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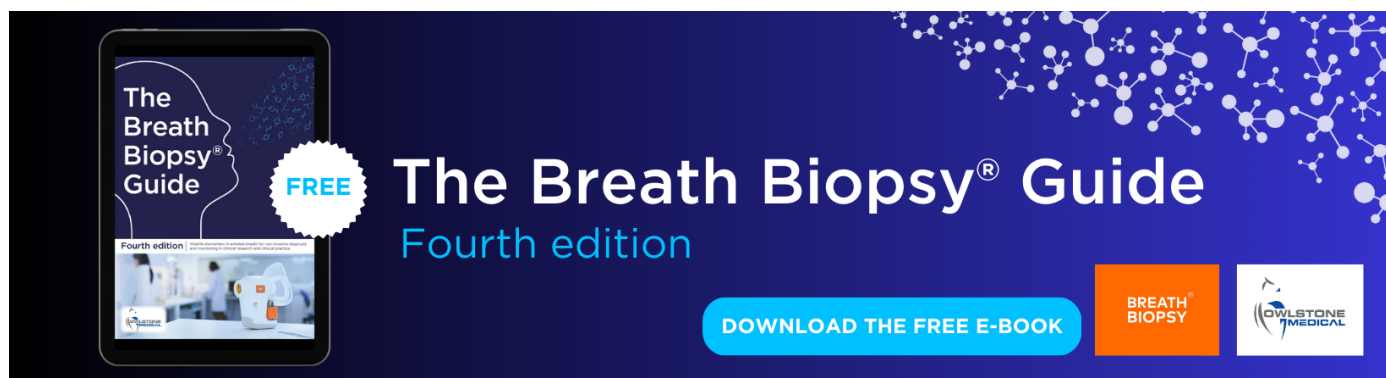
## Endogenous simulation of low-carbon lifestyle change in global climate mitigation pathways

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## LETTER

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Hazel Pettifor<sup>1,\*</sup> , Alessio Mastrucci<sup>2</sup> , Charlie Wilson<sup>1</sup> , Bas van Ruijven<sup>3</sup> , Maureen Agnew<sup>1</sup>  and Thomas Le Gallic<sup>4</sup><sup>1</sup> University of Oxford, Environmental Change Institute, Oxford Centre for the Environment, South Parks Road, Oxford OX1 3QY, United Kingdom<sup>2</sup> International Institute for Applied Systems Analysis, Transformative Institutional and Social Solutions Research Group, Energy, Climate and Environment, Schlossplatz 1, A-2361 Laxenburg, Austria<sup>3</sup> International Institute for Applied Systems Analysis, Sustainable Service Systems Research Group, Energy, Climate and Environment, Schlossplatz 1, A-2361 Laxenburg, Austria<sup>4</sup> Centre International de Recherche sur l'Environnement et le Développement, Nogent-sur-Marne, Île-de-France, Paris

\* Author to whom any correspondence should be addressed.

E-mail: [hazel.pettifor@eci.ox.ac.uk](mailto:hazel.pettifor@eci.ox.ac.uk)**Keywords:** behaviour, modelling, socialSupplementary material for this article is available [online](#)**Abstract**

Global Integrated Assessment Models (IAMs) used to characterise mitigation pathways have very limited or no formal representation of lifestyles and lifestyle change. We demonstrate a novel approach to endogenously simulating low-carbon lifestyle heterogeneity and lifestyle change through soft-coupling with our new empirically-based LIFE model. Coupling LIFE to global IAMs enables dynamic simulation of distinctive lifestyle change contributions to targeted mitigation strategies. We set out the empirical basis of the LIFE model, the methodological steps for soft-coupling to a global IAM, and show results from a test application to the residential sector using the MESSAGEix-Buildings model. A first key insight is that coupling with the LIFE model introduces heterogeneous behaviour between 'engaged' types, who experience faster and higher reductions in final energy demand compared to 'disengaged' types. When we further simulate a widespread shift in normative values, this gap is closed. A second key insight is that drivers of lifestyle change, act differently across 'Improve' and 'Avoid' dimensions. The 'disengaged' types, characterised by lower incomes, are more highly responsive to energy saving 'Avoid' behaviours. Our approach demonstrates how improved understanding of lifestyle change dynamics and more realistic, empirically-based quantitative simulations in climate mitigation pathways enriches scientific and policy analysis of how to achieve Paris Climate Agreement goals.

**1. Introduction**

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 [1–5]. The Sixth Assessment Report of the IPCC suggests that by 2050, global CO<sub>2</sub> emissions could be reduced 40%–70% across all end-use sectors with demand-based mitigation strategies [6, 7].

Global Integrated Assessment Models (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 [8, 9]. 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 [10].

To adequately model lifestyle, IAMs need to capture both the impact of lifestyles and the mechanisms of lifestyle change [11, 12]. Lifestyle is a universal, integrative concept. It involves the interplay between three elements: cognitions, behaviours and context [1, 13–15]. 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 [16–20]. 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) [19, 21, 22]. These three types of low-carbon behavioural changes are captured by the Avoid—Shift—Improve framework [6]. 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 [23, 24].

Cognitions are mental processes which guide and direct low-carbon behaviour [25]. 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') [4, 26–28]; value orientation ('guiding principles which reflect how people live their lives') [18, 29]; health orientation ('feelings related to well-being, health and life satisfaction') [15, 30, 31], and environmental beliefs ('saliency of the need to act to the benefit of the environment') [14, 32].

Context creates an enabling or constraining environment for a low-carbon lifestyle [1, 13–15]. 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) [33].

These three elements of lifestyle are interconnected processes that create affordances, individual learning and habituation, and cognitive responses which shape behaviour [34]. Each element can be viewed as a distinctive mechanism or driver of lifestyle change [35–37]:

1. Lifestyle change is *contextually driven*—lifestyles shift as context becomes more enabling or constraining [38–40]. Changes relate to physical and social environments that sustain or undermine lifestyle change [41–43] and include

affordability, accessibility of infrastructure, digitalisation, social support, access to bike lanes [44, 45]. 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 [21, 46]. Changes in lifestyle relate to individual empowerment, self-management and efficacy [43, 45], shifts in values [46], beliefs [44, 47], and attitudes towards health and wellbeing [41]. 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 [48]. 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 [49, 50]. 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 [10, 36]. 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 [1, 51]. Changes in cognitive drivers are largely assumed as the motivation for changes in behaviour, but these are not explicitly modelled [1, 12, 36]. Exogenous approaches cannot capture the dynamic effects of lifestyle change and its interactions with other technological 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 [10, 11].

The aim of this paper is to fill a major gap in the literature between contextualised empirical studies on low-carbon lifestyles and stylised modelling tools. Guided by strong empirical evidence we develop and demonstrate an approach to endogenizing low-carbon lifestyle heterogeneity and lifestyle change within global IAMs using our novel 'LIFE' model [24]. Our demonstration is specific to one demand-based sectoral model MESSAGEix-Buildings used within a global IAM framework, but our LIFE model is transferable within and across multiple domains of behaviour simultaneously, and applicable across models in the global IAM community. This methodological innovation is a critical enabler of analysis of the contribution of lifestyle change to climate change

mitigation policy within global IAMs as virtual policy laboratories.

## 2. Method

### 2.1. Identification and measurement of heterogeneous low-carbon lifestyle types

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) [52–55]. 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.

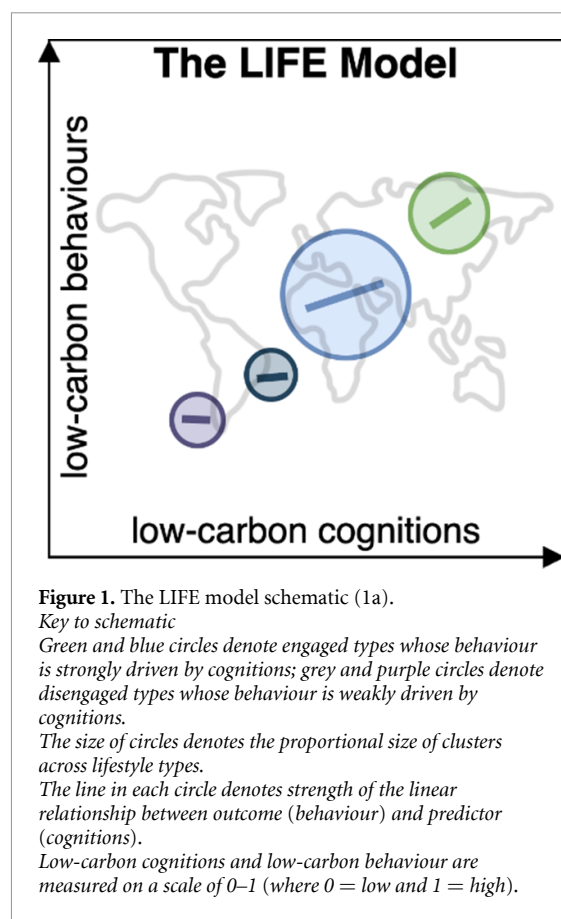
Figure 1 is a schematic representing the relative positioning of the four lifestyle types within a  $2 \times 2$  space defined by strength of low-carbon cognitions and related participation in low-carbon behaviours. Each type has a characteristic cluster size (% of population) which reflects contextual 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 [56].

### 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). For further details, see supplementary information A—Measurement and Extrapolation of Lifestyle Heterogeneity.

### 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



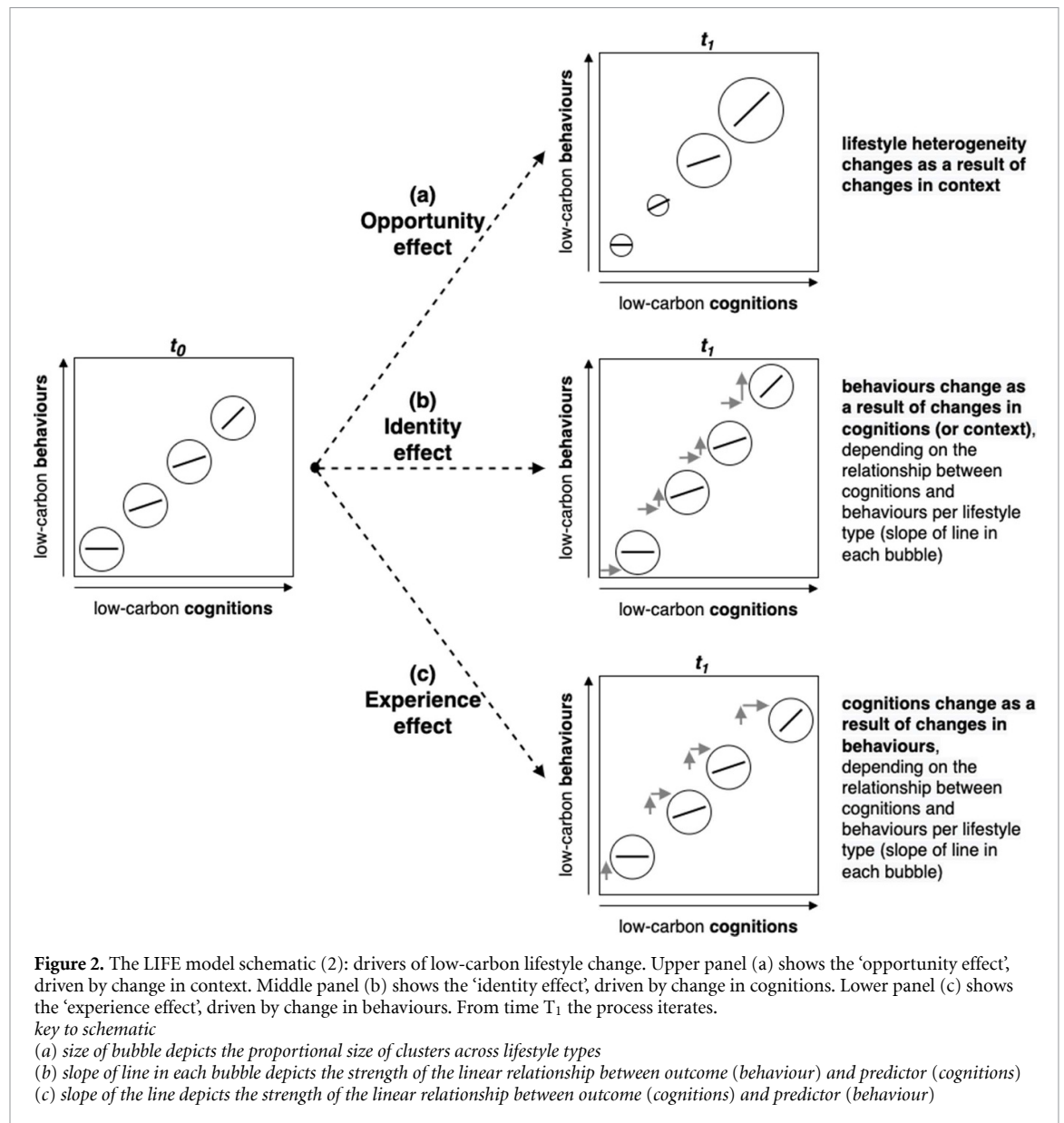
and measure three distinct mechanisms or drivers of lifestyle change over time (see figure 2).

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:

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

where  $Pr_g$  = 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:

$$\text{Beh}_g(t + 1) = \alpha_g + \beta_g(\text{Cog}(t)) \quad (2)$$

where 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:

$$\text{Cog}_g(t) = \alpha_g + \beta_g(\text{Beh}(t)) \quad (3)$$

where Beh = low-carbon behaviours, Cog = low-carbon cognitions,  $g$  = lifestyle types,  $t$  = time.



**Table 1.** Initial starting values for equations (1)–(3).

Outcome	Equation (1)	Equation (2)		Equation (3)	
	Pr cluster size (%) <sup>a</sup>	Low-carbon behaviour (scale 0 (low) to 1 (high))		Low-carbon cognitions (scale 0 (low) to 1 (high))	
Group/type (g)		$\alpha$	$\beta$	$\alpha$	$\beta$
Resourceful	24.64	0.102	0.6	0.549	0.112
Active	36.91	0.145	0.445	0.552	0.134
Constrained	20.83	0.295	0.134	0.466	0.021
Cautious	17.62	0.220	0.210	0.548	0.055

<sup>a</sup> where Age ( $t_0$ ) = 36 years, Income ( $t_0$ ) = IntUSD 35.48, Educational attainment levels ( $t_0$ ) = 48.57%. See also supplementary information C.

The time lag ( $t$ ) identified in equations (2) and (3) is derived from change in the constant term ( $\alpha$ ) over time. This process is explained fully in supplementary information B, Coupling Routine.

Table 1 provides the initial empirical starting values (predicted from the LIFE model) for each of the three equations.

#### 2.4. 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).

Step 1. Using empirical data from national social surveys extrapolated to all countries globally, the LIFE model characterises four lifestyle types with distinct cluster sizes (% of population) and propensities towards low-carbon behaviours. 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. 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 behavioural domain (e.g. homes, mobility, food), or specific to a single behaviour (e.g. energy efficient retrofits). This makes the LIFE model flexible to different IAM input requirements.

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 discount rates are converted 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 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 could be fed into equations in LIFE driving 'Avoid' type 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.

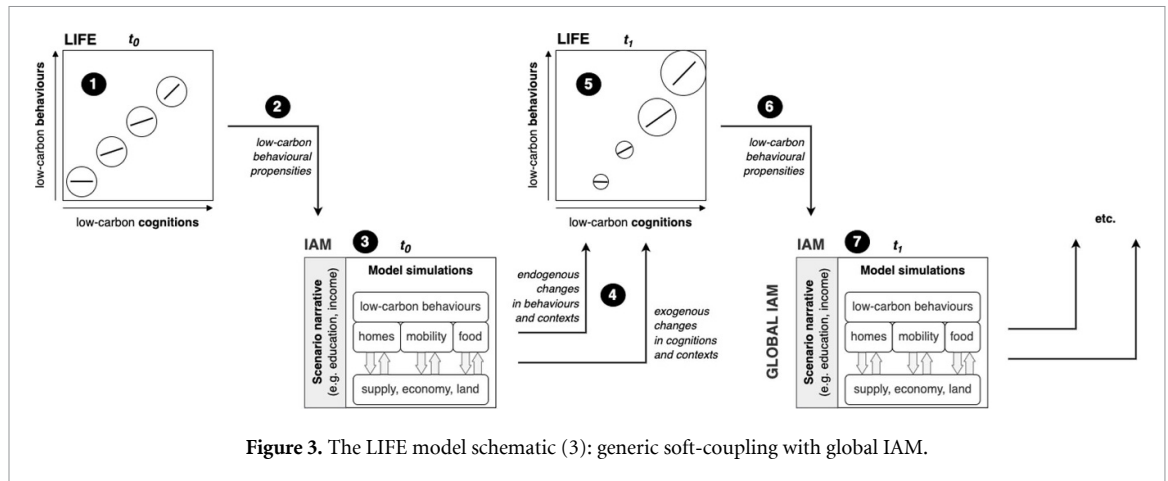


Figure 3. The LIFE model schematic (3): generic soft-coupling with global IAM.

## 2.5. Demonstration using life model coupled to MESSAGEix-buildings

We demonstrate this generic methodology using a single-sector demand-based global model, MESSAGEix-Buildings. This is a bottom-up building stock model with regional spatial resolution, and a five-year temporal resolution [57]. It combines bottom-up modelling of energy demand, stock turnover and discrete choice modelling for energy efficient decisions. 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 (i.e. without disaggregating to regions), universal level (i.e. without disaggregating to domains such as homes, travel, or food). This approach is purposely simplified to enhance clarity of results. At the global, universal level the LIFE model coupling is based on a universally generalised (across domains) set of behavioural propensities (which apply to input equations in MESSAGEix-Buildings). To couple with discrete outcomes in MESSAGEix-Buildings we use two sets of modifiers ('I' and 'A'). The 'I' modifiers relate to 'Improve' behaviours which apply to the uptake of advanced building renovations and new construction in MESSAGEix-Buildings. The 'A' modifiers relate to 'Avoid' behaviours which apply to specific energy efficient decisions (average set-point temperatures) in MESSAGEix-Buildings.

In MESSAGEix-Buildings, the 'Improve' dimension is covered by a discrete choice model to assess the investment decisions of households. The 'Avoid' dimension maps to the share of households adopting a lower set-point for heating [57]. The model calculates life cycle costs associated with various new construction and renovation options, differing by energy efficiency level, considering investment,

operational, and intangible costs. Based on life cycle costs, the model estimates the market share of different available options. In this study, we link intangible costs, representing barriers towards energy efficiency investments in advanced energy efficiency options, to the propensity of different household groups, and report the share of advanced actions on total actions. 'Advanced' level corresponds to new construction complying with passive standards and deep renovation levels in the Global North, as opposed to 'Standard' level, representing the current practice. For the 'Avoid' dimension, the model accounts for two different heating set-point temperatures in energy demand calculations, and reports the share of households adopting a lower set-point. We assume the reference set-point at 21 °C and the low set-point at 20 °C [57].

For further details see supplementary information B—Calibration and Coupling Approach.

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.

Step 4. Changes in final energy for space heating 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 or technology access [58] to re-estimate relative size of lifestyle type. This feedback step into the LIFE model recognises that lifestyle types change because behaviours have changed, external context has changed, and these also cause cognitions to change. *See also supplementary information C—Additional Tables and Results.*

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 five-year timestep, so are aligned over time periods of change in the empirical data (LIFE) and future simulations (MESSAGEix-Buildings).

In this implementation, the coupling is unidirectional, with the MESSAGEix-Buildings model receiving energy price signals from the MESSAGEix-GLOBIOM IAM.

See supplementary information A—The LIFE Model Schematic (1b) for full details of the LIFE model development (Step 1) and application to MESSAGEix-Buildings (Steps 4–5) (figure 2).

## 2.6. Scenario settings for demonstration approach

Using the specific approach for coupling LIFE with MESSAGEix-Buildings, we run two scenarios (to 2050) that demonstrate the value of endogenously simulating low-carbon lifestyle change and compare them to a ‘baseline’ scenario without explicit lifestyles representation. 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’ [59].

First, ‘SSP2 + LIFE’ 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 show this by comparing the baseline SSP2 with the ‘SSP2 + LIFE’ results.

Second, ‘SSP2 + LIFE + Values’ compares the effects of endogenizing low-carbon lifestyle and heterogeneous lifestyle change with and without an additional assumption of enhanced strong 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 2025–2050. Equations measuring lifestyle change effects are artificially forced by assuming alternative values for the slope coefficients ( $\beta$ ) in equation (2) for each lifestyle type at each time period. Rates of change vary between lifestyle types, reflecting varying responsiveness to cognitive drivers. *See Appendix B Calibration and Coupling Routine.*

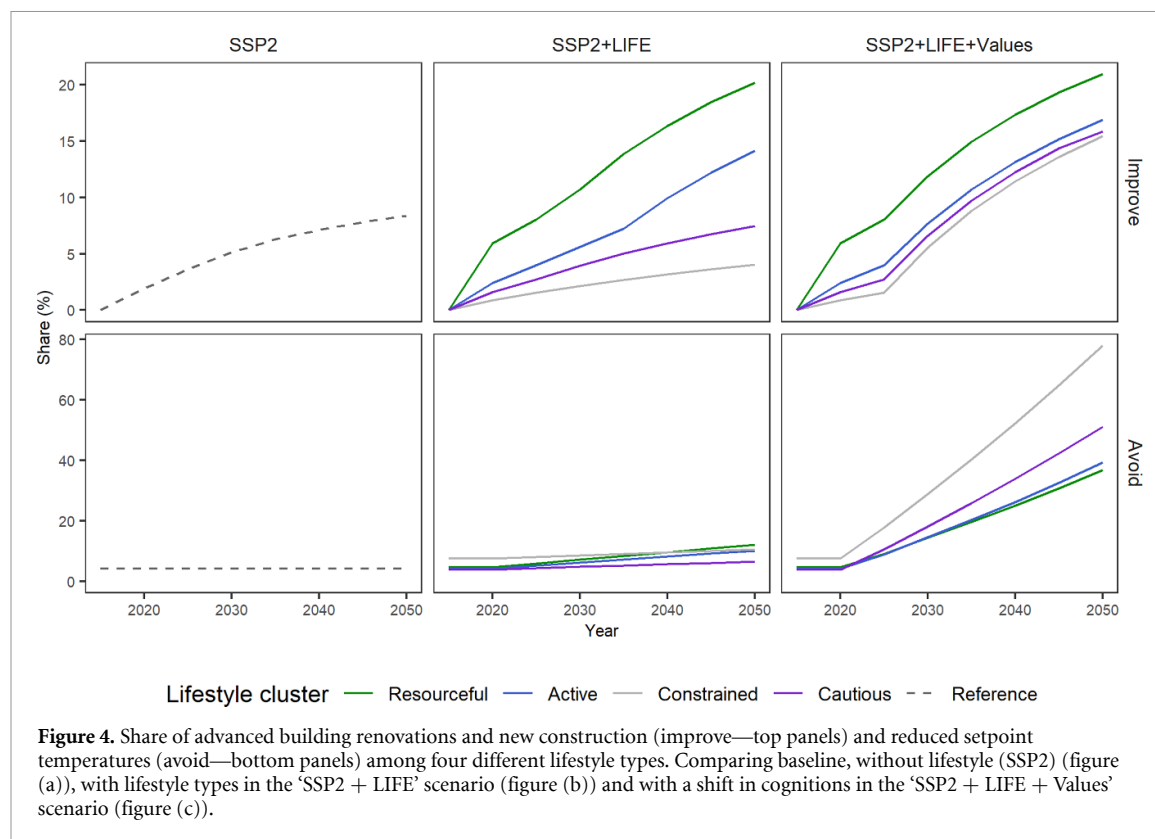
‘SSP2 + LIFE + Values’ enables us to evaluate the sensitivity and flexibility of the coupling parameters to modelling strengthened drivers of low-carbon lifestyle change. We show this by comparing ‘SSP2 + LIFE’ with the ‘SSP + LIFE + Values’ results. Specifically, we are interested in how stronger low-carbon cognitions directly act via the ‘Identity’ effect to strengthen low-carbon behaviours (see figure 2(b)) which in turn have a feedback effect to strengthen low-carbon cognitions via the ‘Experience’ effect (see figure 2(c)). 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.

## 3. Results

### Key Finding 1: Drivers of lifestyle change distinguish between demand across energy-efficient behaviours

Coupling with the LIFE model introduces heterogeneous uptake of advanced building renovations and new construction across the four lifestyle types in MESSAGEix-Buildings (figure 4(b) top panel), compared to baseline (figure 4(a) top panel). This variation is driven by the different levels of intangible costs that moderate the uptake of energy-efficient building renovation within these different lifestyle types. 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. Figure 4(b) (top panel) shows how lifestyle change dynamics lead to an increasing activity gap between the engaged and disengaged lifestyles types by 2050. Our second scenario, ‘SSP2 + Life + Values’ introduces the additional effect of strengthening of low-carbon cognitions (e.g. values, norms) (figure 4(c)) (top panel). This accelerates the uptake of advanced building renovations and new constructions between 2025 and 2050, closing the activity gap between the engaged and disengaged types.

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 + LIFE’ ‘Constrained’ and ‘Cautious’ types, characterised by lower incomes, are more highly responsive to energy saving ‘Avoid’ behaviours. In figure 4(b) (bottom panel), we see no evidence of the activity gap between the engaged and disengaged types. Under ‘SSP2 + LIFE + Values’ shares of ‘Avoid’ behaviour increase more rapidly and are higher in the disengaged types (figure 4(c)) (bottom panel).



**Key Finding 2: Simulated cognitive shifts under ‘SSP2 + LIFE + Values’ reduces final energy intensity in the disengaged types.**

Under ‘SSP2 + LIFE’ 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 + LIFE + 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 + LIFE’.

**Key Finding 3: Drivers of lifestyle change also distinguish between demand in total energy.**

The results of our demonstration coupling show 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 ‘SSP2 + LIFE’ we see only modest reductions compared to baseline SSP2 between 2030 and 2050. This reflects relative inactivity across ‘Avoid’

and ‘Improve’ dimensions in the ‘Constrained’ and ‘Cautious’ types. Under ‘SSP2 + LIFE + Values’ increased activity across the disengaged types reduces final energy demand between 2030 and 2050 relative to baseline SSP2 and ‘SSP2 + LIFE’.

#### 4. Discussion

The novel implementation of a globally-applicable lifestyle change model (LIFE) to a global integrated assessment framework (MESSAGEix-Buildings) described here makes several important contributions.

First, we advance 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 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’.

Second, the LIFE model has strong empirical foundations and uses robust methodological approaches for characterising lifestyle heterogeneity and estimating lifestyle change dynamics. This work contributes towards understanding

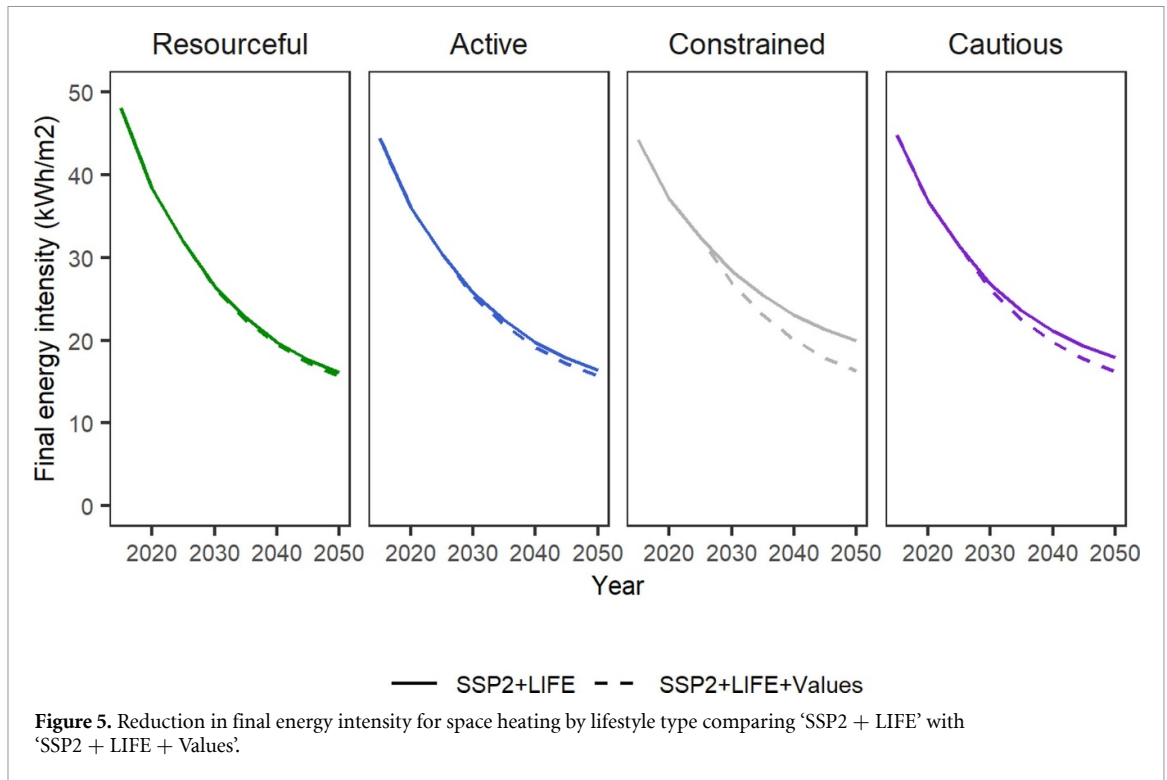


Figure 5. Reduction in final energy intensity for space heating by lifestyle type comparing ‘SSP2 + LIFE’ with ‘SSP2 + LIFE + Values’.

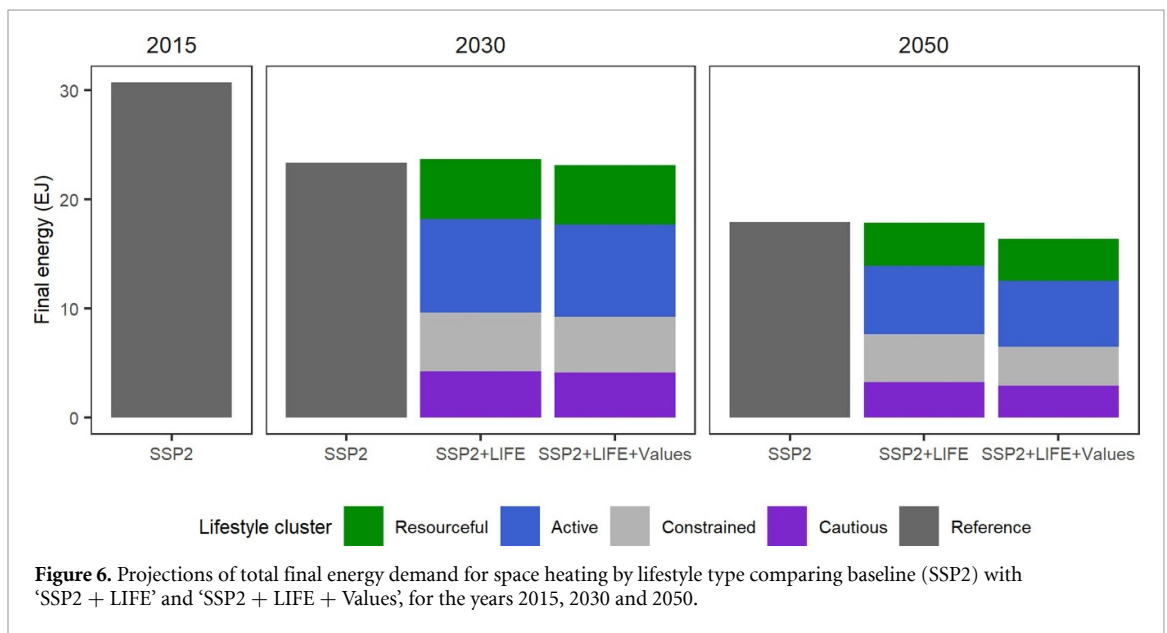


Figure 6. Projections of total final energy demand for space heating by lifestyle type comparing baseline (SSP2) with ‘SSP2 + LIFE’ and ‘SSP2 + LIFE + Values’, for the years 2015, 2030 and 2050.

the relationship between energy use and lifestyle change. It complements other studies which characterise cognitively-driven lifestyle change as a means for changing behaviour towards low-carbon actions that include energy-saving actions in and around households [4, 16], including modes of transportation [22] and across multiple sites of consumption [60]. It widens perspectives on the cognitive drivers of environmental actions, their potential to effect change and provide policy-relevant insights. Barr and Gilg [16] view these changes as ‘deliberative and inclusionary processes’; for Lorenzen [48] it is ‘a deliberate process undertaken

in response to a problem left under addressed by current policies and practices’. Longitudinal data provide evidence of shifts in attitudes as some low-carbon actions and practices become normalised [61]. Coupling LIFE to a dynamic global IAM framework provides a means of scaling up lifestyle change processes over long-time horizons to provide quantitative insights on the future structure of energy demand.

Third, our approach specifically addresses criticisms of the framing and lack of representation of lifestyle heterogeneity and lifestyle change in global IAMs [62]. We provide definitions of lifestyle change

relevant for implementation in IAMs which can harmonise perspectives on lifestyle and lifestyle change within the IAM community [12]. IAMs focus on actions and activities, their impact and not the motivations. Subsequently they model a limited range of transformative solutions towards lifestyle change [10, 12]. Encapsulating and integrating the three key elements of low-carbon lifestyle; behaviour, cognitions and context, the LIFE model widens the potential ‘tool-kit’ of IAMs towards modelling social processes and the mechanisms of socially oriented change [11].

Fourth, the LIFE model is versatile and adaptable for soft-coupling with different IAM frameworks. The input assumptions that the LIFE model needs to dynamically simulate lifestyle change are aggregated IAM behavioural outcomes. For domain specific coupling disaggregated IAM output consistent with the Avoid-Shift-Improve framework could also be interpreted. In the transport domain, for example, behavioural outcomes related to ‘Avoid’ (reduced car use), ‘Shift’ (opt for public transport), and ‘Improve’ (car share or drive EV/ebike) could be aligned with representative behaviours in the IAM. Behaviour propensities and modifiers capture intentions towards behaviours across four types which could be calibrated and coupled with a behaviour adoption framework in the IAM. In the food domain the LIFE model captures perceptions of health and wellbeing and its relationship with dietary preferences (vegetarian/meat free). This could be matched with a health component in the IAM framework. Provided empirically observed behaviours in the LIFE model can be readily matched with aggregated behavioural outcomes in the IAM, the LIFE formulation is adaptable. Ultimately by coupling the LIFE model across multiple domains, the influence of the three mechanisms of lifestyle change could help provide consistent representations of behavioural shifts across domains [12]. A further important development of the LIFE coupling is the development of the endogenous coupling towards perfect foresight IAMs. This could extend the flexibility of the framework vis-à-vis different IAM types.

## 5. Conclusion

In this paper we present and demonstrate the LIFE model for representing lifestyle heterogeneity and distinct lifestyle change mechanisms. We discuss the broad approach to coupling this model with a demand-based global IAM, and then demonstrate a specific application to MESSAGE-ix Buildings. We reflect on the contribution of this approach towards modelling the relationship between energy use and lifestyle change.

Adding lifestyle heterogeneity highlights the potential emissions impact of disengaged lifestyle types. Comparing model simulations with and

without lifestyle heterogeneity shows how cognitive changes over time motivate and incentivise reduced energy use and subsequent emissions, particularly in groups enabled by their contexts but passive in their approach to low-carbon lifestyle.

Adding distinct mechanisms of lifestyle change highlights the importance of changing mind-sets. We demonstrate the contribution of cognitive shift, simulating change in wide-spread normative values and norms of behaviour.

Policy interventions aimed at shifting lifestyles towards a low-carbon society will need to address multiple lifestyle elements, including behaviours, cognitions and contexts. Our simulations show that ‘Constrained’ types are resistant to the modelled cognitive changes as their contextual limitations dominate in determining behavioural outcomes. There is a need for new scenarios that address multiple drivers of low-carbon lifestyle change and their interactions across the three key elements of lifestyle. Future development of this work will concentrate on further applications of the LIFE model in this integrated fashion.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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## ORCID iDs

Hazel Pettifor  <https://orcid.org/0000-0003-3901-2693>

Alessio Mastrucci  <https://orcid.org/0000-0002-5611-7780>

Charlie Wilson  <https://orcid.org/0000-0001-8164-3566>

Bas van Ruijven  <https://orcid.org/0000-0003-1232-5892>

Maureen Agnew  <https://orcid.org/0000-0002-5740-1679>

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