Demand-side solutions to climate change mitigation consistent with high levels of wellbeing

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Abstract. Mitigation solutions are often evaluated in terms of costs and greenhouse gas reduction potentials, missing out on considering direct effects on human wellbeing. Here, we systematically assess the mitigation potential of demand-side options, categorized into avoid, shift and improve, and their human wellbeing links. We show that these options, bridging socio-behavioral, infrastructural and technological domains, can reduce counterfactual sectoral emissions by 40-80% in end use sectors. Based on expert judgement and an extensive literature database, we evaluate 306 combinations of wellbeing outcomes and demand side options, finding largely beneficial effects in improving wellbeing (79% positive, 18% neutral, and 3% negative), even with low confidence on the social dimensions of wellbeing. Implementing such nuanced solutions is based axiomatically on an understanding of malleable not fixed preferences, and procedurally on changing infrastructures and choice architectures. Results demonstrate high mitigation potential of demand-side mitigation options that are synergistic with wellbeing.

Demand-side mitigation options are increasingly discussed in the literature, e.g.,[1–3]. However, a consistent evaluation both in terms of their overall potential and their societal implications is lacking. Even for an ambitious 1.5°C target, several mitigation strategies are plausible – ranging from high dependence on new energy infrastructures to low-demand pathways[4]. Evaluating these options mostly from a macroeconomic cost-benefit perspective is relevant, but it fails to reflect the wider impacts through benefits and costs of mitigation strategies from human wellbeing perspective[5].

There are three closely related shortcomings. First, mitigation options on the demand-side, such as choices toward transport mode for mobility patterns and building design, size and use, interact with the wellbeing of end-users and citizens. Evaluating the marginal monetary costs of these measures, if they can be monetized at all, hardly reflects their full impacts. Second, a focus on costs leads to a tendency to preferably evaluate those solutions that have precise direct market cost values attached, neglecting more systemic or uncertain solutions where market prices are difficult to evaluate or not relevant[6]. Third, income and expenditures only reflect a part of wellbeing, and monetary cost evaluations, even if starting from a broader framework, often ignore encompassing views on multiple dimensions of wellbeing. This critique is not new, and on the aggregate scale, there is agreement among economists and philosophers and in other disciplines that metrics like GDP insufficiently reflect wellbeing, and that these must be complemented by more encompassing metrics[7].

These considerations motivate two related questions: First, what is the climate change mitigation potential of demand-side mitigation options? Second, what are implications for wellbeing of these demand-side mitigation options? Especially answering the second question is a considerable challenge, as there is no single straightforward and agreed upon metric of wellbeing. Wellbeing can be considered on macro level, e.g. in 10 country-level wellbeing domains by the OECD[8], and on micro-level, reflected, for example individual constituents of wellbeing[36]. Approaches can also be separated into subjective understandings of wellbeing (given preferences, happiness) and objective ones (life expectancy, eudaimonic metrics) with diverging implications for climate change mitigation[11,12]. According to some leading eudaimonic approaches, wellbeing has several constituents, and that all of these must be met independently to enable a good life[13,14].

Here, we follow an eudaimonic understanding and examine individual metrics and constituents of wellbeing. We first identify demand-side mitigation options and group them into avoid, shift, and improve (ASI) categories for all end-use sectors[3]. We then estimate their respective potentials across sectors informed by a comprehensive literature review (Methods). Then we ask how they improve or harm individual constituents of wellbeing (Table M1), systematically coding their impact on constituents of wellbeing based on a literature review (Methods).

Demand-side options to reduce emissions across sectors

Following an established definition[3], demand-side solutions for mitigating climate change modify demand for goods and services by targeting choices/adoption of technology, consumption, behavior, lifestyles, coupled production-consumption infrastructures and systems, service provision, and associated socio-technical transitions, as exemplified by options to improve accessibility, better living conditions, and increase nutritional quality while decreasing energy input and GHG emissions. These are distinct from supply side options that involve changes in energy supply, production technologies and deployment of carbon dioxide removal technologies that keep demand by end-users invariant.

Demand-side options can be grouped into ASI categories, constituting a simple analytical framework pertinent for decision makers[3]. Originally applied to the transport sector[15, 16], these categories can also be transferred to other sectors[3,17,18]. However, a comprehensive bottom-up assessment of ASI options is missing. Here, we generalize 'avoid' to denote all mitigation options that reduce unnecessary consumption (i.e. energy or food consumption in developed countries that are not needed for maintaining or improving the levels of services provided) by redesigning service provisioning systems; 'shift' to describe the switch to already existing competitive low-carbon technologies and service provisioning systems; and 'improve' to mean improvements in efficiency in existing technologies where adoption by end users plays an important role.

ASI options offer a high potential for mitigation (Figure 1, Table 1). In all sectors, end-use strategies can help reduce the majority of emissions, ranging from 41% (6.5 $GtCO_2e$) emission reductions in the industry sector, to 41% (7.3 $GtCO_2e$) in the food sectors, to 62% (5.8 $GtCO_2e$) emission reductions in the land transport sector, and 78% (6.8 $GtCO_2e$) in the building sector. These numbers are median estimates and represent benchmark accounting. Estimates are approximations, as they are simple products of individual assessments for each of the three ASI options. If interactions were taken into account, the full mitigation potentials may be higher or lower, independent of relevant barriers to realizing the median potential estimates. Demand-side mitigation potentials here are based on opportunities for action available to end-users, while not considering supply side options, such as the decarbonization of the electricity sector. However, mitigation potentials include technology adoption that reduces carbon intensity, e.g., embedded renewable energy in housing and electric vehicles for transport.

We find that improve options contribute the most in building, transport and industry sectors. Examples include efficient building envelope, household appliances, electric cars, and more efficient material and energy use in industrial production. Shift measures are most relevant for transport, in particular modal shift to walking, cycling, and shared pooled mobility; and for food, in particular shift to flexitarian, vegetarian, or vegan diets. These are options that require physical infrastructures and choice infrastructures that support low-carbon choices, such as safe and convenient transit corridors, and desirable and affordable meat-free menu options. They also require end users to adopt these choices, individually and socially. Avoid options are relevant in all sectors. Cities play an additional role, as more compact designs and higher accessibility reduce demand for km travel and car mobility and also translate into lower average floor size and corresponding heating, cooling and lighting demand. The lifetime extension of products and buildings and more efficient product design also add to avoiding energy use and related emissions. Teleworking is related to high uncertainty with relatively low mitigation potential in consequential assessments, but with possibly higher GHG emission reduction potential if COVID-19 experiences induce a structural shift in working environments from both employees and employers.

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Opportunities for avoiding excess consumption exist for all end use sectors. Reducing food waste is a prime no-regret option, accounting for 4.4 $GtCO_2e$ emissions, or 8% of total annual GHG emissions, if deforestation effects associated with wasted food provision are included[19]. In developed countries, consumers are the largest source of food waste, and habitual adjustments, such as meal planning, re-use of leftovers, and avoidance of over-preparation reduce associated GHG emissions[20,21]. Reregulating expiration labels is an option for policy makers to disincentive unnecessary disposal of unexpired items[22]. The mitigation potential of food waste reductions globally has been estimated at 0.8-6.0 $GtCO_2e$/yr by 2050[23,24].

Diet shifts, as another demand side strategy, are even more impactful in the food sector. Estimated GHG emissions reductions associated with dietary shifts to low meat diets, vegetarian diets, or vegan diets range from 0.7-7.3, 4.3-6.4, and 7.8-8 $GtCO_2e$/yr by 2050, respectively[24].

The transport sector demonstrates the largest divergence between top-down integrated assessment models and aggregation of bottom-up models. A main reason for this divergence is that place-based solutions and those that involve changing social norms and behavioral adaptations are hard to display in Integrated Assessment Models (IAMs)[25–28]. A plethora of country and city specific solutions, many categorized into avoid and shift (ca. 15% and 18% of measures respectively), is estimated to have the potential to bring GHG emissions in the transport sector down to 2.5$GtCO_2e$[29].

Key avoid strategies involve telecommuting, although total emission savings are estimated at not more than 1% of total land transport GHG emissions[30]. For example, COVID-19 confinement induced telecommuting was compensated by more errands with cars, albeit at shorter distances in California[31]. Urban planning, street space rededication, smart logistical systems, and increased street connectivity with smaller distances have the largest potential to reduce need for travel[32,33], with a counterfactual potential of 25% reduction in urban energy use in 2050 only considering newly built cities (repercussion effects in the building sector are included in this estimate)[34]. Improving transport nonetheless has the largest mitigation potential, in particular via electrification. In most ambitious transport energy models, a full electrification of land transport and power-to-fuels for aviation and shipping, can completely decarbonize the transport sector, while also decreasing primary energy required per unit of end use energy, in particular in electric land transport[35]. Vehicle lightweighting strategies can also lead to significant emissions savings through improved fuel economy[36].

Avoiding energy use in buildings starts with adjusting dwellings' size to household size thus reducing overall demand for lighting and space conditioning. Smaller dwellings, shared space for housing and services, and building lifespan extension all reduce the overall demand for carbon-intensive building materials such as concrete and steel[37,38]. It also includes designing buildings based on bioclimatic principles to maximize energy demand reduction through nature and building typology (single-family homes versus multi-family buildings), adapting the size of buildings to the size of households, and redesigning both individual energy end use and building operations: replace artificial light with daylighting[39,40] and use lighting sensors to avoid demand for lumens from artificial light. Other options include designing passive houses that use the thermal mass and smart controllers to avoid demand for space conditioning services[41], and eliminating standby power to reduce energy wasted in appliances/devices (this alone may reduce household energy use by 10%)[42]. 3D printing of buildings further reduces construction waste, optimizes the geometries and minimizes the materials content of structural elements[43]. Overall, 'avoid' potential in the building sector, reducing waste in superfluous floor space, heating and IT equipment, and energy use, is estimated at 10 and 30%, and possibly up to 50%[44]. Improve options, such as energy efficient appliances, insulation, and prosumer renewables on rooftops may similarly reduce GHG emissions, combined, by 50% [30-70%][41,45,46].

While demand-side solutions will change lifestyles, individuals have few opportunities to induce and realize demand-side solutions by themselves. In all three ASI categories, infrastructures and choice architectures play a crucial role. Avoid measures require structural change in organization management (e.g. working time models that enable teleworking[47]), spatial structure (mixed use and compact cities to increase accessibility with active modes[48]), choice architectures (making healthy plant-based meals or co-working in shared spaces the default choice) and incentives (taxing land to incentivize more efficient use of floor space). Similar, shift solutions require the availability of new modes of service provision, e.g., by offering shared pooled mobility[49] and high-quality plant-based diets[50,51] as defaults, and regulation that prohibits high-emitting (and otherwise harmful) practices, such as intensive animal farming and fossil-fuel based heating and instead promote low-carbon solutions, e.g., via social marketing incentivizing reduced red meat consumption[52]. Finally, improve options similarly require policy interventions, such as carbon pricing, banning inefficient heating systems, lightbulbs and cars with internal combustion engine and diesel motor, and mandating market shares of efficient technologies, planning procedures and practices. Making the purchase and management of low-carbon technologies the default, also in public facilities, is another key choice architecture intervention to accelerate adoption of improve options[53].

Implications for near-term mitigation pathways

It is instructive to compare our bottom-up assessment of sector-wise mitigation potentials with the literature on demand-side scenarios. The benchmark was provided by the Low Energy Demand (LED) scenario modelled with the IAM MESSAGE[54], with more recent scenarios emphasizing further opportunities by constraining GHG emissions further in the Global North[55,56]. A key difference is that LED focused on energy demand, whereas this assessment centers on GHG emissions as mitigation metric. Energy demand is appropriate for demand-side evaluation as it separates out carbon intensity effects from supply side measures, also enabling a clearer view on service provisioning systems with low energy demand. GHG emission metrics have the advantages that non-energy sectors, and in particular food for nutritional service, can also be evaluated on an equal basis. Because of different metrics and boundary conditions a direct comparison between this assessment and LED is impossible. However, relative changes between energy/GHG emissions from 2020 until 2050 can be tentatively compared. In buildings, our assessment indicates a potential of up to 81% reduction between 2020 and 2050, whereas the LED scenario suggests 74-79% reduction in energy use for thermal comfort. A difference for our more optimistic value is the inclusion of prosumer centric renewable energies as a demand-side measure. In transport, our assessment suggests up to 70% reduction between 2020 to 2050, which is higher than the 59-60% change in energy demand in the LED scenario. A main reason for this difference is the accelerating uptake of electric vehicles by consumers, making a full-scale transition to electric vehicles until 2050 look possible. In industry, assessments produce similar values (21% here, and 23% reduction in LED). Considering GHG emissions, we also assess the food sector, finding nearly 50% of reduction potential by 2050. These findings suggest that the LED scenario is plausible. Inversely it poses the question why most other scenarios fail to consider these options. Reasons include the insufficient consideration of granular end-use technologies and the absence of representation of structural shifts in service provisioning systems. In essence, high-level climate stabilization models have high resolution on the supply side but little exploration on the demand side.

Instructively, we compare our potential estimates to the IEA's Sustainable Development Scenario (SDS) for 2050[57]. In three sectors demand side options can go a long way to reaching SDS levels, requiring only additional 1.2 Gt CO_2 abatement on the supply side in buildings, 0.4 Gt CO_2 in aviation, and 0.1 Gt CO_2 in shipping. In contrast, other sectors require more additional supply side and land use sector efforts to reach SDS levels: 10.5 Gt CO_2 in food and land use, 5.5 Gt CO_2 in industry, and 3.2 Gt CO_2 in land transport.

Demand-side mitigation strategies improve wellbeing

The IPCC's Special Report on Global Warming of 1.5°C provided evidence that energy demand solutions have more synergies and fewer tradeoffs with sustainable development goals than energy supply side solutions[4] (also see methods). Our own analysis of the weighted statistics shows that energy demand solutions have a ratio of synergies vs tradeoffs with SDGs of 5.3 (with most beneficial strategies in industry and buildings), whereas energy supply solutions show a ratio of 1.9 between synergies and tradeoffs (Figure 2,). Demand-side solutions appear, hence, to be more beneficial to SDGs than supply side solutions. While SDGs overlap with wellbeing, and a detailed analysis of demand-side options on dimensions of wellbeing is missing.

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Based on a database of 54,000 peer reviewed articles and 604 articles with identified relevant input (Table S3-S7), we analyze how sectoral demand-side and service-oriented mitigation strategies influence constituents of wellbeing. We systematically coded whether mitigation strategies for each sector have positive, neutral or negative impact on the 18 constituents of wellbeing introduced in Figure 3. We performed expert judgement by a team of 2-4 researchers for each sector, also comprising explicit expertise on social sciences and wellbeing, and internally reviewed by at least 2 other researchers, to code impact in categories from -3 to +3 and substantiated this with evidence from the literature (Figure 3). Confidence in these judgements varied, because both scale and multitude of effects vary across the underlying literature. In other cases, literature was missing even when experts assumed relevant effects. Hence, we also provide confidence values, associated with each mitigation-strategy/wellbeing-constituent couple (Figure S1) and report the confidence values together with the results of the wellbeing evaluation below (for more information, see Method section). The full table, including level of agreement and evidence and literature substantiating each entry, is in the SI-Extended data.

Demand-side mitigation strategies have positive impacts on human wellbeing (high confidence). Our study shows that among all demand-side option effects on wellbeing 79% (242 out of 306) are positive; 18% (56 out of 306) are neutral (or not relevant/specify); 3% (8 out of 306) are negative. Active mobility (cycling and walking), efficient buildings and prosumer choices of renewable technologies have the most encompassing beneficial effects on wellbeing with no negative outcome detected. Urban and industry strategies are highly positive overall for wellbeing, but they will also reshape supply-side businesses with transient intermediate negative effects. Shared mobility, like all others, has overall highly beneficial effects on wellbeing, but also displays a few negative consequences, depending on implementation, such as a minor decrease in personal security for patrons of ridesourcing(connecting drivers with passengers via apps operated by platform providers). Differentiation, however, is important. For example, shared pooled mobility provides more urban benefits, and also higher climate change mitigation potential, as compared to ridesourcing[49].

Positive links between mitigation measures and wellbeing are 19 times more than negative links. Confidence in 50% of all cases is medium to high (between 3 and 5 on a scale from 0 to 5. However it is higher in the physical constituents and comparatively low confidence in the social constituents of wellbeing.

The highest benefits are observed in air, health and energy (high confidence levels), food (medium confidence), mobility (high confidence), economic stability (high confidence), and water (medium-high confidence) respectively. Although the relation between demand-side mitigation strategies and the social aspects of human wellbeing is important, this has been less reflected in the literature so far, and hence our assessment finds more neutral/unknown interactions.

Wellbeing improvements are most notable in health quality (0.61 in average across all mitigation options on a scale from -1 to +1), air (0.59), and energy (0.57). These categories are also most substantiated in the literature, often under the framing of co-benefits. In many cases, co-benefits outweigh the mitigation benefits of specific GHG emission reduction strategies. This includes clean cook stoves (e.g., powered by liquified petroleum gas) that can improve livelihoods of more than 40% of the world's population by reducing indoor air pollution[58]; it includes co-benefits from improved outdoor air quality in cities resulting from reduced private motorized mobility using combustion and diesel engines, and from more active mobility[59,60], often associated with the more accessible environments of compact cities[61]; and it includes a shift away from high-emission diets that would improve public health considerably, especially in high income countries[62].

Food (0.50), mobility (0.46), and water (0.41) are further categories where wellbeing is improved. Mobility has entries with highest wellbeing rankings for teleworking, compact cities, and urban system approaches. Effects on wellbeing in water and sanitation mostly comes from buildings and urban solutions.

Social dimensions, such as personal security, social cohesion, and especially political stability are less predominantly represented. An exception is economic stability (0.52), suggesting that demand-side options generate stable opportunities to participate in economic activities. Altogether, the literature on social constituents, in relationship to climate change mitigation, is meagre. However, there are still clear indications that many demand-side mitigation strategies also have potential to improve the social constituents of wellbeing. For example, the predominant contribution of clean cook stoves may relate to wellbeing of women, who require less time for biomass collection and cooking and can better participate in economic and social life[63]. Compact cities and urban system solutions have strong albeit ambiguous effects on wellbeing, and positive outcomes depend on urban design[64,65]. Teleworking is ambiguous: if designed without face-to-face interaction, teleworking may result in social isolation[66].

Much public attention is paid to fossil fuel intensive incumbents and the costs of transitioning, suggesting a macroeconomic manifestation of loss aversion. Our analysis shows that demand-side solutions indeed reduce economic performance of incumbents, especially in the extractive industry (Figure 3, last column). Sufficiency measures in buildings require less materials and appliances, animal-free protein compromises the economic outlook of the agricultural meat industry, and active and shared mobility, together with more accessible compact cities implicate a smaller market for cars (Table S3-S7). Importantly, economic stability as a whole is still assessed positively (compare the corresponding column in Figure 3), for example, because demand side options also generate new jobs in new industries (see Tables S3-S7).

A transition not only requires investments into new products and business models with uncertain outlook on future profits, but also requires a psychological transition away from mental models and expertise that were successful in the past[67]. For example, many of Germany's engineers are proud of their world-class expertise in manufacturing internal combustion engines, and acknowledging that this expertise now lacks a viable future is a considerable psychological challenge and a call for strategic planning[68]. Similarly, the meat industry is organized around efficient and highly scaled animal meat production, challenged by a transformation towards low-carbon intensive nutrition services. The concerns of supply-side incumbents must hence be explicitly addressed, e.g., by developing just transition opportunities for workers and employees.

Nearly all wellbeing effects depend on both individual and cultural preconditions (e.g. the previous level of red meat consumption). Our wellbeing evaluation refers to mean expected effects, understanding that wellbeing effects can vary considerably with circumstances. Confidence is highest for the wellbeing dimensions air, health, and mobility, and for the mitigation options compact city, non-motorized transport and building –level sufficiency. The wellbeing dimensions education, shelter, and political stability have lowest confidence, reflecting a respective scarcity in literature.

Prioritizing demand-side options according to wellbeing

Wellbeing analysis closes an epistemic gap and the concurrent analysis of demand-side mitigation options and their wellbeing effects allows for tentative prioritization of mitigation options. Further quantification and ranking of mitigation options should nonetheless also include aggregate additional quantifications where possible, and in particular in the air quality and health domains, where effects have been well quantified and where high and notable effects have been demonstrated[69,70].

A combined assessment of mitigation effect and wellbeing suggests that in the food sector, shifting to plant-based diets is a main option in the developed world: it delivers potentially 40% or even more reduction of GHG emissions, while reducing global mortality by 6–10%, equaling health co-benefits of 0.4–13% of global GDP[62].

In the mobility sector the dominant mitigation option is a transition to electric mobility in land transport, enabling, in combination with a 100% renewable electricity sector, a reduction of GHG emission in land transport to zero before 2050 at country level[71]. This strategy improves air quality and concurrent health, and, for example, as part of an overall mitigation strategy the annualized monetary benefits outweigh the mitigation costs by a factor of 2 in the case of California[69]. However, a shift to active non-motorized transport achieves even larger health benefits than electrification of transport[59,72]. While active mobility has less potential than BEVs for mitigation, its additional effect would not only further amplify health benefits but also alleviate the burden of very high BEV scale-up until 2050. Active mobility also concurs with dominant urban sector strategies, and in particular compact cities that enable accessibility with non-motorized transport.

In the building sector, the design, size and use of the built environment combined with a plethora of technology adoptions can decrease emissions substantially until 2050, ranging from insulation to smart appliances to prosumer renewable energy provision. In that sector, health and air quality effects are well quantified and notable[73], however, visible solar PV panels and digital tools for energy saving are also related to belonging and self-efficacy[74,75], thus contributing to the social domains of wellbeing.

Evaluating wellbeing requires an understanding of malleable preferences, and the opportunity of redesigning infrastructures and services in different ways (Box 1, Table 2). Behaviourial responses, including dietary and mobility choices, depend on choices of new service delivery system, new products, infrastructure designs and access to technologies. Infrastructures and technologies enable shift to low or zero carbon lifestyles. This is important for pragmatic climate change mitigation policy design, emphasizing the importance of low-carbon infrastructure and service provisions. For example, in transport planning decisions are often made based on observed demand of transport modes and distances. Instead, our evaluation suggests that a high quality of accessibility can be justified starting point for transport planning.

There are three limitations and associated directions for future research in co-evaluating climate change mitigation and wellbeing. First, the social constituents of wellbeing deserve better quantification. Systematically advanced case studies, with quantification where possible, and aggregate studies of demand-side mitigation options and their social dimensions at country level, e.g., as captured by the World Value Survey, are important. Second, empirical studies and mechanistic and causal modelling needs to much better address the relationships between broad climate change mitigation options and the social constituents of wellbeing. For example, while the health benefits of active travel and reduced noise of motorized transport in cities are mostly understood, it is less clear how more space availability for pedestrians translates into participation, trust and social protection. Differentiated insights from psychology, neuroscience and sociology deserve more attention in the joint assessment of climate change mitigation options and wellbeing. Third, future research should also assess potential interaction effects for the ASI demand-side options. This could be done by IAMs if these find a way to capture behavioural responses by end-user comprehensively. More modelling, both with IAMs and with sector-specific general equilibrium models, is needed to represent the behavioural effects involved in co-benefits of mitigation actions accurately. Smaller general equilibrium models, which focus on single sectors, are also well suited to assess the effects on the multiple constituencies on well-being better. For example, modelling captures that for food and transport choice the low-carbon option makes people healthier because it incentives them to eat a healthier diet and exercise more[76,77].

Climate mitigation and human wellbeing

Our results matter for the core challenge of climate change mitigation. Even the most optimistic upscaling of low-carbon technologies would remain insufficient to meet currently projected energy demand in 2050, as approximately required by the Paris agreement. Demand-side reduction strategies hence provide essential breathing space needed for meeting climate targets in the short and medium term. We also show that they are consistent with improved wellbeing,.

Further research at higher resolution levels on service provisioning systems that reduce GHG emissions while maintaining or improving constituents of wellbeing will be highly policy-relevant. This is particularly true for developing countries, as most of the options evaluated have been mainly studied in developed countries. A new configuration of work and service provisioning models consistent with low GHG emissions and resource demand is based on appropriate evaluation of wellbeing. Such a configuration needs to supplement cost-based macro-economic metrics with direct measurements of the constituents of wellbeing consistently and include access to health systems, shelter, high-quality nutrition and safe social environments. Our contribution makes an integral step to this evaluation by systematically assessing the literature on demand-side mitigation options through the lens of wellbeing. We demonstrate their large mitigation potential: Starting with a perspective on what people need for a good life adds compelling options to the space of climate change mitigation solutions.

Table 1: Demand-side mitigation strategies and mitigation potentials in end use sectors*. Mitigation potential is estimated from sector-specific studies and models and is reported in percentage to account for potentially diverging baselines and interaction terms with other mitigation strategies (valid if factorial decomposition between mitigation strategies is possible). Ranges reflect variability across the assessments of the underlying literature. Baseline estimates for 2050 are from IEAs stated policy scenario in energy sectors, and from the IPCC SRCCL report and additional sources in the food sector, and thus assume absence of supply side climate change mitigation (see SI for details).*

End-use sector	Gt CO_2e in 2050	Mitigation Strategy	Range of CO_2e emissions reduction potentials for ASI	References
Housing, leisure and services (Building) (total mitigation potential: 78%, 6.8 $GtCO_2$e)	8.8	**Avoid: Sufficiency of energy and resources** (include Compact city and Nature based solution from Urban sector) *Building design, size and use (behavioral and lifestyle change)*	10-40% **[central value: 25%]**	IEA 2020[57]; Kuhnhenn et al 2020[78]; Niamir et al. 2020[79]; Ahl et al. 2019[80]; IGES et al. 2019[81]; ECF 2018[82]; Virage-énergie 2016[83]
		Shift: Improve access and switch to renewables *On-site renewables, micro-grids, switch to lower carbon fuels and electrification for spaceheating, cooling, cooking, hot water and electrical uses*	30-70% **[central value: 50%]**	IEA 2020[57]; Niamir et al. 2020[84]; Mastrucci & Rao 2019[85]; IGES et al. 2019[81]; ECF 2018[82]; Mata et al. 2018[86]; Virage-énergie 2016[83]
		Improve: Efficiency *Improved building envelope, improved building technical systems (for* heating, ventilation, air conditioning, *cooking and electrical uses), smart home and digitalization, efficient appliances, control systems, clean cooking*	30-65% **[central value: 40%]**	IEA 2020[57]; Mata et al. 2020[87]; IGES et al. 2019[81]; Ellsworth-Krebs et al. 2019[88]; ECF 2018[82]; Virage-énergie 2016[83]
Mobility, accessibility (Land Transport) (total mitigation potential: 62%, 5.8 $GtCO_2$e)	9.5	**Avoid: Active travel in highly accessible cities; teleworking** supported by compact highly accessible city design and safe infrastructures for pedestrians and cyclists. *Teleworking or telecommuters partially or entirely replace their out-of-home work activities by working at home or at locations close to home*	0-25% **[central value: 10%]**	Pomponi et al 2021[89]; Brand et al. 2020[90]; Creutzig et al. 2015[34] & 2016[5]; Ivanova et al. 2020[91]; Riggs 2020[31]; ; Mrkajic et al 2015[92]; Senbel et al 2014[93]
		Shift: Shared mobility and convenient and safe public transit *Pooled shared mobility with high occupancy and micro-mobility with high lifetime of vehicle stock; convenient rail-based public transit; supported by urban design and transit-oriented development resulting in reduced travel distances; logistic optimization in last-mile freight.*	0-25% **[central value: 15%]**	Sheppard et al 2021[94]; ITF, 2020[95,96]; ITF, 2017[97,98]; Creutzig et al. 2016[5]; ITF, 2016[99]
		Improve: BEVs *Battery Electric Vehicles (BEVs) when charged with the electricity generated from medium decarbonized power system (IEA stated policies); Behavior change programs on the socio-economic structures that impede adoption of BEV's; the urban structures that enable reduced*	30-100% **[central value: 50%]**	Ehrenberger et al 2021[100]; Hou et al 2021[101]; EEA, 2018[102]; Hill et al 2019[103]; Lutsey 2015; Plötz et al 2017[104]; Khalili et al 2019[35]

		car dependence and how BEV's can assist grids; and the synergies between emerging technologies and shared economy to maximizing the greater benefit of BEVs		
Nutrition (Food) (total mitigation potential: 41%, 7.3 $GtCO_2e$)	16-20 [central value: 18] (includes deforestation and land-use change emissions)	**Avoid:** Food waste (overconsumption not further considered, as diets rich in calories, and in particular sugar, add little to GHG emissions).	8-25% **[central value: 15%]**	Clark et al. 2020[105]; Makov et al 2020[106]; Poore and Nemecek, 2018[107]; Schanes et al. 2018[21]; Gunders & Bloom 2017[20]; IPCC SRCCL, 2019[24]; Hiç et al 2016[108]; Bajželj et al 2014[2]
		Shift: Animal free protein *Switch to animal free protein sources such as soy, lentils, other pulses and meat substitute products.*	18-87% **[central value: 40%]** (applies to farmgate GHG emissions)	Clark et al 2020[105]; Semba et al. 2020[109]; Springmann et al. 2018[110]; Willett et al. 2019[111]; Parodi et al. 2018[112]; IPCC SRCCL, 2019[24]; Bajželj et al 2014[2]
Products and materials (Industry) (total mitigation potential: 41%, 6.5 $GtCO_2e$)	15.8	**Avoid:** Materials efficient services *Avoid materials via dematerialization, the sharing economy, materials-efficient and lightweight designs, and yield improvements in manufacturing.*	5%-22% **[central value: 13%]**	IRP 2021[113]; Pauliuk et al 2021[114]; IEA 2020[57,115]; Grubler et al. 2018[54]; Allwood and Cullen, 2015[116]; Carruth et al., 2011[117]
		Avoid: Lifespan extension *Designing products so that their lifetime can be extended through repair, refurbishing, and remanufacturing, instigated via standardisation, modularity and functional segregation.*	3%-7% **[central value: 5%]**	Lausselet et al 2021[118]; IEA 2020[57,115]; Cooper et al. 2014[119]
		Shift: Reuse and recycling *Increasing the re-usability and recyclability of product's components. Example: dismantle old cars and re-use components for repairing other cars*	4%-7% **[central value: 5%]**	IEA 2020[57,115]; Ellen MacArthur Foundation, 2019[120]; IEA 2019[121]; Material Economics 2018[122]; Hertwich et al 2019[123]
		Improve: Energy Efficiency *Reducing the need for energy consumption through the installation of new efficient technologies and through systems and operating practices that contribute to reduce energy needs*	25%-28% **[central value: 25%]**	Crijns-Graus et al 2020[124]; IEA 2020[57,115]; Material Economics 2018[122]
Mobility, accessbility (Aviation) (total mitigation potential: 40%, 0.7 $GtCO_2e$)	1.8	**Avoid:** flights *Aviation is of low economic value and demand is highly sensitive to prices. A carbon price of aviation fuel of \$400/tCO_2 would halve demand for aviation in 2050.*	0%-47% **[central value: 40%]**	Sharmina et al. 2020; . 2021IATA 2020[125]; Schäfer et al. 2019[126]; Sharmina et al. 2020[127]; Gossling et al. 2021
Mobility, accessbility (Shipping) (total mitigation potential: 69%, 1.3 $GtCO_2e$)	1.9	**Avoid:** Reduce demand and slow steaming *Shifting supply chains, lower demand for consumption goods, and slow steaming of ships would reduce shipping demand substantially.*	40%-60% **[central value: 47%]**	Bouman et al 2017[128], McKinnon 2020[129], ITF, 2018[130]

		Shift: modal shift to train *Shift from ships to long-distance train (especially across the Eurasian continent) reduces GHG emissions, but not more than 1% of expected emissions.*	0%-1% **[central value: 1%]**	ITF, 2018[130]
		Improve: Design and power system *Independent of fuels (supply) better hull design and improved propulsion system can make ships highly more efficient*	30%-50% **[central value: 40%]**	Bouman et al 2017[128], McKinnon 2020[129], ITF, 2018[130]

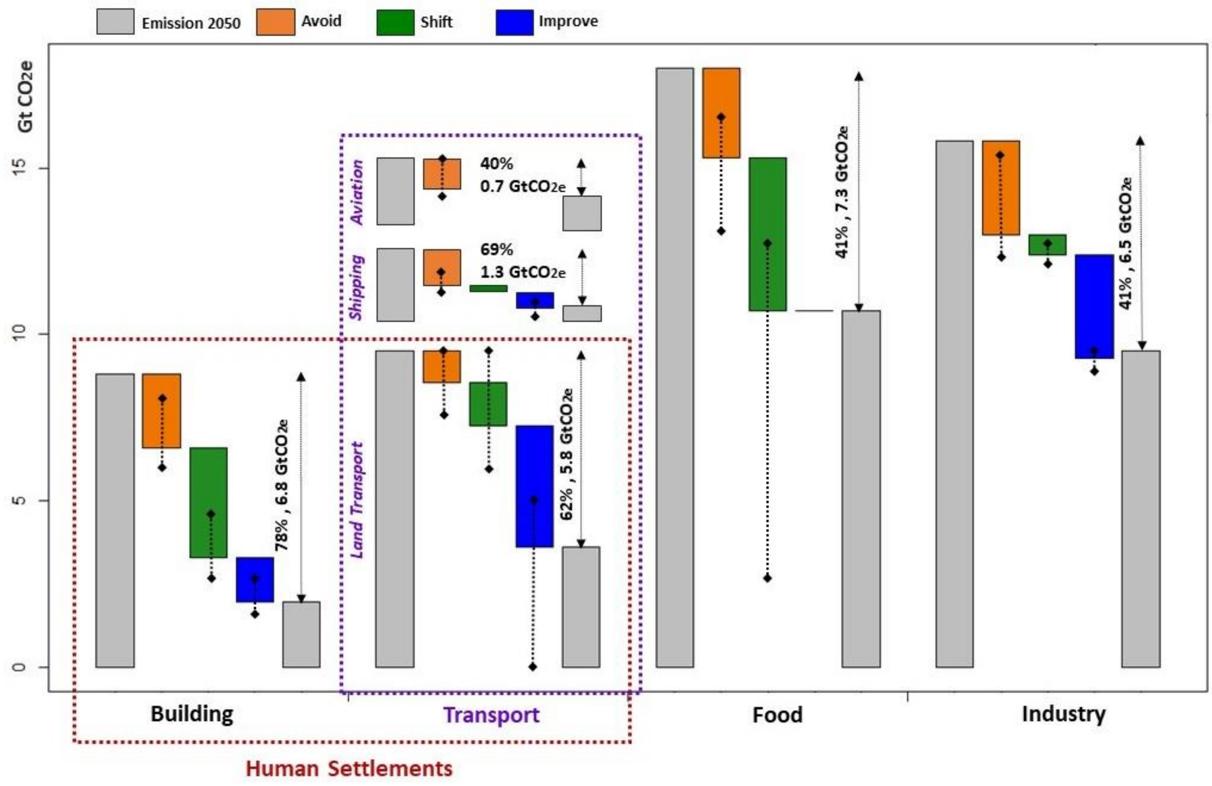

Figure 1. Mitigation potentials in end-use sector classified in avoid, shift, and improve options. *We reviewed studies estimating demand-side mitigation potentials associated with demand-side GHG avoid, shift, and improve emission reduction strategies and summarized results as central values and full ranges (minimal to maximal potential). To be able to give approximation for the full potential across sectors, we ignore interaction effects between the three categories. Mitigation potentials are estimated against 2050 values of IEA's stated policy scenario[57] and baseline assumption from the IPCC's SRCCL report for food. Data sources and explanations: see Table 1 and Table S1.*

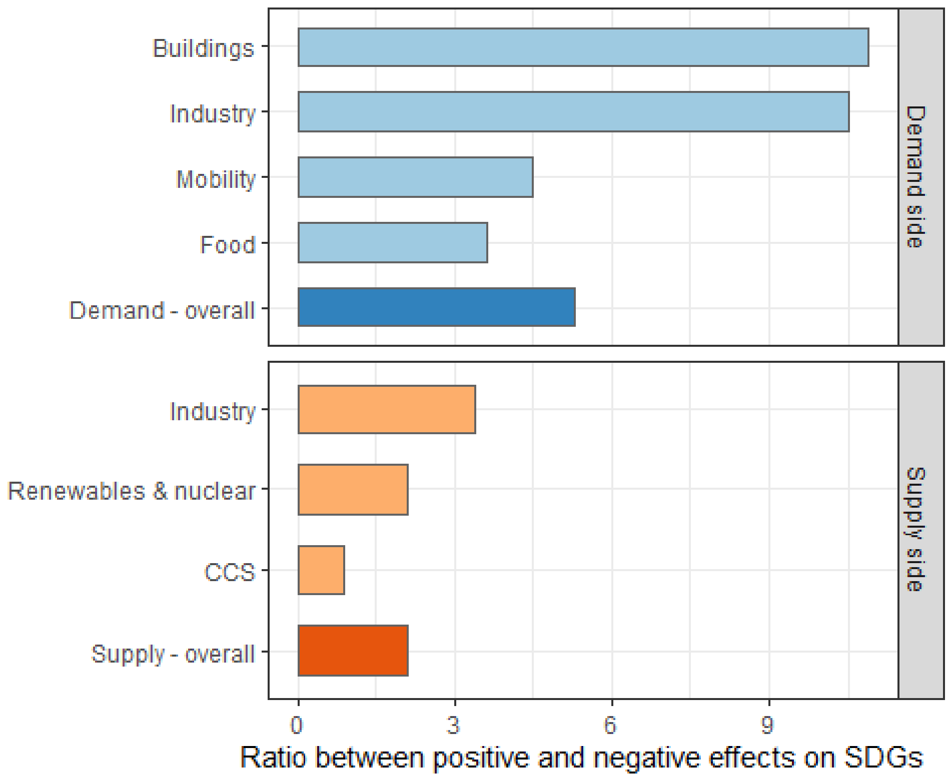

***Figure 2: Ratio between weighted sum of synergies between SDGs and energy demand/supply solutions and weighted sum of tradeoffs between SDGs and demand/supply solutions**. The sum was weighted according to confidence as reported in Roy et al 2018 (i.e. confidence with 1 star was weighted by 1, confidence with 2 stars weighted by 2, etc.)[131]. Ratios are similar for unweighted sums.*

Mitigation strategies / Wellbeing dimensions

(dark green)	High positive impact [+3]
(medium green)	Medium positive impact [+2]
(light green)	Low positive impact [+1]
(beige)	Overall Neutral
(white)	No impact
(light red)	Low negative impact [-1]
(red)	Medium negative impact [-2]
★	Confidence level

Sectors	Mitigation strategies	Food	Water	Air	Health	Sanitation	Energy	Shelter	Mobility	Education	Communication	Social protection	Participation	Personal Security	Social cohesion	Political stability	Economic stability	Material provision	Supply side / incumbents
Building	Sufficiency	[+1] ★★★	[+2] ★★★★	[+2] ★★★★★	[+3] ★★★★★	[+1] ★	[+3] ★★★★	[+1] ★	[+1] ★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★		[+2] ★★★★★		[+2] ★★★★	[+2] ★★★★	[-2] ★★★
Building	Efficiency	[+2] ★	[+2] ★★★★	[+3/-1] ★★★★	[+3/-1] ★★★★★	[+1] ★	[+3] ★★★★	[+2] ★★★★		[+1] ★★★	[+1] ★★★		[+1] ★★★★	[+1] ★★★	[+2/-1] ★★★★		[+2] ★★★★★	[+2/-1] ★★★★	[+2/-2] ★★★
Building	Lower carbon and renewable energy	[+2/-1] ★★★	[+2/-1] ★★★★	[+3] ★★★★★	[+3] ★★★★★		[+3] ★★★★	[+1] ★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★		[+1] ★★★	[+1] ★★★	[+2/-1] ★★★★		[+2/-1] ★★★★★	[+2] ★★★★	[+2/-2] ★★★
Food	Food waste	[+1] ★★★	[+2] ★★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★	[+1] ★★★★				[+1] ★★	[-1/+1] ★★★	[+1] ★★★			[+1] ★	[+1] ★★		[-1] ★★★
Food	Over-consumption	[+1] ★	[+1/-1] ★	[+1/-1] ★	[+3] ★★★★		[+1/-1] ★						[+2] ★★★★			[+1] ★			[+1/-2] ★
Food	Animal free protein	[+2] ★★★	[+2] ★★★★	[+3] ★★★★★	[+3] ★★★						[-1] ★★★	[+3] ★★★★★	[+1] ★★★★		[-1] ★	[+2] ★			[-1] ★★★
Transport	Teleworking and online education system	[+1] ★★		[+3] ★★★★	[+2] ★★★★		[+2] ★★★★	[+1] ★★	[+2] ★★★★	[-1] ★★★	[+2] ★★★★	[+1] ★★★★	[+2] ★★★★	[+1/-1] ★★★★	[+2] ★★★★	[+2] ★★★	[+2] ★★★		[+1] ★★★★
Transport	Non-motorized transport	[+2] ★★	[+1] ★★	[+1] ★★★★★	[+3] ★★★★★		[+2] ★★★★		[+3] ★★★★★	[+1] ★★★★	[+3] ★★★	[+1] ★★★	[+1] ★★	[+2] ★★★★	[+2] ★★★	[+2] ★★	[+2] ★★★		[+1] ★★★
Transport	Shared mobility	[+1] ★★		[+3] ★★★	[+2] ★★★★		[+1] ★★★		[+2] ★★★★		[+1] ★★★	[+2] ★★★	[+1] ★★★	[+1/-1] ★★★	[+1/-1] ★★★★	[-1] ★★★★	[+2] ★★★★	[+2] ★★★★	[-1] ★★
Transport	Evs	[+1] ★★★		[+2] ★★★★	[+1] ★★★★	[+1] ★★★★	[+3 ★★★★		[+2] ★★★★			[+3] ★★★★★	[+2] ★★★				[+2] ★★★★	[-1] ★★	[+1] ★★★
Urabn	Compact city	[+2/-1] ★★★	[+1] ★★	[+2/-1] ★★★	[+3/-1] ★★★★	[+1] ★★	[+3/-1] ★★★★★	[-1] ★★★★★	[+3] ★★★★★	[+1] ★★★★★	[+1/-1] ★★★	[+2] ★★	[+1] ★★	[+1] ★★★★	[+1/-1] ★★★★★		[+1] ★★★★	[+1] ★★	[+1/-2] ★★★
Urabn	Circular and shared economy	[+2] ★★★★	[+1] ★★★	[+2] ★★★	[+2] ★★★		[+3] ★★★	[+2/-1] ★★★	[+3] ★★★★★	[+1] ★★★★	[+1] ★★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★★	[+1] ★★	[+1] ★★	[+2] ★★	[+3] ★★★	[-1] ★★★★
Urabn	Systems approach in urban policy and practice	[+1] ★★★	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★★	[+3] ★★★	[+2] ★★★	[+3] ★★★		[+1] ★★	[-1] ★★	[+1] ★★★	[+2] ★	[+1] ★★		[+1] ★★	[+3] ★★★★★	[+2/-2] ★★
Urabn	Nature based solutions	[+2] ★★★	[+1/-1] ★★★★★	[+3/-1] ★★★★	[+3] ★★★★★	[+1] ★★★	[+3] ★★★	[+1/-1] ★★★	[+1] ★★★	[+2] ★★★★		[+2] ★★	[+3] ★★	[+1] ★★★	[+2/-2] ★★★		[+3] ★★★★	[+1] ★★	[+1] ★★
Industry	Using less material by design	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★	[-2] ★★
Industry	Product life extension	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[-1] ★★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★	[-2] ★★
Industry	Energy Efficiency	[+2] ★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★		[+1] ★★	[+2] ★★★	[+2] ★★	[-2] ★★
Industry	Circular economy	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+2] ★★	[+1] ★★		[+2] ★★★	[+3] ★★	[-2] ★★

Figure 3. Effects of demand-side options on wellbeing in 19 different categories: Magnitude and direction of wellbeing effect*. Detailed data underpinning the assessment is reported in Tables S3-S7.*

Box 1. Evaluation of wellbeing in demand-side climate change mitigation

In economics, evaluations of wellbeing are predominantly based on assuming that preference satisfaction constitutes welfare and that such preferences are given (unchanged by policy). On a simple interpretation of this normative position, demand for goods and services is by definition good for wellbeing. For sustainability transitions, this is, from most perspectives in social science, a too limited view of wellbeing[132] because it ignores that changes in preferences can be an integral part of societal transitions[133]. With fixed preferences, only changes in relative prices will reduce emissions, not changes in citizens' desires, environmental motives, or social norms[134]. In these circumstances, straightforwardly assessing policies by their costs is circular, and hence insufficient, as it ignores potential wellbeing outcomes resulting from collective shifts in preferences (Box Table 1).

Box Table 1. Assuming preferences to be exogenous or endogenous has impact on the evaluation of solutions.

	Supply-side solutions	***Demand-side solution***
Exogenous preferences	Current patterns of service provisions are appropriate and new technologies must substitute current supply-side technologies closely.	Making existing technologies more efficient (improve) is appropriate, but shifting or reducing consumption patterns are insufficiently considered. Social dynamics often directed to enable overconsumption.
Endogenous preferences	Lack of orientation on what should be produced; alternative (partially objective) metrics required.	Societies can choose to modify service provisioning systems and lifestyles; alternative metrics and institutions required.

For transitioning to a low-carbon society, several bits of evidence indicate an important role for endogenous preferences: First, humans can absorb low-carbon food and other preferences and conventions (e.g. seatbelts) through policy interventions[135]. Second, learning about route[136] and mode choice[137,138] have been documented to change transport decisions. Third, peer effects exist for both car purchases[139] and solar panel uptake[140]: a policy that makes a low-carbon good more attractive can change preferences by influencing the social norm. Fourth, in an experimental setting, carbon pricing can also change preferences by crowding-out citizen's intrinsic motivation to choose low-carbon products as documented[141]. For actual carbon tax reforms, however, carbon taxes make consumers reduce emissions more than could be expected from the relative price change alone[142,143], consistent with a change in preferences. In cases of other transitions, such as in smoking, there is also evidence that societies guided the processes of shifting preferences, and that societal values changed along with policies and relative prices[144] (this is also true the other way around: interest groups may shape preferences and values to hinder transitions[145]).

Methods

Overview. A mixed-and multi-methodology framework has been designed and used to identify and assess demand-side mitigation strategies and their impacts on GHG emissions and human well-being (Figure M1). In the following, we explain steps, methods, and validity and reliability in detail.

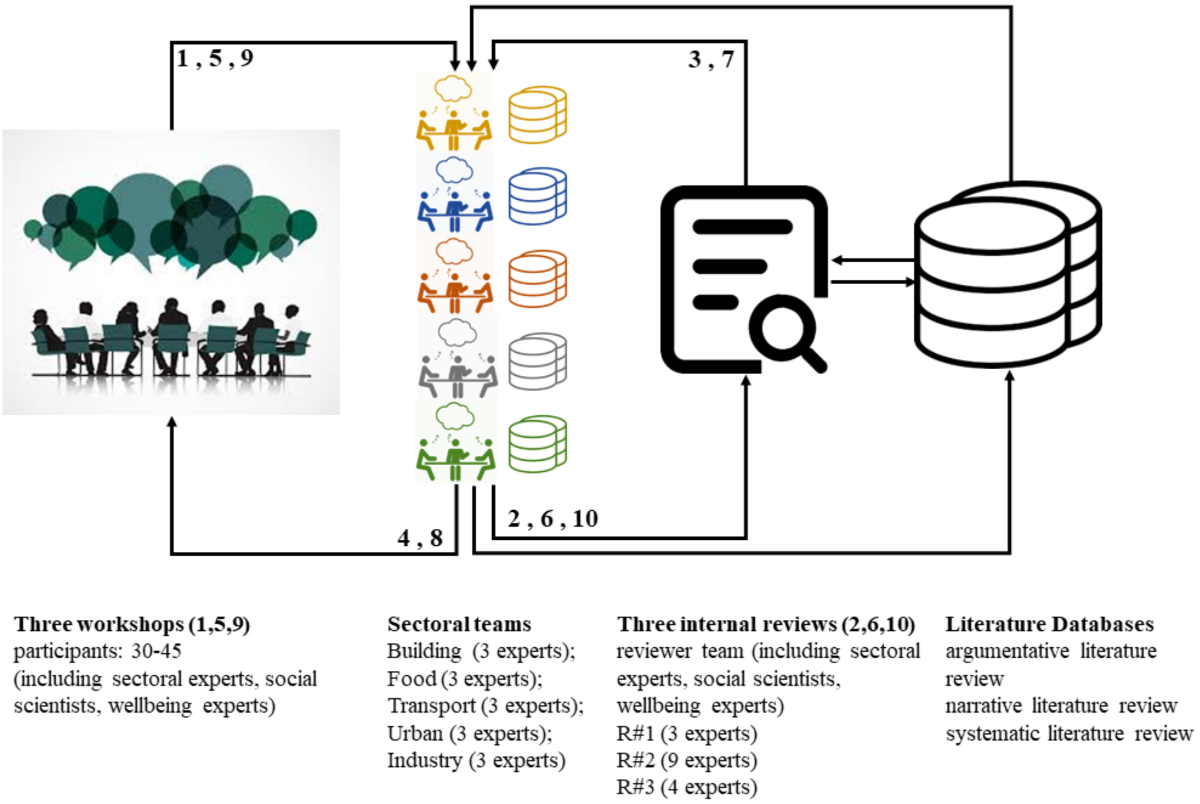

Figure M1: Demand-side mitigation options and wellbeing potentials mixed- and multi-methods framework. *Consist of four main components: workshops, experts' knowledge, literature reviews (3 types), internal reviews; and ten main steps: three rounds of workshops (two in person, one virtual), four rounds of sectoral teams work, three rounds of internal reviews; all supported by comprehensive literature datasets.*

Identifying and assessing demand-side mitigation options. Two workshops are designed (April and October 2019) with the objective of defining, structuring and evaluating demand-side mitigation options (for third workshop see "Assessing effects on wellbeing" below). The first workshop was held in person, April 2019, with the participation of 36 experts - including sectoral (building, food, transport, urban, and industry) experts, and including energy demand-side, technology, finance, wellbeing, and social scientists. Experts were academics with expertise in climate change mitigation and wellbeing evaluation (e.g., via co-benefit approach) in at least one sector, as demonstrated by publication track record. The first workshop aimed to brainstorm and identify demand-side mitigation options, using the categorization of the ASI (Avoid-Shift-Improve) concept. All discussions (two broad rounds and eleven sub-groups discussion) were documented and shared with participants. As a next step, experts in the form of five sectoral team further identify and structure demand-side options within the ASI framework ("1" in Figure M1). Sectoral teams searched, screened and coded the relevant literature – based on their expert knowledge of the relevant literature (for additional systematic confirmation and supplementation see below). From the sector-specific scenario and option literature, reductions potential estimates and ranges (for more information see "Literature databases"). Sectoral teams reported back their findings before the second workshop for an internal review process (R#1, "2" in Figure M1).

The second workshop was also held in-person in October 2019 with 30 experts –including sectoral teams experts and reviewers ("4" in Figure M1). The demand-side mitigation options are further discussed in this workshop, following feedback from the internal review team and workshop co-organizers. As a result, with the help of two in-person workshops (April and October 2019), the sectoral team's extensive studies and an internal review, 3 or 4 comprehensive demand-side strategies are selected for each sector. In this process, several factors were considered: 1) being comprehensive (as an umbrella of several options, which might differ over sectors); 2) categorization within the ASI framework; 3) relevant potential in mitigating climate changes. For example, we identified several demand-side mitigation options in food sector, e.g. changes in diet, shift to regional, seasonal and organic consumption, reduce food consumption, and improve packing technology. We selected "animal free proteins" and "food waste" as top two, simply due to their clear link to mitigation and high impacts. We decided as third option for "overconsumption" because of its very strong impact on wellbeing through its health effect.

We organized demand-side mitigation strategies according to sectors (building, transport, food, urban, industry) and according to mitigation strategy (avoid, shift, improve) (summary in Table 1; full details given in Table S1). Deamnd-side mitigation potentials were assessed through comprehensive litreture review aand in several stages. The lower and upper boudries and the central are identified and reported – in round number- based on what was preseted in the litreture and the expert judgment. Table S1 is internally reviewed together with wellbeing tables by a team of experts – 9 member of this author team with relevant sectoral and/or social science expertise- (R#2, "3" in Figure M1).

Assessing synergies and tradeoff between SDGs and energy demand/supply solutions. In SR1.5 IPCC Report, the assessment presents positive and negative links of individual mitigation options with each of the SDGs by their relative strength and level of confidence. Strengths are scored between 0 to ±3 and confidence levels are presented by 1-4 stars (*, **, ***, ****). Using these detailed information we derive here the ratio of positive links to negative links in more aggregated form, as detailed with the following steps. First, we count confidence level wise positive and negative links for sectors. At the second step, we add them using the numerical values of scores of strengths for each of the links. Then at the third step, aggregate values for demand and supply categories are calculated using corresponding confidence levels as weights. For example, for building sector, total counts of positive links/synergies for very low confidence (*) is 13, for low confidence (**) is 15, for medium confidence (***) is 24, for high confidence (****) is 15 and total trade-offs are 0, 2, 4 and 0 respectively for different levels of confidence. Each of these values is weighted according to the confidence levels as applicable (1, 2, 3, 4) which yields 175 for weighted positive sum and 16 for weighted negative sum and finally the ratio between these two weighted sums is calculated as ($\frac{175}{16}$ =10.9). This has been followed for each of the sectors.

Measuring wellbeing. The literature on human well-being is complicated by varying definitions and overlapping terminology. Terms such as 'human needs', 'well-being', 'subjective well-being', 'happiness', 'welfare' and 'quality of life' are often used interchangeably and imprecisely. A widely perceived divide separates well-being concepts into three broad camps: preference satisfaction, hedonic and eudaimonic positions[9,109,10] with diverging implications for climate change mitigation[11,1211,12]. The preference satisfaction position, as introduced above, takes citizens' preferences satisfaction as constituting wellbeing and is therefore in some form committed to the view that whatever people choose makes them better off. It is hence closely related to associating higher income with higher well-being, and typically measures the degree to which preferences are satisfied in market transactions and beyond markets as income. Second, in the hedonic view, well-being is a matter of maximizing individuals' happiness, or health. It can be measured for example, via 'life satisfaction' and 'happiness' surveys, and is often interpreted as the subjective perception of well-being conditions in society. A great deal of research examines the individual and social determinants of variation in happiness, health and life satisfaction. This approach builds upon utilitarian philosophy.

A third category of 'eudaimonic' concepts focus on objective conditions and actions that underpin well-being. This constitutes a large family of theories, most notably on 'capabilities'[13,14613,146], 'human needs'[14,147,148], multi-dimensional poverty[149] and so forth. The core claim is to identify and separate a universal set of basic conditions that are required by all humans for a good life, from their satisfiers, which can be culturally and individually diverse. We adopt the 'eudaimonic' position on well-being by the analysis that follows, because of two reasons. First, a eudaimonic approach is consistent with changing preferences, as the focus is on substantive conditions of a good life that are independent of changing preferences (nonetheless, even if preferences are changing, demand-side solutions could also be evaluated by approaches that account for fundamental preferences[150–152]). Second, a eudaimonic approach is largely underrepresented in the context of climate change mitigation, as the current literature evaluating climate policies and measures is nearly exclusively taking an implicit or explicit given preference approach, often shortcut with economic growth metrics.

Despite the very diverse nature of the literature on eudaimonic wellbeing, broad surveys have centered on a number core conditions that achieve consensus across epistemic divides[11,153]. The constituents of eudaimonic wellbeing include essential material conditions of a good life, such as food and energy, but also clean water, sanitation, air quality, and also social dimensions, such as social cohesion and political stability (Table M1). Importantly, these constituents are nearly all reflected in the SDGs (Table M1), and thus have political legitimacy among nations worldwide.

During the second workshop (October 2019) wellbeing concept is presented by workshop co-organizers, and the potential metrics, links to SDGs and demand-side mitigation strategies are discussed. Workshop co-organizers proposed a matrix of sectoral demand-side mitigation options and wellbeing dimensions (used to organize Tables S3-7).

Table M1: Constituents of wellbeing and their relationship to SDGs. Constituents of wellbeing include physical dimensions, such as food and water, and social dimensions, such participation and political stability.

Well-being dimension	SDG	Potential metric and definition
Food	2 ZERO HUNGER	access to sufficient and safe nutrition
Water	6 CLEAN WATER AND SANITATION	access to adequate and clean drinking water
Air	7 AFFORDABLE AND CLEAN ENERGY; 11 SUSTAINABLE CITIES AND COMMUNITIES	exposure to dangerous concentrations; pollutants both indoor and outdoor
Health	3 GOOD HEALTH AND WELL-BEING	access to health services; physical and mental health ; obesity
Sanitation	6 CLEAN WATER AND SANITATION	access to adequate sanitation; waste and sewage management
Energy	7 AFFORDABLE AND CLEAN ENERGY	ability to attain a socially and materially necessitated level of energy services (often related to access to electricity) ; access to affordable, reliable and sustainable fuels (electricity); renewable and clean electricity
Shelter	11 SUSTAINABLE CITIES AND COMMUNITIES	access to accommodation ; affordable housing market
Mobility	11 SUSTAINABLE CITIES AND COMMUNITIES	ability to access key other services physically in a safe and affordable manner; access to safe walking and cycling infrastructures, and to public transport
Education	4 QUALITY EDUCATION	education for all ; access to education and material ; knowledge and information
Communication		ability to make human connections with and without personal meetings; access to information and entertainment
Social protection	1 NO POVERTY; 2 ZERO HUNGER; 8 DECENT WORK AND ECONOMIC GROWTH; 10 REDUCED INEQUALITIES	community, social insurance, social assistance, and labor markets that enhance people’s capacity to manage economic and social risks, e.g. unemployment, exclusion, sickness, disability and old age.

Participation	16, 5, 10	democratic rights (voting, association, etc.)
Personal Security	16, 5	exposed to homicide, crime, war/state violence
Social cohesion	16, 10	social trust; bottom-up initiatives; reduce inequality; sense of usefulness
Political stability	16, 11	trust in politicians; good governance; quality of governance
Economic stability	8	not having to fear unexpected expenses; access to jobs
Economic supply side effects	8, 12	upstream effects of demand-side measures on upstream production systems (e.g.: compact cities make reduce demand for cars, increase demand for shared mobility)
Material provision	9, 12	ability to access wellbeing services which are derived from materials; provision of adequate industrial capacity; access to infrastructure

Assessing effects on wellbeing. As a result of the second workshop, workshop co-organizers designed and developed an online platform for sectoral teams, this online platform provided a space for each sectoral teams to code the effects of demand-side options on wellbeing in 19 different categories, presented in Table M1. In addition, it allowed them to see other sectors coding and progress. We used sectoral teams' judgment and evaluation ("5" in Figure M1) and a concurrent literature search on 306 combinations of wellbeing and demand-side measures used to create Tables S3-7 and Figure 3 (for more information see "Literature databases").

While not all combinations were judged relevant, we supported judgements for existing relationships between demand-side options and wellbeing with 604 references. Experts identified potentially relevant publications through a mixture of their in-depth knowledge of the field and targeted keyword-based queries in relevant bibliographic databases (for more information see "Literature databases"). In addition, in order to develop our key findings, expert teams evaluated the associated *evidence*, *agreement* and *confidence* levels of each entry. *Confidence* in the validity of a finding, based on the type, amount, quality, and consistency of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of *agreement* (for more information see tables S3-7). Further, all steps were subjected to three rounds of internal review including social scientists, wellbeing, and sector- and domain-specific experts (Table S3-7). To also reflect the state of the literature, reflecting highly different literature bases on the combination of wellbeing dimensions and demand-side measures, and to represent uncertainty in interpretation of the literature, we also coded for the confidence of wellbeing impacts in all 306 combinations (Figure S1).

Within our online platform, five comprehensive sectoral tables are designed: Building, Food, Transport, Urban and Industry (see Table S3-7). The potential of each demand-side mitigation strategy on wellbeing dimensions are evaluated by expert teams based on the existing literature and experts scientific judgments. The impact is coded = {-3, -2, -1, 0, +1, +2, +3} while +3 stands for high positive and -3 high negative impact. In addition, in order to develop our key findings, expert teams evaluated the associated evidence, agreement and confidence levels of each entry. Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement.

The level of evidence {limited, medium, robust}, and degree of agreement {low, medium, high}, presented by ▤ and ☺ respectively in the Tables S3-7, are evaluated by sectoral expert teams based on the amount, quality and consistency of evidence. The level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high; presented by ★ in the Tables S3-7. It synthesizes the expert teams' judgments about the validity of findings as determined through evaluation of evidence and agreement.

Five sectoral teams reported back their assessments before the third workshop for an internal review process (R#2, "6" in Figure M1). In the second round of internal review (R#2), at least two reviewers (members of the author team), based on their expertise, were assigned to look at 3 or 4 wellbeing dimensions over five sectors, review and evaluate sectoral teams assessment, Internal reviewers reported back their comprehensive evaluation with detailed notes and suggestions to the sectoral teams ("7" in Figure M1).

In April 2020, the third workshop was held virtually (via Zoom), where we hosted 45 participants ("8" in Figure M1). By presenting a preliminary version of Figure 1, co-organizers discussed demand-side mitigation options and potentials in the context of avoid-shift-improve over five sectors. Links to human wellbeing and SDGs were explained by presenting a preliminary version of Figure 3 (summary and simplified version of Table S3-7). In addition, a great discussion was shaped on how to deal with and measure cross-sectors and cross-cutting issues. The third workshop is guided us to further assessment, re-evaluation and re-coding mitigation potentials and wellbeing measures, and therefore further develop Table 1 and Tables S3-7 ("9" in Figure M1). Experts used our comprehensive literature (about 54,000 documents) database to assess the relevant literature, and responded to internal review comments (R#2) even they discussed crucial points with internal reviewers bilaterally. The revised version of Table 1 and Tables S3-7 is again reviewed by five experts ("10" in Figure M1). The last several comments and suggestions are implemented in Table1 and Table S3-7 in coordination with sectoral teams.

Literature databases. In this study, three techniques/types of literature review are used over various stages. First, sectoral teams used the narrative and argumentative literature review techniques to review relevant literature on demand-side mitigation options and potentials. By narrowing down search queries, each sectoral team scanned over 500 relevant publications, assessed, and coded sectoral mitigation options and their impact on GHG emission (Table S1), as well as coding wellbeing impacts (Table S3-7). Our internal reviewers used an argumentative review technique to evaluate expert judgments and examine the confidence levels (Table S3-7). Only through these techniques, more than 1000 papers were screened.

In order to improve the validity and reliability of this study and avoid bias in expert's opinion, with the help of systematic literature survey and machine learning techniques, a comprehensive literature database on demand-side mitigation strategies and wellbeing was designed. First, queries were designed for each 17 demand-side mitigation strategies and 19 dimensions of wellbeing separately (Table S2a). We extracted the title, author, year, and abstract of 54,000 documents from Web of Science, and automatically compiled lists of studies matching the 360 combinations of mitigation strategies and dimensions of wellbeing. This database was used by experts – sectoral teams and internal reviewers- to assess the demand-side mitigation strategies potential and wellbeing impacts. We set up the interactive database such that by clicking on each cell experts were guided to the associate dataset (Table S2b).

Data availability statement. All data used for Figure 1 and Figure 3 are fully presented in the SI – Extended data. The literature database is openly available at the following: https://doi.org/10.5281/zenodo.5163965

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