures of semi-durable and energy-using durable goods in CIRCEE.

The recalibration routine takes as input in the LIFE_CE model's behavioural frequencies for the universal lifestyle and for each heterogeneous lifestyle:

1. The first run of the CIRCEE model, called *run_0*, in which all modifiers are set to zero reproduces the results of the LIFE_CE model for the universal case in which lifestyles are homogenous across heterogeneous households. In response to exogenous shocks and policies, the behaviours of the three different households in the universal case can still be different because they are also heterogeneous in their budget constraints.
2. Depending on the ‘circular’ behaviour studied (repair, share and sufficiency), the relevant output of CIRCEE (for example, the volume of sharing energy services for sharing behaviour, the volume of durable good repairing investments for repair behaviour ...) is taken as a proxy for the LIFE_CE behaviour frequency. For example, a 10% difference in the behaviour frequency between the universal case and the “Cautious” lifestyle in LIFE_CE should be equivalent to a 10% difference between the values of the corresponding output for the “Cautious” lifestyle in CIRCEE *run_0* and in its tuned version.
3. As a specific A-S-I behaviour of one lifestyle is also impacted by the modifiers of other lifestyles, the modifiers are iteratively recalibrated until we reach a fixed point, where the modifier values do not evolve between two iterations.

Table 3 shows the values of matched LIFE frequencies during the recalibration process as well as the behavioural modifier values in LIFE and the recalibrated CIRCEE behavioural modifiers used to endogenize lifestyle changes for sufficiency, repair and sharing. It is worth noting that the value of some recalibrated modifiers (repair and sufficiency) can be close to the one of the LIFE model, hinting a close behaviour of the two models regarding these A-S-I behaviours. The values are for Japan. In a future version it will include the EU27 region.

		Matched Frequencies in LIFE	Pre-calibrated modifiers in LIFE	Recalibrated modifiers in CIRCEE
<i>Sufficiency_AVOID</i>	Universal	0.363745	0	0
	Lowcarbon	0.320882	0.133579	0.1115112304
	Cautious	0.292805	0.242277	0.1858520507
	Constrained	0.387203	-0.060583	-0.0601196288
<i>Sufficiency_IMPROVE</i>	Universal	0.4936561	0	0
	Lowcarbon	0.5249899	-0.059685	-0.0595031738
	Cautious	0.4331766	0.139619	0.1161315917
	Constrained	0.3364443	0.467274	0.3072082519
<i>Repair_AVOID</i>	Universal	0.075201	0	0
	Lowcarbon	0.052485	0.432816	0.4335456847
	Cautious	0.046262	0.625554	0.6269279479
	Constrained	0.129535	-0.419459	-0.4191520690
<i>Sharing_IMPROVE</i>	Universal	0.1352	0	0
	Lowcarbon	0.1407	-0.039090263	-0.0346069335
	Cautious	0.1159	0.166522865	0.1234741210
	Constrained	0.1389	-0.026637869	-0.0231567382
<i>Sharing_AVOID</i>	Universal	0.0418342	0	0
	Lowcarbon	0.0302964	0.38082965	0.2383056640
	Cautious	0.0257029	0.62760267	0.3363037109
	Constrained	0.0622750	-0.32823454	-0.3381103515
<i>Sharing_SHIFT</i>	Universal	0.186665	0	0
	Lowcarbon	0.215541	-0.133971	-0.1308837890
	Cautious	0.146572	0.273540	0.1871337890
	Constrained	0.102912	0.813833	0.3957275390

Table 3 Recalibrated modifiers for CIRCEE for year 2025

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