

## Review

# Assessing Lifestyle Transformations and Their Systemic Effects in Energy-System and Integrated Assessment Models: A Review of Current Methods and Data

Andreas Andreou, Panagiotis Fragkos , Theofano Fotiou and Faidra Filippidou

E3-Modelling, 70-72 Panormou Street, P.O. Box 11523, 115 23 Athens, Greece; andreou@e3modelling.com (A.A.); fotiou@e3modelling.com (T.F.); filippidou@e3modelling.com (F.F.)

\* Correspondence: fragkos@e3modelling.com

**Abstract:** Achieving the ambitious climate targets required to limit global warming to 1.5 °C requires a deep transformation of the supply-and-demand side of energy–environmental–economic systems. Recent articles have shown that environmentally sustainable consumer behaviors driven by lifestyle changes can significantly contribute to climate-change mitigation and sustainable development goals. However, lifestyle changes are not adequately captured by scenarios developed with integrated assessment and energy-system models (IAMs/ESMs), which provide limited policy insights. This article conducts a systematic review of the IAM and ESM literature to identify the most important lifestyle changes in current mitigation pathways for the residential and transport sectors, review the employed state-of-the-art modeling approaches and scenario assumptions, and propose improvements to existing methodological frameworks. The review finds that mode shifts towards public transport and active transport modes, shared mobility, and eco-driving have the greatest impact in the transport sector, while actions that reduce space and water-heating requirements and the circular economy are the most effective practices in households. Common modeling approaches lack sophistication as they omit (1) the dynamics and costs of demand-side transitions, (2) the heterogeneous responses of different consumer groups, and (3) the structural effects of lifestyles on the macro-economy. New approaches employing innovative methodologies combined with big data collected from users offer new avenues to overcome these challenges and improve the modeling of lifestyle changes in large-scale models.

**Keywords:** integrated assessment models (IAMs); energy-system models; behavioral change; lifestyle transformation; mitigation pathways



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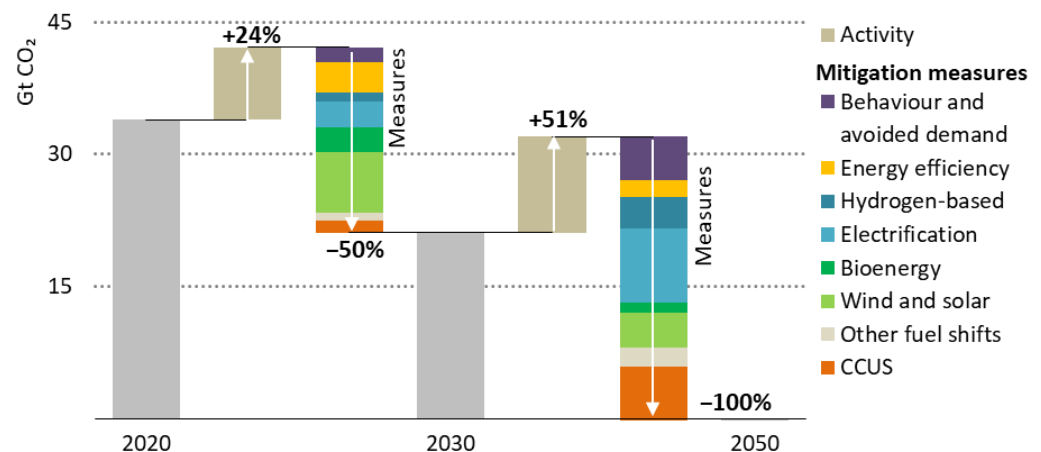


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## 1. Introduction

Mitigation pathways consistent with the ambitious goals of the Paris Agreement (PA) to limit the increase in global average temperature to well below 2 °C and pursue efforts for 1.5 °C, above pre-industrial levels, require a rapid and large-scale transformation in energy, economic, and land systems [1]. These pathways often signify the role of behavioral or lifestyle changes (the two terms are used interchangeably in the text) in driving greenhouse-gas (GHG) emissions for several demand sectors, such as transport and buildings. The recent IPCC 6th Assessment report confirms that demand-side mitigation strategies can reduce emissions across all sectors by 40–70% by 2050 [2]. Thus, demand-side transformations can play an important role in future emission reductions to achieve the PA goals, alongside supply-side transformations [3]. The significant contribution of behavioral change in achieving decarbonization targets and wider sustainable development goals (SDGs), such as that of improving well-being and reducing poverty, is stressed by recent studies, such as the 1.5 °C warming report by the Intergovernmental Panel on Climate Change (IPCC) [1] and the Net Zero by 2050 report by the International Energy Agency (IEA) [4,5]. As an example, Figure 1 shows that for the IEA's net-zero pathway [4,6], about

24% and 22% of carbon dioxide (CO<sub>2</sub>) emission reductions in 2030 and 2050, respectively, can be attributed to changes in behavior and other demand-curtailment measures, including energy efficiency. In 2050, the contribution of lifestyle changes will equal the combined contribution from growing bioenergy supply and from rapidly expanding wind and solar-power capacity.



**Figure 1.** Decomposition of CO<sub>2</sub> emission reductions in 2030 and 2050 by mitigation measure according to the Net-Zero emissions scenario of the IEA [6]. CCUS: Carbon Capture, Usage, Storage.

Integrated assessment (IAMs) and energy-system models (ESMs) lie at the center of climate-change mitigation research and policy analysis [7]. IAMs are computational modeling tools integrating the global dynamics of various interconnected systems, such as energy, economy, trade, land use, and climate into a single unified framework [8]. IAMs have been systematically utilized to assess potential trajectories towards the achievement of long-term decarbonization goals [9] and broad SDGs [10]. In the same fashion, ESMs have been widely used to develop quantitative scenarios about the future evolution of the energy sector, as well as its interactions with the economy, aiming to inform policy makers about the measures required to achieve energy- and climate-policy goals. However, despite the strong evidence in the literature for the importance of demand-side transitions in mitigation pathways [11,12], the representation of lifestyle changes in IAMs and energy-economy models lacks sophistication and theoretical and/or empirical validation, and it is mostly exogenous, as dynamics relating to societal transformations have been difficult to implement in large-scale models [13]. As a result, while IAMs and energy-system models adequately capture supply-side emission-reduction options [14], they are often criticized for the limited insights they provide about consumer-side transitions [15] and lifestyle changes. This in effect prohibits a comprehensive analysis of the specific drivers and effects of behavioral change, as well as of the associated implementation barriers for policy. Therefore, most mitigation pathways depend mostly on supply-side technological solutions to achieve ambitious decarbonization targets, with limited focus on demand-side options, lifestyle changes, and societal transitions [16]. This has begun to change in recent years through emergence of new scientific evidence and associated research on the large contribution of lifestyle transformations towards meeting ambitious climate goals, and how these lifestyle changes can be represented in large-scale quantitative models.

Previous reviews on this topic sought to provide a comprehensive description of the approaches that have been applied to model lifestyles in global scenarios via IAMs [15,17]. More specifically, Van den Berg et al. (2019) elaborated on the application of the Avoid-Shift-Improve (ASI) framework [18] to define and categorize various mitigation measures. Based on this conceptual framework, changes in lifestyles fall primarily under the *avoid* and *shift* categories, whereas technological upgrades belong to the set of *improve* options. Moreover, the same study [18] attempted to explain how different disciplinary approaches with quantitative or qualitative focus could help to bridge the gap between intent-oriented perspectives, which

seek to understand the determinants of behavioral change, and impact-oriented perspectives, which focus on the environmental effects of lifestyle changes. The latter perspective has been the focal point in the majority of previous energy-modeling exercises; therefore, questions about the determinants of behavioral change have been overlooked to a significant extent. Saujot et al. (2021) reiterated the need for a better integration of lifestyle changes in IAM-based mitigation pathways, through placing increased emphasis on incorporating complex social phenomena and portraying the heterogeneous responses of different population groups. Representing actor heterogeneity in models is especially relevant when the objective is to simulate social processes, such as lifestyle and behavioral changes, which arise from the coordinated action of consumer groups interacting through (for example) social-influence dynamics [16]. Apart from the knowledge-production process, the authors of [17] highlighted the importance of improving the political relevance of lifestyle-led mitigation pathways by increasing the transparency of model assumptions, fostering cross-disciplinary collaboration, and incorporating citizens' views in scenario formulation [16].

Drawing from previous works and scientific evidence, this review paper aims to move the literature forward by shifting the focus from general methodological considerations to the specific methods and data adopted to model lifestyle changes in IAMs and energy-system models. More specifically, the article initially seeks to identify the common types of lifestyle changes that have been included in IAM-based climate–economy pathways and evaluate their relative mitigation potential, based on the relevant literature and empirical results. Furthermore, it reviews the specific methodological approaches applied for representing lifestyle transformations in the major sectors relevant to mitigation, namely buildings and transport. Finally, this review paper provides practical recommendations based on which IAMs and energy-system models can improve the representation of consumer-led transitions and lifestyle changes, with a focus both on their drivers and their effects on the energy–economy–climate system.

The structure of this review paper is as follows. Section 2 delineates the boundaries of this literature review and describes the methodological steps applied in conducting the systematic review of lifestyle-change modeling. Section 3 presents the results of the literature review across different themes, and Section 4 synthesizes the findings from the literature to propose potential extensions to existing state-of-the-art modeling frameworks. Section 5 also concludes by summarizing the main findings of this paper and paving the way for future research.

## 2. Materials and Methods

### 2.1. Defining the Boundaries of the Literature Review

A vital initial step of this assessment involves setting the boundaries of the literature review, most importantly with respect to mitigation measures, which can be categorized as lifestyle-related actions. Broadly speaking, a sustainable lifestyle is defined as a “cluster of habits and patterns of behaviour embedded in a society” [19,20], which is shaped by “preferences, social values and norms” [21], institutions and policies [22], and infrastructures [15], in ways that minimize the associated environmental effects. These lifestyles can be grouped under four major themes/categories according to the sector in which they take place [15,23,24]: (1) transport/mobility, (2) residential/housing, (3) food/nutrition, and (4) other/consumer goods and services. Based on [23], the transport and residential sectors currently have the highest consumption-based carbon footprint globally. This paper reports carbon footprints in the range between 0.2 and 4.6 tCO<sub>2</sub>eq/cap for transport, 0.5 and 3.7 tCO<sub>2</sub>eq/cap for residential, 0.4 and 1.9 tCO<sub>2</sub>eq/cap for food, and 0.4 and 3.2 tCO<sub>2</sub>eq/cap for other consumption categories. According to the recent IPCC 6th Assessment Report [2], changing housing and mobility practices rank amongst the interventions with the highest emission-reduction potential, and are therefore the primary focus of this review. The review also covers mitigation actions that do not take place in the residential and transport sectors, but their effects also extend to other sectors (i.e., the effect of sharing economy practices on industrial demand and production). The indirect effects of these behavioral measures on

the demand for energy services are commonly allocated to the category of consumer goods and services [15].

Under the strict definitions of the ASI framework [24], mitigation measures are classified as lifestyle-based if they have the potential to reduce (*avoid*) the activity and the overall level of demanded energy services (e.g., cutting down on vehicle use, living in smaller dwellings, taking shorter showers). In addition to *avoid* practices, lifestyle changes include the *shift* to more environmentally friendly behaviors (e.g., switching to public modes of transport, altering thermostat temperature settings to reduce heating requirements, using appliances more sustainably). Depending on the context, some behaviors that *improve* the physical efficiency of energy and transport processes can also be weakly linked to lifestyle-related mitigation practices. Two prominent examples of such behaviors are the choice between conventional and alternative-fuel vehicles (AFV) in transport and the installation of decentralized mini-grids based on renewable-energy sources (RES), such as small-scale PV, in the residential sector [25,26]. While these options mainly involve technology substitution towards low-emission alternatives, they require a very different infrastructure to support them compared to the conventional technology they replace. Therefore, they alter (i.e., *shift*) the service consumers receive. In this literature review, we focus primarily on improving the modeling and representation of *avoid* and *shift* sets of mitigation actions that conform to the “strict” definition of lifestyle changes, as these require mainly voluntary actions from consumers in their everyday lives, without needing large upfront investments, as is usually the case with technological “*improve*” options. Nevertheless, assessments examining the behavioral dimension of mitigation actions, which can be classified as both *shift* and *improve*, are also included in this literature review to highlight common themes and novel modeling practices.

## 2.2. Strategy of the Literature Search

This article aims to review the specific methods and data employed to develop climate-mitigation pathways characterized by sector-specific lifestyle transitions in state-of-the-art IAMs and ESMs. The work is based on a systematic, structured review of the academic literature and aims to source information about the modeling frameworks and implementation techniques that various modeling teams have adopted to integrate lifestyle changes in their models. In order to compile a comprehensive list of relevant literature, broad search criteria were applied within article titles, abstracts, and keywords, using the Scopus citation database. The search combined keywords relating to mitigation pathways, lifestyle transformations, energy-modeling tools, and IAMs via AND/OR Boolean operators. The full list of keywords and the remaining steps of the literature search are presented in Table 1. The academic literature was also complemented by scientific gray literature, especially from scientifically-sound, state-of-the-art assessments from well-renowned international organizations, such as the IEA [5,27], IPCC [28,29], EC [30], and the International Institute for Applied Systems Analysis (IIASA) [31].

The search results were subsequently narrowed down by removing duplicates and articles in non-English languages or unrelated to the subject, as discussed in the previous sub-section. The review was also limited to studies published during the last 15 years (2007–2022), in order for the reviewed assessments to be representative of the current state-of-the-art knowledge on this topic. Additional article titles were collected from previously conducted reviews [11,13,15,17] and key scientific reports [1,2]. Finally, three additional criteria were applied to refine the final list of references. As shown in Table 1, these final steps aimed to filter out any papers conducting analyses of energy behaviors at the micro-level, namely at the level of households, neighborhoods, or districts (e.g., [32,33]). Moreover, the analysis excluded assessments using (semi-) qualitative modeling techniques (e.g., [34]) or articles discussing only in qualitative terms the potential contribution of consumer-led transitions to environmental and sustainability goals. Lastly, we chose to omit articles in which the reduction in energy demand was not explicitly caused by lifestyle or behavioral change. This criterion eliminated, for example, studies in which energy demand adjusted

only as a result of end users foregoing a certain level of consumption/utility in response to higher energy service prices, which implicitly depends on the product of changes in fuel and technology prices, as well as demand elasticities (e.g., [35]). While fuel prices, taxes, and capital costs are important determinants of energy-demand changes, these factors have been implemented and widely analyzed before in IAM and ESM frameworks, in contrast to lifestyle and behavioral changes, which have been studied in much less detail and are the focus of the current paper.

**Table 1.** Description of steps followed in identifying, compiling, and filtering academic papers for the literature search.

Step	Stage of Literature Search	Description
1	Search terms in Scopus	(Mitigation OR “demand reduction” OR “low demand” OR “low consumption” OR decarbonization/decarbonisation) AND (scenarios OR pathways OR cases) AND (lifestyle OR behaviour/behavior/behavioural/behavioral) AND (change OR transformation) AND (energy OR “energy system” OR “integrated assessment”) AND (model/modelling/modeling OR tool)
2	Non-applicable references	Filter out duplicate articles, published before 2007, and those outside the scope of the review and of non-English language
3	Additional references	Identify relevant articles from key references and previous literature reviews
4	Extra filtering criterion	Identify studies performed at the macro-level (global, regional, national, sub-national) <sup>1</sup>
5	Extra filtering criterion	Cover empirical assessments of lifestyle transformation based on model-based quantitative scenarios
6	Extra filtering criterion	Select studies in which the adjustment of energy service demand is a result of lifestyle or behavioral change.

<sup>1</sup> For countries with a large geographical area, such as the USA, China, and Canada.

To facilitate the discussion on lifestyle transformations in IAM-based mitigation pathways, the following information was extracted from the collected manuscripts:

- General statistics (year of publication, geographical coverage, time horizon of study);
- The type of modeled lifestyles and covered domains/sectors;
- The range of evaluated effects on energy, economy, and other systems, as well as on CO<sub>2</sub>/GHG emissions, as quantified through relevant indicators;
- The structure of modeling tools used in the analysis, with a distinction between applications of IAMs and energy-system models;
- Assumptions about the future transformations in lifestyles in the respective sectors.

### 3. Results

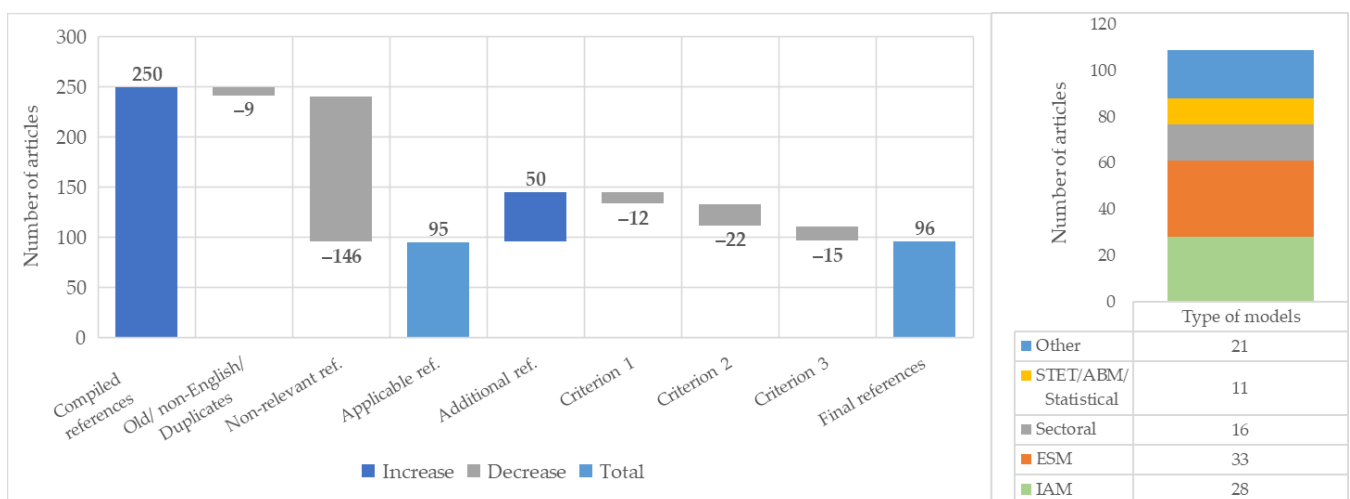
This section presents the detailed results of the literature review on how IAMs and ESMs represent lifestyle changes. Section 3.1 provides an overview of the key characteristics of the identified literature through general statistics on the geographical and temporal coverage of conducted empirical or forward-looking modeling assessments. Section 3.2 then identifies the most common lifestyle transitions modeled in IAM-based decarbonization pathways, with a focus on interventions taking place in the transport and residential sector. Section 3.3 elaborates on the general methodological frameworks and specific techniques employed to represent consumer-led transitions in climate-change mitigation scenarios, in the context of integrated assessment and energy-systems modeling.

#### 3.1. General Statistics of the Reviewed Papers

This section presents the outcome of the literature search, in accordance with the steps outlined in Table 1. As demonstrated in Figure 2, the search query through broad keywords in the Scopus database returned 250 references (Step 1—Table 1), which consisted of research articles, scientific reviews, conference papers, book chapters, and scientific reports. Of the 250 references, 9 were removed as they were either duplicates, written in a non-English



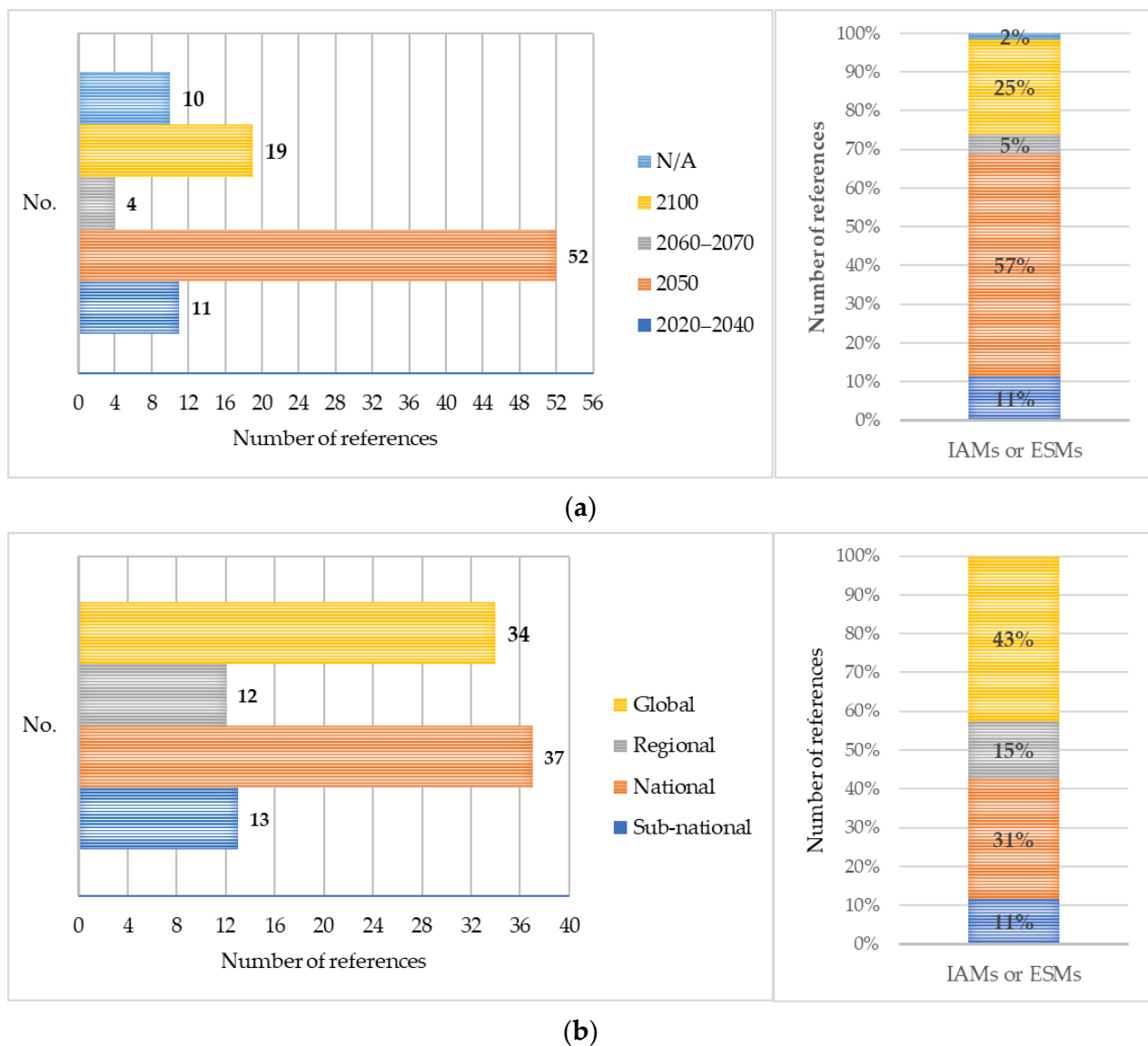
language, or outside the considered time horizon of the analysis (published before 2007). Following the initial screening phase and the elimination of material irrelevant to this study (Step 2—Table 1), 95 references were chosen for further consideration. In the third step, these titles were subsequently complemented by 50 additional references obtained from previous reviews (e.g., [15,17]) and major scientific assessments from international organizations (e.g., [2,27]). The application of the extra set of qualitative criteria described in steps 4 (only macro-level studies), 5 (only quantitative studies), and 6 (only lifestyle-induced changes in energy demand) in Table 1 resulted in the final list of 96 references qualifying for the purposes of this literature review. It is important to highlight that the final list of references consisted mainly of studies (>80%) employing either IAMs, ESMs, or sectoral energy models to develop scenarios for lifestyle transitions, as also depicted in Figure 2. In addition, some studies alternatively employ agent-based models (ABMs), models of socio-technical energy transitions (STET), and statistical analysis tools. Furthermore, a few studies make use of other modeling tools, including lifecycle and input–output analysis. The complete list of the references selected for the purposes of this literature review is provided as a Supplementary Material in Table S1.



**Figure 2.** Reference selection and filtering process broken down to individual stages of the literature search. Selected studies are split according to the type of model used in the investigation. Note: Totals in the column chart are higher than the number of selected papers as some studies use more than one type of model.

The literature on lifestyle transformations included in scenarios assessing the Paris Agreement goals and national decarbonization targets has attracted significant attention in recent years, as demonstrated through the distribution of the articles' publication years. More than three quarters of the obtained references (77) were published after the year 2015 (when the PA was formulated), and 36 of these were published after 2020, signaling the increased focus on demand-side transitions in the energy-system and integrated assessment modeling community [36]. More than half of the identified assessments are based on quantitative model-based scenarios with a time horizon up to 2050 (Figure 3a), which reflects the high interest in mid-century targets, given the large amount of net-zero emission goals recently adopted by dozens of countries globally. A sizeable portion of papers extend the analysis of lifestyle-driven mitigation pathways to the year 2100 (especially the studies based on IAMs), although there is a recognition of the large uncertainty in the long-term evolution of the drivers of energy demand, consumption preferences, societal transitions, and technological characteristics [37]. A few articles produce scenarios with a shorter time frame to assess medium-term climate-policy goals, such as those included in the nationally determined contributions for 2030 [38]. Some of the articles did not conduct scenario analyses for the evolution of energy–economic systems to a particular time horizon, but

instead assessed the magnitude of emission savings for a combination of lifestyle measures in comparison with the 1.5 °C and 2 °C climate targets.



**Figure 3.** Descriptive statistics of the reviewed papers (for total sample and those employing IAM and ESM-based tools) with respect to the (a) time horizon and (b) spatial coverage of conducted modeling exercises.

Finally, in terms of the papers' geographical coverage, Figure 3b reveals that most of the papers had either a national (39%) or global (35%) scope, while most of the regional assessments were conducted for countries belonging to the European Union (EU). Considering only the IAM and ESM-based applications, the percentage of global-level studies was higher than that of national-level studies due to the wider system boundaries defined in these modeling frameworks. The majority of the national and sub-national studies in the complete sample (~80%) were performed for countries located in the Global North, which consist mainly of developed OECD (Organisation for Economic Co-operation and Development) economies (e.g., USA [39], United Kingdom [40], Japan [41] and a number of EU member states [42]). On the other hand, only a few modeling studies were identified with a focus on developing or less-developed nations (e.g., China [43] and India [44]). This signifies the leading role developed economies are expected to take in achieving climate targets through lifestyle transformations, but also poses a requirement to expand the analy-

sis to developing countries, which have a very large unexplored potential for the uptake of environmentally friendly lifestyles.

### 3.2. Identified Lifestyle Effects and Sectoral Coverage

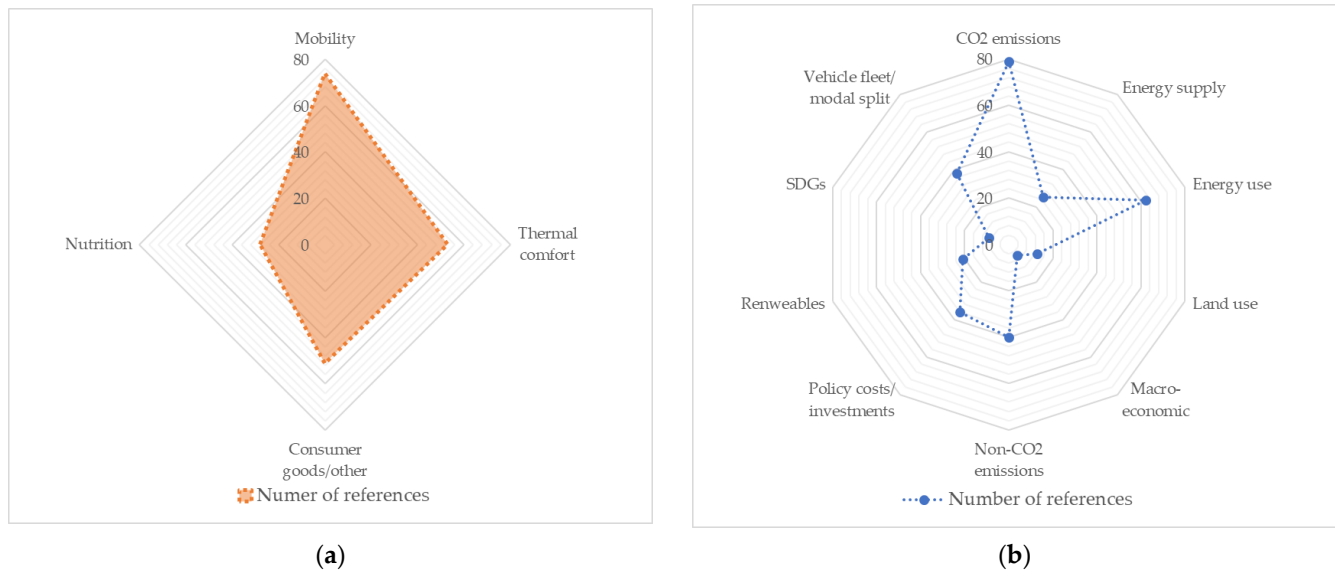
There is strong evidence in the literature about the potential contribution of lifestyle changes towards climate-change mitigation and other environmental and sustainability targets. First, changes in consumers' behavior were found to significantly reduce energy demand and associated CO<sub>2</sub> emissions in different end-use sectors. Van Sluisveld et al. (2016) ([45]), for example, examined the effects of selected behavioral measures in the global transport and residential sectors using the IMAGE IAM model and found that they could reduce sectoral CO<sub>2</sub> emissions by 33% and 16% by 2050, respectively, compared to a business-as-usual (BAU) scenario. Recently developed low-demand scenarios projected the level of global final energy demand in 2050 to be at 245EJ [12], or even lower, at 149 EJ [46] (representing a 40–60% reduction from current levels), when sufficiency in end-use sectors is combined with extensive energy-efficiency improvements. Second, demand-side transitions achieve emissions savings in hard-to-mitigate sectors, such as buildings and transport, thereby reducing the need for radical transformations in the supply-side sector and lowering overall mitigation costs. Liu et al. (2018) ([47]) modeled pathways consistent with a global warming of below 2 °C and 1.5 °C up to 2100 in the AIM/CGE IAM model and demonstrated that a variant including lifestyle changes towards environmentally sustainable behaviors requires a lower carbon price and results in a loss of gross domestic product (GDP) that is 14% lower relative to the baseline to meet the same climate targets. Moreover, a sensitivity analysis performed for the IEA's NZE scenario ([4]) showed that, in the absence of behavioral change, reaching net-zero emissions would require cumulative investments in low-carbon-supply technologies to increase by USD 4 trillion (+4%) over 2021–2050. The Clean Planet For All study based on the PRIMES model results for Europe [30] also estimated that a 1.5 °C lifestyle-change scenario results in annual energy system investments that are 8% lower relative to other trajectories towards climate neutrality in the 2030–2050 period.

Third, lifestyle changes have the potential to reduce reliance on negative emission technologies, such as bioenergy, with carbon capture and storage (BECCS), which are currently expensive and immature and have low social acceptance. Van Vuuren et al. (2018) ([48]) used the IMAGE IAM model to demonstrate that under a scenario of achieving the Paris goal of 1.5 °C through behavioral change, the use of BECCS is reduced by about 40% in 2100 relative to the default mitigation scenario. In another IAM-based study with the PROMETHEUS and TIAM-ECN models, Dalla Longa et al. (2022) ([36]) showed that in a strong-energy-efficiency scenario, the use of CCS and the carbon price may decline by 13–90% and 10–50%, respectively, in 2050, compared to the default pathway consistent with 2 °C, while additional energy-system costs may decrease by 6–30%. Finally, there is an emerging body of research on the multiple benefits of consumer-led transitions in relation to the achievement of SDG targets. In a global analysis with the REMIND-MagPIE IAM model, Bertram et al. (2018) ([49]) showed that policy packages inducing lifestyle transitions would be very effective in alleviating the climate-mitigation risks linked to food security and long-term economic growth. Aside from monetary benefits, it is suggested in [50] that lifestyle transitions, such as switching to non-meat-based diets, can positively affect societal health and improve animals' well-being.

Previous assessments of consumer-led transitions using IAMs and energy modeling tools have mostly focused on lifestyle measures relating to mobility and thermal-comfort practices in buildings (Figure 4a). Switching to public or non-motorized and active modes of transport [51], such as walking and cycling, and reducing purchases of new vehicles through the increased utilization of the current stock (e.g., through carpooling, or the emergence of a sharing economy and mobility-as-a-service) [52] are amongst the most commonly modeled interventions in decarbonization pathways for the transport sector. On the other hand, changing thermal-comfort practices comprises actions aiming to reduce the demand for heating and cooling in buildings, achieved mainly through adjustments to the temperature settings of thermostats [50] and reductions in hot-water use [45]. In



addition to thermal comfort, mitigation pathways also incorporate behavioral changes with respect to the sustainable use of consumer goods (including the purchase and use of highly efficient equipment and appliances) and the dematerialization of the economy as a consequence, for example, of recycling, digitalization, and the diffusion of multi-purpose devices in buildings [12]. Scenarios depicting shifts in nutritional patterns and the potential substitution of animal-based products with plant-based products were found in fewer articles, since their modeling exceeds the boundaries of the energy sector and concerns the evolution of agricultural- and livestock-production systems, which are only captured by specific integrated assessment models [53].



**Figure 4.** Descriptive statistics of reviewed papers with respect to the (a) type of investigated behavioral measures and (b) indicators used to quantify lifestyle effects.

The most frequent indicators adopted for the quantification of lifestyle-change effects in IAMs and large-scale ESMs relate to changes in GHG (CO<sub>2</sub> and non-CO<sub>2</sub>) emissions and energy use (Figure 4b), which is logical, given that these indicators are widely used to inform policy makers. A considerable number of articles that focus on the transport sector also develop future scenarios of mobility split by transport mode (e.g., private cars versus public transport or cycling) and fleet composition (e.g., conventional fossil fuel vehicles versus plug-in hybrid-electric or battery-electric vehicles). This relates, in particular, to modeling exercises evaluating the mechanisms through which behavioral factors affect personal preferences and, eventually, the choice between alternative transport modes or different light-duty vehicles for heterogeneous consumer groups [25,54,55]. Other assessments have provided an estimation of policy costs incurred through the transition to a 1.5-degree-centigrade or a well-below-2-degrees-centigrade world, including an evaluation of the required carbon prices, total energy-system costs, and marginal abatement cost curves [44,47,56,57]. These articles found that integrating lifestyle changes in IAM-based mitigation pathways reduces the carbon prices required to achieve PA targets while decreasing the total mitigation costs and GDP losses of the transition [44,47,56–58]. However, none of the articles reviewed here made an attempt to quantify the costs of the policies required to transform the lifestyles of consumers, such as the costs of information and educational policies and awareness campaigns, as it is difficult to properly monetize and quantify the costs of such interventions in large-scale models.

Moreover, the supply-side effects of lifestyle transformations are often represented in mitigation pathways, with articles often exemplifying the role of energy-demand reductions in the rapid electrification of end-use sectors and the increased uptake of low-carbon technologies [12]. In essence, lifestyle transformations leading to lower levels of energy

demand reduce the need for supply-side investment, especially in immature and/or expensive technologies, such as nuclear and carbon capture and storage (CCS) [41].

Aside from energy-related effects, IAM studies attempt to quantify the effects of changing diets on land use, specifically through metrics representing the amount of grassland and cropland that could be freed up through the substitution of animal-based products [53]. Linking IAMs with other models (e.g., the global biodiversity model (GLOBIO) and the model of human development (GISMO) [10]) provided insights into the effects of the adoption of climate-friendly lifestyles on the progress towards meeting specific SDGs. This was achieved through composite metrics gauging the stress of different policy pathways on biodiversity (e.g., mean species abundance index [10,59]), water supply, and child-mortality rates [10,60]. Finally, the least investigated category of metrics is addresses lifestyle-change effects on macro-economic indicators. Only a few articles to date have investigated the effect of low-energy-demand practices on economic growth and employment [19,61], with the consensus being that less resource-intensive lifestyles lead to an increase in the activity of the services sector, as consumers spend less on energy, food, and consumer goods. However, this also implies some risks, especially for the production of energy-intensive materials and products (e.g., car manufacturers or steel producers will probably suffer from reduced activity and revenues), with possible negative implications for job creation and wages in these sectors [62].

While the reviewed literature offers mixed findings about the magnitude of lifestyle-change effects in different sectors, some conclusions can be drawn for the transport and residential sector, which are summarized in the following paragraphs. Significant GHG emission savings also stem from changes in nutrition; however, these reductions mostly relate to non-CO<sub>2</sub> emissions (e.g., methane (CH<sub>4</sub>) emissions from enteric fermentation and nitrous oxide (N<sub>2</sub>O) from animal manure) and CO<sub>2</sub> emissions from land-use change [53]. Here, the focus is placed primarily on energy-related carbon emissions, which form the largest share of global GHG emissions [3]. Table 2 provides a summary of studies employing IAMs and ESMs to evaluate the relative importance of lifestyle-change effects on energy use and emissions. These represent only a small sample of the reviewed articles, as most modeling exercises examine only the combined effect of various lifestyle changes on the energy–environment–economy system compared to alternative trajectories, focusing, for example, on the increased proliferation of renewables [48], improved energy efficiency [47], and different levels of carbon tax [63]. On the other hand, common approaches used to evaluate the impact of individual behavioral options involve sensitivity analyses in the models, conducted by alternately switching different lifestyle options on and off (e.g., [52]), or varying the level of their ambition (e.g., [64]), and then comparing the resulting emissions with a benchmark value each time. Moreover, decomposition techniques have recently been employed to break down future changes in carbon emissions between baseline and lifestyle-based mitigation scenarios to the effects of activity, structural-change, energy-intensity, and fuel-mix parameters (e.g., [24,65]). Table 2 also includes results from articles included in the review employing other large-scale models, such as lifecycle and input-output analysis (e.g., [66]) to further support our conclusions.

**Table 2.** List of studies with an assessment of the relative importance of individual lifestyle changes.

Refs.	Scale	Time Horizon	Model Used	Indicator for Lifestyle Effects	Most Important Lifestyle Changes (Based on Their Impact on the Assessed Indicator)
[50]	Regional (European Union)	2050	IAM (GCAM)	Accumulated GHG emissions (2011–2050)	Change compared to the baseline scenario: <ul style="list-style-type: none"> <li>• Transport: Carpooling (↓ 1.2%), car sharing (↓ 1.1%), shift to public transport (↓ 0.7%)</li> <li>• Residential: Recycling of plastic, metal, glass (↓ 1.7%), recycling of organic waste * (↓ 1.1%), thermostat setting (↓ 0.6%)</li> </ul>
[24]	Global	2050	IAM (IMAGE 3.0)	Per capita CO <sub>2</sub> emissions	Change compared to the baseline scenario: <ul style="list-style-type: none"> <li>• Transport (developed regions): Shift from car/airplane to high-speed trains</li> <li>• Transport (developing regions): Shift from car to bus and train</li> <li>• Residential (developed regions): Living in smaller dwellings, water-conservation actions</li> <li>• Residential (developing regions): Lower diffusion rates of appliances</li> </ul>
[65]	Global	2100	Demand model (EDGE)	Final energy demand	Change compared to the baseline scenario: <ul style="list-style-type: none"> <li>• Residential: Water-conservation measures (↓ ~20%), thermostat setting (↓ ~10%)</li> </ul>
[67]	National (USA)	Year 10	Bottom-up calculation	CO <sub>2</sub> emissions	Change compared to current (2005) levels: <ul style="list-style-type: none"> <li>• Transport: Eco-driving (↓ 1.2%), carpooling (↓ 1.0%)</li> <li>• Residential: Thermostat setting (↓ 0.7%), reducing electricity use in standby mode (↓ 0.5%)</li> </ul>
[68]	National (Portugal)	2050	Energy-system model (TIMES)	Useful energy demand per end use	Change compared to current (2017) levels: <ul style="list-style-type: none"> <li>• Heating and cooling: Thermal comfort level (−47% to 84%)</li> <li>• Water heating: Water usage patterns (−47% to 84%)</li> <li>• Dish washing: Number of washing cycles (−50% to 75%)</li> </ul>
[66,69]	National (various)	N/A	Lifecycle assessment, input-output model	Per capita GHG emissions	Change compared to the baseline scenario: <ul style="list-style-type: none"> <li>• Transport (Finland): Shift to public transport for traveling (↓ 20%), active travel modes (↓ 5%), electric bikes for commuting (↓ 5%)</li> <li>• Transport (Japan): Shift to public transport for traveling (↓ 7%), carpooling (↓ 4%), active travel modes (↓ 3%)</li> <li>• Residential (Finland): Living in smaller dwellings (↓ 3%), water-conservation actions (↓ 2%)</li> <li>• Residential (Japan): Living in smaller dwellings (↓ 3%), water-conservation actions (↓ 2%)</li> </ul>
[52]	Global	2100	IAM (AIM/CGE)	Energy demand, CO <sub>2</sub> emissions	Change in CO <sub>2</sub> emissions compared to the baseline scenario: <ul style="list-style-type: none"> <li>• Transport (developing regions): Shift to public transport (up to ↓ ~30%), carpooling (up to ↓ ~10%)</li> <li>• Transport (developed regions): Carpooling (up to ↓ ~15%)</li> </ul>
[64]	Global	2050	System dynamics model	GHG emissions	Change compared to the baseline scenario for different levers of ambition: <ul style="list-style-type: none"> <li>• Transport: Shift to public and active modes of transport (up to ↓ ~10 GtCO<sub>2</sub>eq/yr)</li> <li>• Residential: Living in smaller dwellings (up to ↓ ~13 GtCO<sub>2</sub>eq/yr)</li> </ul>

\* This behavioral option mostly relates to non-CO<sub>2</sub> (methane) emissions from landfills.

First, the lifestyle changes taking place in the transport sector are overall more effective in reducing sectoral energy demand and associated CO<sub>2</sub> emissions compared to the measures adopted in the residential sector, especially in developed regions [19,45]. Van de Ven et al. (2018) ([50]) analyzed the impact of individual behavioral changes for the EU using the GCAM model and found that the most effective emission-reduction measures are carpooling and carsharing mechanisms. The same study showed that in the residential sector, the most effective measure to reduce energy-related CO<sub>2</sub> emissions was the recycling of plastics, metals, and glass; however, while recycling is commonly performed at the household level, its effects are propagated through the energy–economy system to the activity and energy production level of industrial sectors (i.e., *upstream* effect). In a study on the United States (USA), Dietz et al. (2009) ([67]) also showed that eco-driving and carpooling practices have a larger impact on reducing CO<sub>2</sub> emissions compared to actions taking place in households, such as adjusting the temperature setpoint of thermostats. Based on a review of lifecycle-assessment and input/output studies [23], the mitigation potential of lower-consumption practices in transport could be as high as 2.0 tCO<sub>2</sub>eq/cap (median value for car-free travel). The corresponding highest GHG-saving potential in households comes from purchasing renewable electricity (median value of 1.6 tCO<sub>2</sub>eq/cap),

which, however, does not abide by the strict definition of lifestyle change provided in Section 3.1. The latest IPCC assessment [2] reports an average 30% reduction potential in 2050 for land-transport GHG emissions from promoting public transport, shared mobility, and compact city forms, and a 40% mitigation potential for the aviation sector from avoiding long-haul flights. The lifestyle-related mitigation potential in the buildings sector was estimated to be relatively low, at 15%.

Second, in developing countries, lifestyle changes are less effective in mitigating CO<sub>2</sub> emissions as rising incomes lead to increases in future residential and transport activity levels compensating for lifestyle-led demand reductions, in the absence of strong climate policies. In the transport sector, this increasing trend is mainly due to rising ownership levels of private cars as incomes grow, whereas, in households, this is caused by the increased penetration and use of electric, heating, and cooking appliances to satisfy household needs and comfort. Behavioral changes can therefore moderately limit the uptake of inefficient carbon-intensive appliances in households and cause a relatively small shift away from private cars to public modes of transport [52], especially to trains and buses. For the latter, however, a shift to less expensive public modes of transport is accompanied with an increase in overall transport activity [24]. In general, there is weaker confidence as to the relative size of lifestyle-change effects for developing and low-income countries, where the demand for energy and goods is far from reaching its saturation point. This contrasts with several countries in the Global North, especially in the EU, where saturation has already been achieved for many transport and household energy services [12].

Third, in developed countries, the most effective behavioral measures to mitigate transport-related CO<sub>2</sub> emissions were found to be carpooling and shifts to public and active travel modes, while significant savings also arise from sharing-economy practices, such as car sharing, and more responsible driving (Table 2). The high mitigation potential of actions such as carpooling and carsharing, the shift towards mobility-as-a-service through reducing overall vehicle use, and shifts to low-carbon modes of transport was reaffirmed by a recent meta-review [23]. The evidence from the IAM-based modeling literature does not enable a complete breakdown of the contribution of specific low-emission transport modes (e.g., potential CO<sub>2</sub> emission savings from a shift from private cars to buses or to the use of bicycles for commuting), as the results are sensitive to the current split between transport modes and model-specific scenario assumptions. In addition, large emission savings are generated from substituting private cars and airplane travel with high-speed trains [24,70,71], especially targeting specific transport segments, such as business aviation trips.

Fourth, our literature review shows that in developed regions, the most effective lifestyle measures to decarbonize the residential sector are conserving hot water, adjusting thermostats for space heating and cooling, and living in smaller dwellings. The effects of water-conservation measures are twofold: they reduce energy consumption for the water heating used for (a) hygiene purposes and (b) clothes and dish washing. In a global scenario of very low energy demand in 2100, Levesque et al. (2019) ([65]) demonstrated that the two actions have approximately the same impact on residential energy demand. Limiting the expansion of household floor areas in combination with a reduction in thermostat temperature settings during winter provide important emission savings, especially in developed OECD economies in the northern EU and North America, through reducing the demand for space heating. An important source of uncertainty in future projections of residential energy demand, according to [68], is the level of thermal comfort, namely the heating needs that are actually met; the latter are linked to energy-poverty levels, which have recently become a crucial energy policy issue in the EU and globally, given the large increases in energy prices. Mitigation strategies aiming to enable deep energy demand reductions through lifestyle changes therefore need to guarantee that decarbonization is not achieved at the expense of human well-being, especially for low-income households [18]. This could be achieved especially if decent living standards for shelter (including space heating), mobility, and other needs are secured in the decarbonization policy context [72].

In addition to the aforementioned measures, recycling and other actions aligned with the circular economy model, such as the re-use and extension of product lifetimes [73,74] can also have an important indirect effect on industrial energy demand and production and associated emissions.

Summarizing the above, in this literature review, we identified the most important lifestyle changes based on the modeling results from IAM and ESM studies, which are more applicable to developed economies. These are summarized in Table 3. In the transport sector, for which the largest GHG emission-mitigation potential exists due to behavioral change, the most important demand-side measures relate to different options of mode shifts (with a particular focus on the switch from private cars to public and active modes of transport and the replacement of flights with high-speed train travel when available). Additionally, sharing-economy practices, such as carpooling, car sharing, and mobility-as-a-service, also have a significant effect on direct and indirect (*upstream*) emissions, while some evidence points to the mitigating role of eco-driving. On the other hand, while, in buildings, the mitigation potential of behavioral change was found to be lower, a number of “avoid” actions can significantly reduce energy consumption, such as conserving water, adjusting thermostat set points, and limiting the expansion of household floor areas. Finally, circular-economy options, such as reusing, recycling, and extending the lifetimes of products, can reduce the use of material and energy resources, particularly in industry, and thus contribute to PA targets. Based on this review, the aforementioned lifestyle changes are the most important candidates for inclusion in energy-system models and IAMs to examine their effects on mitigation pathways and systemic transformations at global, regional, and national levels.

**Table 3.** Summary of most important lifestyle changes for energy-system and IAM-based modeling studies for the transport and residential sectors.

Sector	Domain	Lifestyle Change Category	Most Important Lifestyle Changes
Transport	Mobility	Transport-mode shifts	<ul style="list-style-type: none"> <li>• Shift from private cars to public transport (e.g., buses, railways)</li> <li>• Shift from airplane to high-speed trains (reduction in flights)</li> <li>• Shift to active modes of transport (cycling, walking)</li> </ul>
		Shared-mobility practices	<ul style="list-style-type: none"> <li>• Carpool commuting</li> <li>• Car-sharing schemes (mobility-as-a-service)</li> </ul>
		Driving habits	<ul style="list-style-type: none"> <li>• Eco-driving practices (e.g., lower speeds)</li> </ul>
Residential	Thermal Comfort	“Avoid” energy-demand actions	<ul style="list-style-type: none"> <li>• Conservation of hot water for showering, clothes, and dish washing</li> <li>• Adjustment of thermostat-temperature set points</li> <li>• Living in smaller dwellings</li> </ul>
	Consumer goods	Circular economy practices	<ul style="list-style-type: none"> <li>• Re-cycling, re-using, and extending the lifetime of consumer goods</li> </ul>

### 3.3. The Most Common Modeling Approaches

The previous section focused on evidence from previous empirical assessments and modeling studies about the relative size of lifestyle-change effects on energy demand and GHG emissions. This section explores the key methodological approaches followed for representing demand-side transitions in ESM- and IAM-based mitigation pathways. We specifically focus on the methods and scenario assumptions adopted in modeling the most important lifestyle measures in the transport and residential sectors, as identified in the previous section (Table 3).

In general, the demand for energy services and travel is treated as an external parameter in most IAMs and energy-economy models. This demand is projected into the future based on the evolution of demographic (e.g., population), socio-economic (e.g.,



personal income, GDP) and climatic (e.g., heating- and cooling-degree by day) indicators [52,75]. Treating service demand as an input for IAMs implies that potential changes in consumption patterns driven by lifestyle transitions are also externally defined, usually in the definition of the scenarios and associated narratives [22]. The representation of lifestyle changes in IAM and ESM modeling environments is mainly stylized, since the dynamics of such processes are not explicitly captured through the mathematical formulation of models, but rather their *impact* on energy consumption is mediated through ad hoc modifications of the relevant model parameters [17]. For example, a change in social norms and individual behaviors leading to increased preferences towards living in smaller dwellings is operationalized by imposing a constraint on floor-area parameters (included in the models), usually at a value representing the current size of dwellings in a developed country [45,76]. Furthermore, in transport, preferences towards shared mobility options, such as carpooling or car sharing, are often represented in IAM-based pathways through scenario-specific modifications of exogenous parameters, such as the number and load factor of light-duty vehicles [50,77], by, for instance, setting an occupancy limit of two people per car across all regions [52]. A more detailed description of the main methods used to represent lifestyle changes in the transport and buildings sectors is provided in the following sub-sections.

### 3.3.1. Modeling Lifestyle Changes in the Transport Sector

This sub-section discusses the main methodologies used to represent the most important transport-related lifestyle changes in large-scale IAMs and ESMs:

- Transport-mode shifts:** Transport-mode shifts are amongst the very few types of lifestyle change modeled endogenously in IAMs and energy–economy models. The share of different transport modes (as well as of car sizes and/or technologies) is usually determined through multinomial logit functions factoring in the generalized costs (direct and perceived) of competing transport modes (and technologies), in addition to preference factors and the cost of time [78]. The latter is positively related to income; as people become wealthier, the opportunity cost of time increases, implying that they will opt for faster transport modes, such as private cars. Travel-time budgets (TTBs) are also used as constraints in the solution of the models to illustrate the maximum time people are willing to spend daily on transportation [79]. The parameters included as drivers of modal shifts, specifically in linear cost optimization models, are the speed of competing modes, the cost of infrastructure, and intangible costs, such as level-of-service variables (e.g., travel and congestion time) and the value of time [80,81]. The sensitivity of transport modal shares with respect to changes in total costs is commonly governed by substitution elasticity values [82,83], which are derived from historical aggregate transportation data [84]. At the same time, a growing body of literature has focused on monetizing the non-financial attributes that shape preferences for alternative car technologies, such as range anxiety and perceptions of the risk of new technologies, and including them in the logit function [25,85]. In general, ESM- and IAM-based scenarios with a description of lifestyle transitions in the transport sector operationalize mode shifts to public or active travel modes (walking and cycling) by: (a) modifying the preference factor to encourage a switch to slower, but more climate-friendly, transport modes, such as buses, rail, or even walking [52], (b) relaxing the TTB constraint [45], (c) imposing higher fuel taxes on cars and motorcycles to trigger a reduction in the use of private cars [86], or (d) simulating the effect of investment in new infrastructure by improving the level-of-service variables for public transport [81].
- Shared-mobility practices:** Shared mobility, the practice of sharing assets such as cars and e-scooters, thus increasing the delivered service per product [2], is often represented as an external feature in transport-energy models. The shared-mobility options commonly reported in modeled mitigation pathways are carpooling and car-sharing initiatives [12,38], both of which have a decreasing effect on overall car travel activity, car registrations, and associated emissions. The adoption of such services is expected to be accelerated in the future through the development of digital platforms offering

essential trip information and convenient interfaces for electronic payments [72]. In common modeling frameworks [45], the number of cars in service (per 1000 inhabitants) is linked to the travel-money budget (TMB), namely the share of income people spend on transportation. The combined effect of carpooling and carsharing measures on motorization is then quantified, first, by making the assumption that the TMB will become smaller in the future as it will converge to values typical of developed economies, such as the EU or Japan [45]. Second, the measures limit motorization by weakening the decreasing effect of growing income on vehicle load factors; however, as the authors of [78] warn, increasing the occupancy rate of cars can have unintended rebound effects on energy use as the cost of technologies decreases with rising load factors, meaning that the saved income will be re-spent (if the TMB is not decreased). In [50], an attempt was made to distinguish between the effects of carpooling and carsharing: the impact of carpooling was implicitly modeled by assuming a future increase in car-load factors across the EU, while for car sharing, back-of-the-envelope calculations were performed to estimate the energy saved from decommissioning private vehicles. Finally, a few ESM- and IAM-based mitigation pathways [12,41,50] have included the indirect effect of car sharing on industrial energy demand through a dematerialization factor applied on the activity parameter for steel production.

- **Eco-driving practices:** Eco-driving refers to the adoption of more climate-friendly driving styles through the avoidance of speeding, the removal of unnecessary loads from vehicles, and the performance of regular maintenance checks [51]. The driving patterns in ESM frameworks are usually represented through vehicle-specific driving profiles or based on the relationship between speed and infrastructure utilization [87]. The effect of eco-driving on energy consumption is mediated through improvements in the fuel efficiency of cars, vans, and trucks, as less fuel is required to cover the same distance. In energy-system models, eco-driving is also a lifestyle change, and treated as an exogenous driving force: scenario assumptions are usually needed about (a) the share of passenger-kilometers affected by eco-driving practices (which can differ between private- and business-car travel [21]), and (b) the increase in the fuel efficiency of four-wheel-vehicle technologies (assumed to be in the range of 5–10% [88]).

### 3.3.2. Modeling Lifestyle Changes in the Residential Sector

This sub-section discusses the main methodologies used to represent the most important lifestyle changes for the residential sector in IAMs and ESMs:

- **“Avoid” actions:** Several voluntary actions (listed in Table 3) can reduce service demand in the residential sector, especially through conserving hot water, residing in smaller dwellings, and adjusting thermostats for heating and cooling in buildings. As with most lifestyle changes assessed in the transport sector, “avoid” actions in the residential domain are not modeled explicitly in IAMs and ESMs, but their effect on energy use is indirectly captured through adjusting/capping relevant model parameters. For water-conservation measures, their impact is usually modeled by simply applying a reduction factor on the overall water-heating demand (25% in global studies [24,45,48], 10% in a US study for California [89]), based on the assumption that daily shower time is reduced. A more elaborate analytical approach was described in [65]: in addition to cutting down showering time, the authors assumed changes in the number of showers per person per day and showerhead flow rates, with both factors reducing water-heating demand. Aside from showering, the authors investigated the impact of low-demand practices in clothes and dish washing by imposing additional scenario assumptions about the number of wash cycles and temperature elevation. The household floor area is generally projected to increase as incomes grow across the globe in ESM-based scenarios [27]. Limiting unnecessary floor area per capita through, for example, compact city and building designs, is represented by setting a cap on household areas in the majority of lifestyle-led mitigation pathways [19,28] according to living standards in selected developed economies. Contrary

to the customary approach, the authors of [42,90] established a statistical relationship between housing floor area and a set of factors, such as cohabitation practices and dwelling location, based on information from national surveys in France. By changing the strength of the statistical relationship, the authors simulated the potential effects of lifestyle changes on household floor area, which were then fed as inputs to an energy-system model to analyze the wider effects on energy use and emissions. Finally, adjustments to the temperature at which consumers heat or cool their household because of changing habits has a direct effect on the energy demand for space heating and cooling. The most common approach to quantifying thermostat adjustments for heating/cooling in IAM and ESM frameworks is to exogenously reduce/increase the base temperature based on which heating/cooling degree days are calculated (e.g., by 1 °C in [45,48,50]). Degree days are a measure of heat or cold stress, as they capture the daily deviation of the mean outdoor temperature from a pre-established baseline value [91] and, therefore, are not direct indicators of indoor thermal environments. Two ESM-based assessments deviate from this framework: (a) the authors of [65] calculated the degree days in their demand model based on assumptions from the adaptive thermal-comfort model about desired indoor-temperature ranges, on internal heat gains, and on resident heterogeneity, while (b) the authors of [92] estimated the heating-energy demand (using the PRIMES-Buimo module [93]) via bottom-up calculations based on various other factors, including U-values and the ventilation characteristics of building classes, encompassing indoor thermostat settings. However, none of the large-scale model assessments have used real-world data to assess the real-world energy-saving potential of changing thermostat behaviors and the potential rebound effects on energy consumption and associated emissions.

- **“Circular-economy” practices:** Similar to those of the shared economy, circular-economy practices aim to increase the efficiency of resource use, without compromising the level of the provided service [2]. The most common circular-economy measure studied in integrated assessment models is waste management and recycling, such as that of plastic [45], paper, metal, and organic waste [50]. In contrast to car sharing and carpooling, recycling occurs at the disposal phase of consumer goods, but its effect is propagated through the production output in industrial sectors, as the requirement for raw materials and products declines. Reductions in industrial energy demand are also achieved through the re-use of materials and by extending the life span of consumer goods [71]. The effect of waste management and recycling on GHG emissions is studied in large-scale ESMs by decreasing industrial production (e.g., lower activity in non-energy industries from reduced plastic demand [12,30,94]). In [50], a separate module was developed to map the streams of household recycling and waste.

## 4. Discussion

### 4.1. Scope and Limitations of the Review

The conducted review searched for academic articles assessing the value of lifestyle changes in climate-change-mitigation pathways using integrated assessment and energy-system models. The query using broad search criteria in Scopus returned a variety of articles employing models other than IAMs and ESMs, such as lifecycle assessment and input/output models. The information from these assessments was used to complement the discussion about the magnitude of lifestyle-change effects on energy and GHG emissions in Section 3.2, but was not used in the main methodological analysis, as this remains outside the scope of this review. The review was also enriched with articles from previous literature reviews in the field (e.g., [15]), and with scientific reports produced by internationally renowned organizations and institutions, such as the IPCC (e.g., [28]), IEA (e.g., [4]), IIASA (e.g., [31]), and the European Commission [30]. However, one limitation of this review is that it may have omitted other global/regional reports from the gray literature and national or sub-national (e.g., at the household level) impact assessments (especially of non-English language), which could have also contributed to our discussion.

Another limitation of this review is that it focused on reviewing methods for modeling lifestyle changes in the transport and residential sectors, but not in the food sector. Changes in diets and food-waste management are also important sources of savings in non-CO<sub>2</sub> emissions and can increase the amount of land used for afforestation and growing energy crops [53]. However, our choice to focus on the two aforementioned sectors is based on the evidence from the wider literature review about the current carbon footprint and the mitigation potential of demand-side strategies in different sectors (66%/67% for housing/transport versus 44% for the food sector in 2050, according to [2]). Future research may discuss how lifestyle changes are modeled in the food sector.

#### 4.2. Synthesis of Results from the Literature Review

This article reviews the findings and main conclusions from the growing literature on demand-side transitions embedded in climate-change-mitigation pathways developed via integrated assessment and energy-system models. First, there is substantial evidence from global, regional, and national studies about the significant role of lifestyle changes in achieving decarbonization goals and wider sustainability targets. When combined with energy efficiency, changing consumer behaviors are strong facilitators of (a) deep reductions in the direct and indirect GHG emissions of end-use sectors, primarily in buildings and transport, (b) downsizing the scale of the investment required by supply-side transformations, (c) preventing overreliance on expensive, risky, and immature negative-emission technologies, such as BECCS, and (d) progressing towards key environmental and socio-economic SDGs, such as those related to preserving bio-diversity, food security, and human health.

Second, strong effects on energy use and associated carbon emissions were identified for *avoid* and *shift* actions in the transport and housing sectors of developed OECD economies. The highest mitigation potential from the lifestyle changes in the model-based mitigation scenarios was found for the mobility domain, with *modal shifts* and *shared mobility practices* (carpooling, car sharing, mobility-as-a-service) constituting the most promising options. The specific modal shifts that warrant further investigation are those involving a switch to public and active (walking and cycling) transport modes, but also those replacing long flights with traveling by high-speed train. Significant potential for emission savings in the residential sector stems from actions curtailing the demand for energy services, such as space heating and cooling, the most influential being *managing the demand for hot water*, *limiting the size of dwellings*, and *adjusting thermostats for heating and cooling*. Moreover, circular-economy practices in the residential sector, including *recycling* and *waste management*, are also effective ways to reduce the demand for materials and energy in the industrial sectors. On the other hand, the evidence about the impact of lifestyle changes on GHG emissions is weaker for developing and low-income countries, as the demand for energy and mobility services is projected to continue growing, driven by increases in income and population, and has still not reached saturation levels.

Third, ESM- and IAM- based modeling frameworks capture lifestyle changes in the transport and residential sectors by using simplistic and aggregate approaches, which mainly involve ad hoc modifications to existing model parameters exogenously based on stylized scenario assumptions without integrating theoretical insights, empirical evidence, or real-world data. These modifications have the effect of altering the social and behavioral dynamics embedded in the mathematical formulation of models by allowing the relaxation of specific model constraints (e.g., travel-time budget), applying caps on internal parameters (e.g., household floor area), or directly correcting final demand (e.g., useful water-heating demand). Furthermore, the treatment of lifestyle changes via simplified modeling frameworks and the application of exogenous scenario-dependent assumptions that reflect only the average behavior of consumers in a region poses inherent disadvantages/challenges to meaningful policy analysis:

- **Challenge 1:** Since the social and behavioral determinants and corresponding policy levers influencing changes in lifestyles remain undetermined, the true cost of the

transition to low-demand societies cannot be reliably estimated. For example, shifting to low-carbon transport modes essentially requires overcoming a set of behavioral, institutional, and infrastructural lock-in effects and barriers through policies aiming, for example, to increase awareness of the health benefits of walking, imposing extra tolls on cars, and developing safer infrastructures for cycling in cities [23]. A rare attempt to assess some of the elements of these transition costs is found in [79]. The authors introduced the concept of travel-time investment to study the impact of reducing the time taken to complete travel trips, through investments in public transport infrastructure, on modal shifts. However, the value given to the travel-time-investment variable was not empirically estimated based on real data, but was exogenously assigned based on stylized assumptions. An example using the MARKAL model can be found in [95], in which the authors attempted to simulate the effect of awareness campaigns and information provision on household energy conservation and technology choices for lighting by representing campaigns as “virtual technologies” with known efficiencies and investment costs. However, this would require large amounts of data from sociological surveys on consumers’ willingness to engage in low-consumption behaviors [87], which is restrictive for large-scale applications.

- **Challenge 2:** In general, the wider the spatial and temporal boundaries of a modeled system, the lower the levels of detail and granularity that are used to model its constituent components, as a result of the increased computational complexity [7]. As a result, global IAMs with long time horizons often have a coarser representation of consumer groups and their decision-making process compared to regional and national models (including ESMs) with a shorter analysis period, which can more easily integrate national-level details and specificities. Using aggregate approaches to model the impact of lifestyle changes on energy consumption means that consumer heterogeneity is not adequately captured. Modeling the decision making in energy-demand sectors based on cost-optimization—a usual feature of bottom-up IAMs and ESMs—may require aggregating the population of consumers/decision makers to a single representative agent with fixed preferences over time [16]. Ignoring consumer heterogeneity in modeling frameworks when studying social phenomena prohibits the assessment of responses to policies for different consumer groups (based on different income classes and locations, for example), and the effect of interactions between different groups (through social learning, for example). Recent assessments have updated and expanded modeling frameworks to overcome some of these caveats. This was performed, for example, through capturing the idiosyncratic preferences of consumers in assessing the distributional effect of energy-efficiency policies in the residential sector [96], through modeling the impact of social learning on vehicle selection in combination with technological learning [54] and varying cultural influences [55], and through perceptions of transport modes [81]. However, similar assessments of a broader set of lifestyle changes in IAM-based mitigation pathways accounting for consumer heterogeneity are still lacking, with rare exceptions, such as in [42]. Such assessments require rich data input from national surveys, making it difficult to reproduce them in regional or global contexts. Agent-based models also offer opportunities to endogenize the impact of social dynamics [61] and psychological factors (such as awareness [97]) on individual energy behaviors in small-scale studies, but scaling up their spatial coverage requires strong (and usually simplistic) assumptions about the comparability of behaviors in different regions. Finally, efforts have recently been made in the IAM research community to downscale global-level results to country-level projections of service-energy use for different household categories and decomposed to activity–structure–intensity indicators (making it suitable to study lifestyle transitions) [98].
- **Challenge 3:** The structural changes in the economy brought about by lifestyle changes, such as shared mobility and the circular economy, are difficult to assess using bottom-up energy models and IAMs, as these models do not analyze the effects of lifestyle



changes on socio-economic and production indicators (macro-economic effects are the least discussed indicators in the relevant literature, as shown in Figure 4). Demand-side transitions have the potential to shift consumption patterns for services and materials (such as people buying fewer cars due to carpooling and the provision of fewer household devices due to extended product lifetimes), which affects both the demand for (and production of) industrial products and the performance of the entire economy (e.g., GDP, employment, competitiveness, etc.). The evidence shows that lifestyle changes will shift the economic activity from carbon-intensive sectors, such as the automotive industry, to services that could lead to reduced jobs in traditional manufacturing sectors, but could offer new, high-quality jobs to support future digitalization and green growth [19,62]. Moreover, business models for car sharing favoring the penetration of electric vehicles into the market, thereby accelerating the electrification of the transport sector [99], could also positively affect employment in the electricity [100] and electric-vehicle-manufacturing sectors. However, to our best knowledge, the effects on employment have not been studied in detail for different industrial sectors under mitigation pathways, including lifestyle changes, thereby inhibiting a complete assessment of the economic risks and opportunities of demand-side transitions.

#### 4.3. Pathways for Future Research

According to the latest IPCC report [2], further research is required to improve the modeling of transport and residential services and the influence of consumer lifestyles in large-scale models, supported by big-data techniques. Raw data on consumer behavior collected through Information and Communication Technology (ICT) tools can be processed and integrated to large-scale energy–economy models, as shown by previous examples in the literature. For example, the authors of [101] studied the impact on residential electricity use and energy efficiency in Austria from the roll-out of smartphone apps providing users with information about dynamic electricity prices. Based on econometrically estimated price elasticities, the authors investigated the systemic effects of incorporating flexible electricity demand via a bottom-up optimization energy model. The authors of [102] also extended the mathematical framework of the UK TIMES energy system model to incorporate demand-side flexibility for appliances and electric vehicles, based on experimental data on smart-appliance acceptance.

Similarly, big data from apps and other ICT tools could be analyzed with statistical tools to extract information about the energy behavior and preferences of various consumer groups, differentiated, for example by income class, location (urban/rural), and gender, with a focus on consumption for mobility, housing, and consumer goods. This information could then be used to update and extend the existing functions, mathematical formulations, and parameters in state-of-the-art energy systems and integrated assessment models to endogenize more social phenomena, such as carpooling and car sharing, in the transport sector, and living in smaller dwellings or adjusting thermostats, in the housing sector. The mitigation potential of lifestyle changes and the related costs (including those of the supporting infrastructure) can also be assessed and compared with those of alternative mitigation strategies and options (addressing **Challenges 1 and 2**, as mentioned in the previous section). Moreover, lifestyle-led pathways can also account for the potential trade-off between the positive and negative effects that may occur through sustained behavioral changes in the post-COVID world [43,103,104] (e.g., increased teleworking and a lower demand for business trips, reducing transport emissions, counterbalanced by a reduced shift to public transport due to safety concerns). Finally, the results from bottom-up energy-system models relating to shifting consumption patterns in end-use and energy-supply sectors can be integrated to macro-economic general-equilibrium models to assess the effects of lifestyle-induced structural changes on socio-economic variables, such as employment, industrial production, GDP, and trade (addressing **Challenge 3** from the previous section).

## 5. Conclusions

Transforming energy–economy–environmental systems to achieve the ambitious decarbonization goals set by the PA agreement will require interventions both on the energy-supply and demand side. Regarding the demand side, the review of previous modeling exercises showed that changes in consumer behaviors sustained by lifestyle changes with respect to mobility and thermal comfort practices, diets, and the use of consumer goods can significantly contribute to climate-change mitigation and sustainable development goals. In contrast to supply-side and technological measures, lifestyle transitions are captured by scenarios developed with IAMs and ESMs in a non-sophisticated way, which limits our understanding of the drivers, potentials, and associated costs of behavioral change. This paper presented a structured literature review to identify the most important lifestyle changes widely studied in IAM- and ESM-based mitigation pathways specifically for the residential and transport sectors, with regards to their impact on energy use and emissions. Additionally, this paper reviewed the most common modeling frameworks and scenario assumptions used in the assessment of lifestyle-led transitions in the two sectors. Shifting to public and active modes of transport, adopting shared mobility practices, and improving driving behaviors were found to be the most important lifestyle changes in the transport sector, while actions “avoiding” the demand for space and water heating and circular-economy practices were the most effective in the residential sector. The analysis of common methodological approaches in the IAM and ESM literature showed that research efforts should focus on improving the representation of (1) the social dynamics and costs of demand-side transitions, (2) the heterogeneity of energy-use preferences and behaviors between consumer groups, and (3) the effects of lifestyles on the wider economy. Finally, the review provided practical recommendations and pathways for future research on lifestyle changes, primarily through innovative methodological frameworks involving big-data techniques.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/en15144948/s1>. Table S1: Full list of references selected for the literature review.

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