Beyond Technology: Demand-Side Solutions for Climate Change Mitigation

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Abstract

The assessment literature on climate change solutions to date has emphasized technologies and options based on cost-effectiveness analysis. However, many solutions to climate change mitigation misalign with such analytical frameworks. Here, we examine demand-side solutions, a crucial class of mitigation options that go beyond technological specification and cost-benefit analysis. To do so, we synthesize demand-side mitigation options in the urban, building, transport, and agricultural sectors. We also highlight the specific nature of demand-side solutions in the context of development. We then discuss key analytical considerations to integrate demand-side options into overarching assessments on mitigation. Such a framework would include infrastructure solutions that interact with endogenous preference formation. Both hard infrastructures, such as the built environment, and soft infrastructures, such as habits and norms, shape behavior and as a consequence offer significant potential for reducing overall energy demand and greenhouse gas emissions. We conclude that systemic infrastructural and behavioral change will likely be a necessary component of a transition to a low-carbon society.

Contents

1. MOTIVATION

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (1) leaves no doubt that humanity is on track to potentially warm up the planet beyond 4°C by the end of this century and that the impacts of such changes in climate on human populations will be severe, especially for the most vulnerable populations and places (2). At the same time, the AR5 shows that through vigorous actions by all nations, temperature increases could still be limited to approximately 2°C above preindustrial levels (3). Limiting climate change to 2°C can only be achieved by staying within a global carbon budget of approximately 1,000 Gt CO_2 eq through the end of this century. But current emissions rates exceed 50 Gt CO_2 eq/year. At these rates, the remaining carbon budget will be used up in 20 years. Although the Paris Agreement resolves to hold the increase in global average temperature to well below 2°C over preindustrial levels, some estimates suggest that the current country contributions under the Agreement could miss the target aspired to by wide margins. Drawing on the full set of available mitigation options is thus crucial to the Paris Agreement's 2°C goal.

Climate change mitigation is a focus of the contribution from IPCC Working Group III (WGIII) to the AR5. The report emphasizes technological options, and its key conclusions are that (*a*) immediate action would result in mitigation at low costs, whereas any delay would increase the costs of meeting a 2°C target; (*b*) mitigation efforts involve a transition from fossil fuels to renewable energies and/or nuclear power combined with progress in energy efficiency; and (*c*) so-called negative emissions achieved through either bioenergy carbon capture and storage (BECCS) or afforestation would increase flexibility in reaching the 2°C target, reduce costs of meeting the target, and likely be a necessary component of any trajectory capable of limiting warming to approximately 2°C if stringent mitigation action is further delayed. Indeed, of the 400 scenarios reviewed in AR5 that limit warming to 2°C, 344 (86%) rely on negative emission technologies, in particular on BECCS, and the remaining 56 scenarios indicate emissions peaking around 2010 (4), in contrast to observed trajectories (5). However, BECCS and other negative emission technologies remain controversial, mostly speculative, and some of them would require massive global-scale changes in land use (6–8). Hence, even aggressive transformation of the supply side of the energy system could be insufficient to stay within the 2°C limit. This poses the urgent question of whether demand-side mitigation options could help fill the gap, thereby also lowering the need for risky technologies such as BECCS.

Although demand-side solutions are promising, they are not given the same level of attention as technological supply-side solutions in assessments, like the IPCC's AR5, and in integrated assessment models in general, or in the popular media, as mirrored in the observation that directed innovation perversely privileges energy-supply technologies over efficient end-use technologies (9). This is possibly due to the dominance of some epistemic communities in AR5 and the relatively few scholars from the humanities and social sciences outside of economics (10, 11).[1] Yet, other reasons for this perceived bias are likely to be more important. First, technological solutions are usually more accessible for quantitative investigation and are more straightforward to implement in models, where it often suffices to modify one or a few specific parameter(s), such as efficiency or CO_2 intensity. This focus on specific quantities has been characterized as a quest for golden numbers (14). Demand-side solutions, by contrast, are often embedded in a complex network of social institutions and practices (15), and thus less prone to quantitative analysis and clear-cut implementation. Second, demand-side solutions also often involve explicit normative positions, or values, making those solutions subject to value-laden discourses (16). Specifically, as demand-side solutions presuppose modified behavior, they are less compatible with the revealed-preference framework prevalent in economics.

In this review, we systematically investigate demand-side solutions that influence either direct emissions, for example, in transportation, buildings, agriculture, and cities, or indirect emissions through their influence on consumption patterns. This review fills a surprisingly large gap in the literature on climate change mitigation, which has been dominated by studies of specific end-use sectors. An important exception is work by Roy et al. (17), who assessed the significance of lifestyle changes for energy choices. Here, we report insights from AR5 WGIII and other literature to advance the comprehensive assessment of demand-side solutions to climate change. We conclude that demand-side solutions are a crucial component of climate change mitigation and can slow the rate of, or reduce, emissions growth. Yet, they alone cannot halt climate change. Methodologically, we observe that cost-effectiveness analysis, though not always perfectly adequate, could be more systematically applied to investigate demand-side solutions. However, normative considerations and behavioral choice models point to a more complex overall assessment framework. Demand-side solutions and lifestyle changes could trigger and coevolve with systemic changes in law, values, and lifestyles to become a necessary component of a transition to a low-carbon society.

2. DEMAND-SIDE SOLUTIONS IN END-USE SECTORS

This section investigates demand-side solutions in transportation, buildings, cities, and the agriculture and food sector. Several characteristics of urban areas influence emissions from the transport

[1]Carbon pricing, then, emerges as a primary solution in the AR5 and is presented as the instrument most likely to induce technological and behavioral changes. However, although pricing GHG emissions is possibly the single most important policy instrument for climate change mitigation and is likely to induce behavioral change, it is not the primary reason for the observed self-organized action and climate-friendly behavior by individuals, businesses, and communities (12). In turn, carbon (or fuel) pricing remains a necessary component of an effective mitigation policy portfolio, inter alia, to avoid or reduce rebound effects associated with efficiency improvements (13).

and buildings sectors. Key among these is the spatial organization of urban areas, particularly the geometric characteristics established by the relationship between the configuration of roads; buildings; the primary elements of public structures, including green spaces; the distribution and mix of land uses; and the relative location of activities and places of origin and destination. Although the terms urban form and structure are used by different disciplines in slightly different ways, it is well established that urban spatial characteristics such as connectivity, accessibility, land use mix, and density strongly affect transport demand and building size. Urban spatial characteristics can also direct behavioral action, for example, by advancing a low-carbon lifestyle that incentivizes modal shift from car transport to cycling. Here, we review a significant range of solutions and their potential benefits, as well as reasons for optimism about effective climate change solutions at a local level.

Throughout this section, we emphasize the role of hard and soft infrastructures in fostering demand-side solutions. The term hard infrastructure refers to the physical, built environment, such as walkable neighborhoods, public transit systems, and highways, but also to buildings themselves; soft infrastructure and choice architecture refer to norms, habits, and behavioral framings. We assign a focal role to infrastructures because they preshape the available action space and provide an opportunity for behavior that is associated with low greenhouse gas (GHG) emissions. Or, put more technically, infrastructure investments (capital costs) enable the reduction of marginal costs of low-carbon activities. Clearly, infrastructure investments become crucial parts of the policy instrument set to realize climate mitigation solutions on the demand side.

We start by investigating the urban perspective (Section 2.1), as it provides a bracket for more specific transport (Section 2.2) and building (Section 2.3) solutions. In fact, it will become clear that many demand-side solutions related to hard infrastructures have an explicit spatial dimension. We proceed with investigating solutions in the agriculture and food sector (Section 2.4) and conclude this section with summarizing demand-side solutions in end-use sectors (Section 2.5).

2.1. Urban Areas and Spatial Planning

AR5 WGIII (18) established that urban areas could achieve lower emissions if they had certain spatial characteristics: (*a*) high population and employment densities that are colocated, (*b*) compact and mixed land uses, (*c*) a high degree of connectivity, and (*d*) a high degree of accessibility (**Figure 1**).

The literature shows that there is a high degree of correlation between population, employment densities, and transport modes. The relationship between the relative locations of residence and employment also affects modes of travel (19, 20). Lower population and employment densities entrench the use of the private motor vehicle. Longer distances between the point of origin and destination make modes of transport such as walking and other forms of nonmotorized transport less viable, whereas public transportation is possible only with minimum levels of either population or employment density (21–23).

Urban settlements with smaller city blocks, where buildings are close together, building size is small, and streets are narrow, promote walking and other nonmotorized travel. Moreover, a system of smaller city blocks enables pedestrians to change direction easily, a factor that promotes convenience and accessibility. In contrast, a coarser-grained urban fabric with larger city blocks, where buildings are large and streets are wide, encourages fast-moving vehicular traffic and discourages pedestrian activity. The quality of the built environment affects the type and choice of travel behavior. When urban space is pleasant and safe—characterized by people-centric design, aesthetically appealing vegetation, and a mix of interesting and lively street life—it fosters walking and other nonmotorized transport as well as public transport modes (24).

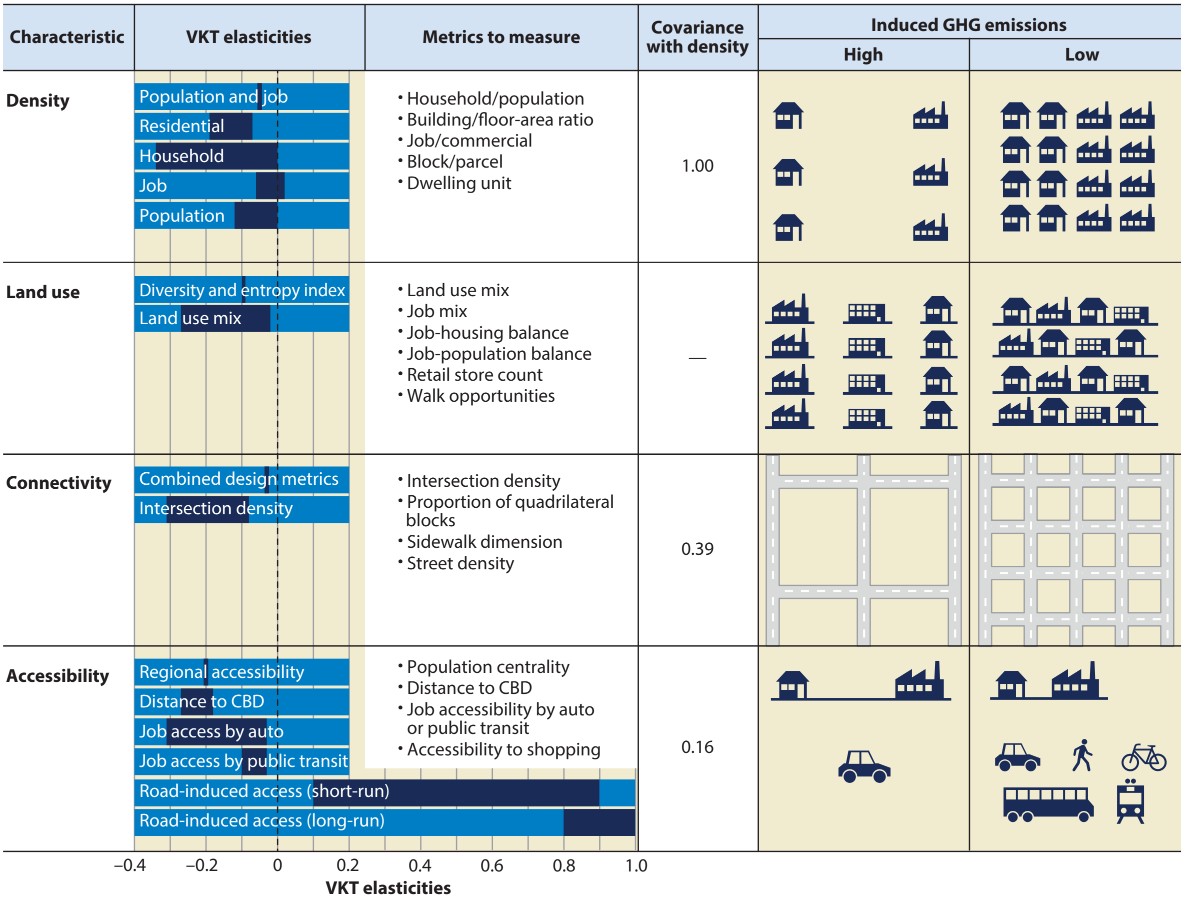

Figure 1

Four characteristics of urban form that affect transport emissions and associated elasticity in distance traveled, relevant metrics to measure, covariance with density, and visualization of greenhouse gas (GHG) emission ranges. Adapted and modified with permission from IPCC, *Climate Change 2014: Mitigation of Climate Change*. *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, figure 12.14, p. 953 (18). Abbreviations: CBD, central business district; VKT, vehicle kilometers traveled.

A recent study found that lack of connectivity is a predictor of urban sprawl and vehicle ownership in the United States (25). During the twentieth century, many communities, especially residential areas, were designed with cul-de-sacs, dead-end streets, and low street connectivity. Typical destinations were rarely within walking distance from the home. These were urban environments that required private motorized transport. In recent years, many countries have been rethinking urban design toward developing complete streets that explicitly integrate walking and other nonmotorized travel via sidewalks, bicycle lanes, and traffic-calming measures to lower the speed of motorized traffic. A related concept is that of neotraditional neighborhood development, which aims to reverse the contemporary trend of low-density, automobile-oriented, single-use developments that lack local character by creating vibrant, mixed-use neighborhoods with higher residential and employment densities, complementary land uses, and place making (26).

Another important factor that influences urban emissions is the land use mix, or the spatial distribution of economic activity. Strong coordination between land use and public transportation routes is essential for reducing private vehicle use. Intensification of mixed-use development along or around public transport routes and stops brings a number of benefits. It reduces aggregate amounts of motorized travel, encourages walking, and improves the viability and efficiency of public transportation.

Urban design, therefore, is of utmost importance in shaping forms of transport, mode choice, and building size and use. For example, good urban design can reduce paved areas for parking, make use of shared walls to reduce embodied energy, and promote smaller residential units. Building height is an important dimension of urban form. The operational energy requirement of buildings is a function of climate, design, quality of the building stock, function and location, orientation, height, and user behavior. Semidetached, three-story buildings have been shown to be significantly more efficient in terms of operational energy than freestanding, single-story units. For example, in Sydney, Australia, low-rise, attached housing has 15–20% lower energy use than detached housing with the same number of bedrooms (27).

Housing is a durable good, and the quality of housing varies tremendously within cities. Thus, two kinds of path dependencies emerge from the spatial structure and development history of cities. First, the street and transport network develop together with buildings, inducing a spatial pattern of cities that endures for decades and sometimes centuries. Crucially, when residential and employment locations are spatially dislocated, it induces substantial transport, often individual and motorized, and hence GHG emissions that are difficult to change on short timescales, if at all. Second, buildings have a lifetime of decades to centuries, and the turnover rates, often desirable to improve the energy efficiency of buildings, are expensive to increase. These path dependencies are central and pose tough challenges, but they also indicate where low-carbon cities are easiest to build: in places where there is no lock-in of entrenched or established urban form, for example, in some newly urbanizing places found especially in Asia, the Middle East, and Africa. In these places, most of the urban development that will be on the ground in 2050 has not yet been built, thus offering an unprecedented opportunity to develop low-carbon pathways. A recent study analyzing driving factors of GHG emissions in urban settlements suggests that modifying the emerging urbanization on these continents alone could reduce future urban energy use by 20–25% until 2050 (28). On the other hand, developed countries also offer ample opportunity for infrastructural demand-side solutions as they often have highly inefficient built environments (see examples in Sections 2.3 and 2.4).

Key drivers of urban spatial structure include economic conditions, market failures, and policies and regulations that affect the spatial distribution of investments, land use, and economic activity. The degree to which individuals choose to live in places with certain spatial characteristics (e.g., walkability) is debated in the literature. The Tiebout (29) model suggests that individuals sort into neighborhoods and communities according to their preferences. Thus, even if walkable communities were designed and built, households that preferred driving over walking would sort themselves into automobile-friendly neighborhoods. Individuals who like density tend to live in denser areas, whereas individuals who value accessibility and land use mix will also sort into those neighborhoods. Because individuals sort in space based on their preferences and budgets, many traditional spatial planning strategies to alter urban form (and hence demand-side behavior) may have limited effectiveness, as individuals can easily counteract these policies through behavioral adjustments such as moving to another neighborhood. Specifically, an econometric study of the United States suggests that restrictive urban planning may improve local sustainability but is nearly fully compensated for by sprawled development in other parts of the country (30). But a detailed meta-analysis revealed that the built environment plays a more important role in travel behavior in the United States and residential preferences a minor role (31).

Nonetheless, two arguments point to a crucial role for urban planning in spite of the endogeneity of spatial choice. First, only if low-carbon, sustainable housing is built can it be the choice of residents who prefer such environments. Second, preferences in location and transit mode are not exogenous but endogenous to social norms and upbringing. In other words, it is possible that over generations, more sustainable living will generate a greater demand for even more sustainable living.

2.2. Transportation

In global assessments, policy options aimed at reducing transport emissions in general and the need for land transportation in particular typically receive far less attention than do technological measures (32). But such options are likely essential to meet the goals of GHG reduction by midcentury (33, 34): On the one hand, demand reduction can be induced by physical infrastructures and urban forms that enable high accessibility and low-carbon modes (see Section 2.1); on the other hand, measures that directly incentivize different behavior can additionally reduce emissions. The transport chapter of the AR5 WGIII (35) discusses these options systematically, highlighting infrastructure options on the urban interface. Subsequent literature has provided quantitative estimates of the importance of urban transport and behavioral options (34, 36).

Urban transportation solutions would add a small but significant component to halving transport emissions between 2010 and 2050, a requirement for ambitious climate mitigation targets (36). Overall, behavioral and infrastructural measures in cities can potentially reduce GHG emissions from urban passenger transport by 20–50% until 2050 (32). This may be achieved via three routes, technological change, modal shift, and reduced travel demand, and information technology plays a key role in all three areas of innovation (37).

Adequate urban planning and alternative mobility services reduce travel demand and foster modal shifts toward nonmotorized modes. Compactification is seen as a primary strategy for reducing emissions. Relatively compact cities (i.e., Hong Kong; Seville, Spain; Turin, Italy) show that per capita travel distance remains up to seven times lower than in sprawled cities (i.e., Chicago; Washington, DC; Houston) (38). A meta-study concluded that compact versus sprawled development reduces GHG emissions by 20–40% (39). Key modifying variables include density, diversity, design, destination accessibility, and distance to transit. If such compact development measures were applied to all new development in the United States, it could enable a 7–10% reduction (compared to business-as-usual development) in distance traveled and associated GHG emissions between 2007 and 2050 (39). Modeling studies of California and England find a demand decrease of approximately 5% for reasonable compactification scenarios over the next 30 years (21, 40).

Optimal pricing of motorized urban transport, in order to reduce air pollution and congestion, can reduce transport demand and incentivize modal shift considerably. Pricing is often coaligned with well-managed urban planning, a relatively dense development, and a long-term increase in public and nonmotorized transport. Both pricing of private motorized transport and provision of alternative mode choice encourage modal shift. Parking prices can lower distance traveled by 2–12% (41), and congestion charging, as implemented in London, Stockholm, and Singapore, can reduce distance traveled within the charging zone by 10–20% (42, 43). Modeling studies of health and climate change in the context of urban transport show that a modal shift from car and motorcycle use toward walking and cycling could reduce GHG emissions by 38% in London and 47% in Delhi in 2030 (44). Another modeling study of Beijing urban transport shows that an optimal combination of congestion charging and investment in bus rapid transit would reduce distance traveled by up to 30% (45). Combining pricing with investment in bicycle infrastructures and public transport, along with long-term land use planning (which is most relevant where populations are growing), could realize a 50% reduction in urban transport GHG emissions between 2010 and 2040 in European cities (46). And, complementing subway line building with land use planning and pricing instruments could reduce GHG emissions by 36% (versus trend in 20 years) in Bengaluru, India (47). For Paris, a mix of urban planning and public transport subsidies (excluding pricing of car transport) results in a 36% reduction of vehicle kilometers traveled (VKT) as compared to baseline in a model that extends to 2030 (48).

Behavioral options could be fostered by information campaigns that facilitate social learning, active choice, and frame alternative mobility choices. A recent review provides a summary of behavioral options with confirmed experimental effectiveness (49). The direct costs of many options are negligible. For example, providing free one-day or monthly public transport tickets on a trial basis, particularly to commuters or households after they have relocated (50, 51), or presenting information from a novel perspective (52, 53) proved to be surprisingly effective in inducing changes in travel patterns.

Information technology solutions such as telebanking, teleworking, teleconferencing, and online shopping are relevant on an individual level. Changes in car travel distances for telecommuters are large (50–75%), but absolute citywide average effects are unclear. A study from the United States shows that employer-based trip reduction achieves reductions in car travel distances of approximately 4–6% among participants, with region-wide effects of approximately 1%; voluntary travel behavior change programs achieve reductions of citywide car travel distances of up to 5–7% (41). In addition to directed information measures, social network and spillover effects can lead to nonlinear uptakes of low-carbon modes such as cycling (54). In addition, carpooling, especially in urban areas, shows great mitigation potential (55, 56). For example, a survey from Delhi reveals that carpooling could potentially reduce annual fuel use within the metropolitan area by up to 30% (57). Altogether, behavioral measures, including marketing, information provision, and customized new services, such as car-sharing services, may reduce transport demand by approximately 10% (41, 58).

When considering the prospect of rapidly increasing carbon-intensive transportation in many countries with historically low emissions per capita due to relatively low vehicle ownership, innovation in a single area such as fuel economy cannot guarantee the targets needed to achieve low-carbon mobility. The large differences in national per capita light-duty vehicle (LDV) emissions (range: 100–4,000 kg CO_2 eq/year) are principally explained by LDV use per capita (range: 300–13,000 VKT/year) rather than fleet average fuel efficiency and carbon intensity factors (59). Global growth of per capita LDV use to the level of contemporary high-income countries (approximately 10,000 km/year) would necessitate vehicle technology options that far exceed optimistic technology scenarios for the year 2050 to achieve the 2°C mitigation scenario. However, if per capita levels of LDV use were to converge at those of today's typical middle-income countries (approximately 3,000 km/year), 2050 targets could be met with medium-term technologies (59).

The tourism sector offers another instructive example of the interaction between technological and behavioral mitigation potentials. In the case of a business-as-usual scenario, CO_2 emissions in the global tourism sector may experience growth beyond 150% between 2005 and 2035 (60, 61). If maximum assumed technological efficiencies were achieved for all transport modes, accommodations, and activities, 38% lower emissions could result. On the demand side, reducing energy use by a combination of transport modal shifts and increases in average length of stay could result in a reduction in emissions by 44% worldwide. Using a combination of both of the above measures, emissions in the business-as-usual scenario in 2035 could be reduced by 68%, thus achieving a 16% reduction of emissions with respect to 2005 levels (61).

2.3. Buildings

AR5 WGIII identifies buildings as one of the largest energy-consuming end-use sectors worldwide. In 2010, buildings accounted for 32% of total global final energy use and 19% of energy-related GHG emissions (62). Both energy use and GHG emissions are predicted to at least double by midcentury. The AR5 discusses four sets of mitigation options in buildings: (*a*) increasing carbon efficiency (such as the inclusion of renewables), (*b*) increasing the energy efficiency of technology (e.g., in building envelopes and air-conditioning), (*c*) increasing system or infrastructure efficiency (e.g., urban planning with district heating and cooling), and (*d*) reducing service demand (e.g., smart metering).

Path dependency is a central issue when approaching any of these mitigation options, as the long lifespans of buildings generate the risk of long-term carbon lock-in. The buildings sector is deeply embedded in urban form and spatial planning, both of which determine structural energy demand from buildings independent of technology (Section 2.1). A more compact urban form tends to lessen building energy consumption and GHG emissions due to lower per capita floor areas, reduced building surface-to-volume ratio, increased shading, and more opportunities for district heating and cooling systems (63). However, there might be energy-related trade-offs at higher densities: Although three-story buildings have lower operational energy use and emissions associated with construction than detached housing, higher densities can, at a minimum, increase the energy embodied in construction (27, 64).

Technological solutions to realize the energy efficiency potential from buildings are well demonstrated. In addition to technologies and architecture, behavior, lifestyle, and culture have a major effect on buildings' energy use; for instance, three- to fivefold differences in energy use have been shown for the provision of similar building-related energy service levels (65–67). The additional potential is more fully represented in sectorial than integrated models, as the latter seldom represent any of the building energy mitigation options and instead focus on the supply side. More generally, too, the potential social and environmental benefits from building measures beyond energy cost savings are rarely internalized by policies, especially if they are difficult to quantify and monetize in cost-effectiveness or cost-benefit analysis (68, 69). The rest of this section focuses on the additional potential from buildings achieved from soft infrastructure solutions.

There are substantial differences in building energy use driven largely by behavior and culture. Residential energy use can differ by a factor of 3 to 10 worldwide for similar dwellings with the same occupancy and comfort levels (70), and energy use in some office buildings can be up to 10 times greater than in others with the same building functions and climate and similar comfort and health levels for occupants (70–74). Buildings and their energy infrastructure thus need to be designed, built, and used taking into account culture, norms, and occupant behavior.

This is particularly true for developed countries where energy service levels are already high. Short-term behavioral change potential is estimated to be at least 20% in the United States (75); over long periods of time, more substantial reductions (typically 50%) are possible (76, 77). Similar absolute reductions are not possible in developing countries with development needs, although the rate of growth of energy service demands can be reduced (78, 79) (Section 3).

Further, there is a range in the energy savings achievable in buildings due to behavioral changes, depending on the type of end use. For example, savings from heating loads of 10–30% are possible for changes in thermostat setting. Similarly, cooling savings of 50–67% are recorded with measures such as substituting air-conditioning with fans in moderately hot climates with tolerable, brief heat exposures. In another example, increasing the thermostat setting from 24°C to 28°C reduces annual cooling energy use by more than a factor of 3 for a typical office building in Zurich, by more than a factor of 2 in Rome (80), and by a factor of 2 to 3 if increased from 23°C to 27°C at night in residential Hong Kong (81). Because these settings are influenced by dress codes and cultural expectations regarding attire, major energy savings can be achieved through changes in cultural standards (63).

Behavior and lifestyle are also drivers of building energy use when interacting with cooling infrastructures. Electricity use for summer cooling in apartments in the same building with similar households in Beijing ranges from 0.5 to 14.2 kWh/(m^2·year) (72). The difference is explained by fewer operating hours of the split air conditioner units compared with central air-conditioning. Buildings with high-performance, central air-conditioning can use much more energy than decentralized split units that operate part-time and for partial-space cooling (72, 82).

There are similar findings for energy reduction from other end uses. The savings based on differing clothes drying behavior ranges from 10–100%, at the lower end, for example, by operation at full load versus one-third to one-half load (83). Other examples are water heating savings of 50% (e.g., by shorter showers or switching from baths to showers); cooking energy savings of 50% (e.g., by using different cooking practices); lighting energy savings of 70% (e.g., by turning off unneeded lights); refrigerator energy savings of 30–50% (e.g., by smaller refrigerator and freezer volumes and elimination of a second refrigerator); dishwasher energy savings of 75% (e.g., by operation at full load versus typical partial load); and clothes washer energy savings of 60–85% (e.g., by cold- versus hot-water washing) (84). Policies to target such behavioral change include progressive appliance standards and building codes, for example, with absolute consumption limits (kilowatt-hours per person per year) rather than efficiency requirements (kilowatt-hours per square meter per year) (85).

In more recent literature, published after the AR5, it has been found that the consideration of occupant behavior has often been overly simplistic, resulting in a gap between building design and operational energy consumption. Instead, researchers argue that the discussion of behavior should be guided by the social context of habits, occupant motives, and attitudes (86). Measures aimed at habits, such as information disclosure and feedback on energy consumption (particularly through smart meters) can result in substantial household energy savings (86–89). The framing of the problem also affects the types of policies proposed, and there is an increasing need to integrate engineering, economic, and behavioral perspectives for effective policy (90–93).

2.4. Agriculture and Other Land Use

Earth's productive lands provide humans with a large array of resources, including nonsubstitutable resources such as food but also raw materials such as wood and fibers for clothing and other purposes, as well as energy (94). Most analysts expect that rising population numbers and affluence will result in increases in the demand for agricultural products of 70–100% until 2050 (95). AR5 WGIII (96, ch. 11) analyzed GHG reduction potentials associated with both supply- and demand-side measures. It found large GHG reduction potentials associated with demand-side measures related to agriculture, forest, and other land use, such as diet change, reduction of food waste, and use of timber instead of steel or concrete frames in buildings.

Many climate change mitigation scenarios analyzed in AR5 WGIII, in particular all those relying heavily on bioenergy with or without carbon capture and storage or on options to sequester carbon through afforestation (96), would require substantial additional land areas to be used for energy crops or afforestation (97). In the latter case, maintenance of the newly established forests is a prerequisite for keeping the carbon out of the atmosphere.

As three-quarters of Earth's land (except Antarctica and Greenland) are already used by humans, substantial land demand for climate change mitigation options is bound to intensify land use competition, which could potentially result in a host of socioeconomic (loss of livelihood,

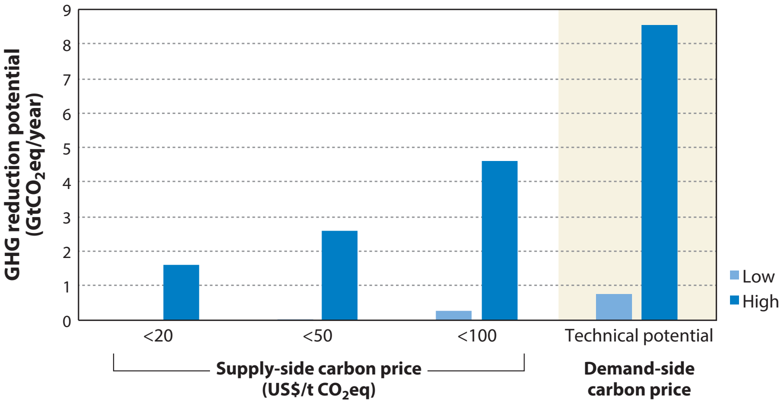

Figure 2

Economic potentials of supply-side options to reduce GHG emissions in agriculture depending on the carbon price for 2030 compared with the technical potential related to demand-side options for 2050 (96, 99). Note that the Intergovernmental Panel on Climate Change Working Group III does not report aggregated data on technical GHG reduction potentials on the supply side. Abbreviations: GHG, greenhouse gas; US$/t CO_2 eq, US dollars/ton CO_2 equivalent.

negative impacts on food security) and environmental (GHG emissions, degradation of ecosystems, biodiversity loss) issues (98). Changes in future food demand will have strong effects on GHG emissions, both directly through agricultural GHG emissions from cropping and livestock and indirectly by influencing the availability of areas for production of biogenic, low-GHG resources, such as some forms of bioenergy, raw materials, or timber, for carbon sequestration, including through afforestation (99, 100).

Technical GHG reduction potentials related to behavioral changes (dietary change, waste reduction) concerning agricultural products strongly exceed the potentials of supply-side mitigation options, even at a carbon price of 100 US$/t CO_2 eq (96), as shown in **Figure 2**. Comparability between economic potentials (supply side) and technical potentials (demand side) is limited because demand-side options are difficult or impossible to judge in terms of cost-benefit analyses. Indeed, the costs of buying healthier, plant-based food with low environmental impact may even be lower than those of diets richer in animal-based products (101).

Studies based on either life cycle assessment or integrated modeling show that changes in diets strongly affect future GHG emissions from food production (100, 102). Most plant-based foodstuffs have substantially lower GHG emissions than animal products (96), although there are exceptions, for example, vegetables grown in heated greenhouses or fruits transported by airfreight (87). GHG benefits of plant-based food over animal products also hold when compared per unit of protein (103).

Agricultural non-CO_2 (CH_4 and N_2O) emissions would triple by 2055 to 15.3 $GtCO_2$ eq/year were current dietary trends and population growth to continue (102). Technical mitigation options on the supply side, such as improved cropland or livestock management alone, could reduce that value to 9.8 Gt CO_2 eq/year; in fact, emissions were reduced to 4.3 $GtCO_2$ eq/year in a behavioral dietary change scenario and to 2.5 Gt CO_2 eq/year when both technical mitigation and dietary change were assumed (102). Along the same lines, another study showed that large greenhouse gas emissions savings (a reduction by 36% compared to a business-as-usual scenario) could be achieved by adopting a healthy diet that included meat, fish, and egg consumption of 90 g/(person·day) (100).

2.5. Summary of End-Use Sectors

We reviewed the potential contribution to climate change mitigation from three sectors, buildings, transport, and food, under the two main perspectives, hard urban infrastructures and soft behavioral frameworks (**Table 1**). We argue that the full potential of demand-side solutions becomes visible in these two perspectives.

Table 1 Climate change mitigation options and their quantitative reduction potential[a]

End-use sector	Mitigation option	Reduction potential	Reference(s)
Urban areas and spatial planning	Modifying the emerging urbanization	20–25% reduction of future urban energy use until 2050	28
Transportation	Optimal pricing	15–20% reduction in automobile transport	28
	Compactness	United States: 10% reduction in distance traveled	39
		Europe: 5% reduction in distance traveled	40
	Behavioral measures (marketing, information provision, and tailored services)	10% reduction in transport demand	41, 58
	Total	20–50%	
Tourism	Transport modal shifts and increases in average length of stay	44% emission reductions worldwide until 2035	61
Buildings	Developed context: short-term behavioral change potential	>20%	75
	Developed context: long-term behavioral change potential	50%	76, 77
	Developing context: behavioral change potential	Relevant but lower potential	78, 79
	Heating: adjusting thermostat setting	10–30%	80
	Cooling: using substitutes for air-conditioning, increasing thermostat setting, changing dress codes	50–67%	80, 81
	Clothes washing and drying behavior (e.g., by operation at full load versus one-third to one-half load)	10–100%	83
	Water-heating and cooking energy savings (e.g., by shorter showers, using different cooking practices)	50%	83
	Lighting energy savings (e.g., by turning off unneeded lights)	70%	83
	Refrigerator energy savings (e.g., by smaller refrigerators)	30–50%	83
	Dishwasher energy savings (e.g., by full-load operation)	75%	83
Agriculture and other land use	Technical potential of demand-side options for 2050	70%	96, 99
	Healthy diet: meat, fish, and egg consumption of 90 g/(person/day)	36% greenhouse gas savings	100

[a]As baseline scenarios have been insufficiently specified and may be inconsistent, the provided quantitative estimates display the respective relevance of demand-side options but generally cannot be simply added or multiplied to savings taken from other solution options.

Overall, urban planning could reduce GHG emissions from urban transport by 5–10%, with significantly higher values expected in rapidly growing cities; by 10–30% through pricing measures and infrastructure provision for nonmotorized and public transport; and by approximately 5–7% through information. A combination of these measures might achieve between 20% and 50% reduction in GHG emissions, by activity reduction or shifted transport, until 2050 relative to baseline growth, although the synergies and trade-offs between these measures deserve further research (32) (Section 2.2.).

The existing variation in per capita transport-related energy consumption within high-income cities indicates that there are different infrastructure trajectories with different carbon intensities. Low- and middle-income countries can avoid locking-in high carbon modes and choose urban developments that enable cheaper future abatement (59). But urban infrastructures influence not only transport but also buildings in terms of GHG emissions (104). Overall, urbanization choices in developing cities, especially in Asia and Africa, could make a difference of 190 EJ in 2050 energy use (28) (**Figure 3**). Crucially, the cost structure of urban transport choices is a strong determinant of urban form and hence both transport and building emissions (23).

Behavioral change provides additional demand-side potential for climate mitigation. Typically, behavioral change options are cost-effective, though their costs have not been systematically studied (105). For building energy use, the behavioral change potential can be as high as 50% over long periods of time (Section 2.3). In the agricultural sector, diet shift toward more healthy nutrition would reduce mitigation more than what would be possible by technological options alone (Section 2.4).

In many cases, behavioral and lifestyle issues are tightly entangled with hard infrastructures. A detailed typology of residential GHG emissions in England revealed tight correspondence between the built infrastructure and lifestyles (106). In that study, English human settlements were endogenously clustered according to their drivers of GHG emissions, including density and income, but also to household size, heating systems, and local climate. Some of the resulting types of human settlement coincided with a high prevalence of lifestyle groups designated young

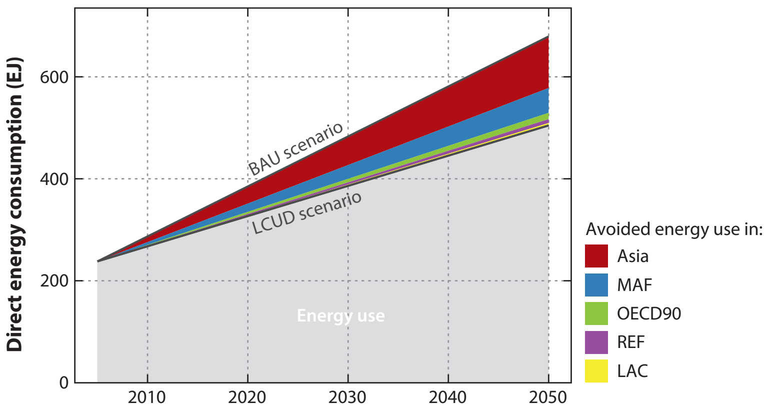

Figure 3

A low-carbon urban development (LCUD) scenario would save approximately 190 EJ in the annual direct final energy use of cities, including electricity consumption and heating in buildings and energy use from urban transport compared with the BAU scenario (28). Abbreviations: Asia, developing economies in Asia; BAU, business as usual; LAC, Latin America and the Caribbean; MAF, Middle East and Africa; OECD90, region including all member countries of the Organisation for Economic Co-operation and Development as of 1990; REF, countries undergoing reform.

city professionals, multicultural inner city dwellers, or affluent urban commuters. This observation points to great potential for exploring joint infrastructure and behavioral solutions in the transport, building, and settlement sectors.

3. DEMAND-SIDE SOLUTIONS IN THE CONTEXT OF DEVELOPMENT

Demand-side solutions play important mitigation roles in developed and developing countries (as specified in Section 2). In this section, we discuss how the solution space differs between countries with respect to their development stage. We focus exclusively on the demand-side options for developing countries where, because of ongoing structural transitions, there is a timely opportunity to align development and climate objectives by shaping spaces and preferences. Developed countries, by contrast, already have most of their infrastructures built and will require a retrofit of existing spaces and habits, indicating the importance of behavioral change (as discussed in the previous section).

3.1. Aligning Development and Climate Change Objectives

The growing importance of developing countries is highlighted by the tripling of emerging economic output since 1990, and its doubling in low-income countries (107). Yet, in spite of this growth, a number of outstanding developmental challenges still remain. To start with, the benefits of growth are not equitably distributed among countries and within countries, particularly in fast-growing, middle-income countries in Asia and Sub-Saharan Africa (108). Approximately 70% of the population in Africa and 20% in Asia have no access to electricity and have comparably poor access to basic services. The statistics imply that the demand for resources for development is expected to continue, but if unmanaged, there is potential to threaten the very ecosystems that sustain economies and livelihoods. Moreover, climate change acts as a threat multiplier to poverty and sustainability risks, adding to existing stresses and potentially exacerbating social tensions. Conventional models of development have usually focused on increased economic growth and mobilizing new technologies without considering the local and global environmental consequences and social (and distributional) costs associated with the growth pathways (109). However, in the context of a changing climate and the Paris Agreement, bold efforts are needed to rethink the utility of conventional models in addressing pressing development goals, particularly for emerging economies (110).

The co-benefits framework is widely cited as a way forward in enabling a sustainable development transition and also meeting climate goals (110, 111). Co-benefits offer countries an approach to promote their multiple development objectives, such as energy for growth, energy security, access, jobs, and healthy local environments, while also yielding benefits for addressing climate change effectively (112). The linkages between sustainable development and climate benefits are alternatively also expressed by a multiple-objectives framework, which does not require declaring one objective as primary. A growing research base supports the evidence of co-benefits or multiple objectives (113). For example, according to a recent World Bank report titled *Decarbonizing Development* (114), a country's low-carbon pathway and its achievement of socioeconomic development and prosperity can be strongly aligned. That is, the mission to move away from carbon-intensive production and consumption patterns need not supersede the efforts to reduce poverty and meet basic needs (115).

It follows that developing countries, because of impending structural transitions in their infrastructures and economy, can be well positioned to shape and reap the potential win-win opportunities that can stimulate development and simultaneously prevent carbon lock-in (116, 117).

Although supply-side options play a significant role in assembling the arsenal of options required for the pursuit of such a low-carbon transition, demand-side options are potentially as crucial. We explore the salience of these choices in developing countries and their challenges across different demand-side sectors in the next section.

3.2. Demand-Side Options for Multiple-Objectives-Based Development

Developing countries have the challenge of achieving their development goals, often in conjunction with climate-related interventions (as discussed in Section 3.1). These goals can be articulated in many forms, through nationally determined priorities or sustainable development goals. We now discuss demand-side options that can support developing countries in transition to achieve their multiple development objectives.

New infrastructure construction in developing countries represents one of the most significant opportunities (and risks) from a mitigation perspective. As real estate is one of the longest-lived components of the economy, the sector is particularly prone to lock-in. Recent research has found that by 2050, the infrastructure lock-in risk in Southeast Asia (including India) will be more than 200% of the 2005 levels for heating and cooling energy use (63). Countries and regions undergoing early stages of urbanization therefore have the potential to reduce future emissions, particularly in cases where income levels, infrastructure, and motorization trends are rapidly changing, providing occasion to shape the spaces for different technologies and behaviors (118–124) (**Figure 3**). At the same time, energy efficiency and demand-side measures also help reduce costs due to lowered overall demand, with benefits in terms of the balance of payments from avoided fossil fuel imports, and improved levels of energy services (125).

In terms of hard infrastructures, the growth of building energy use, especially in developing countries, can be moderated through the provision of high levels of building services at much lower energy inputs, for example, by incorporating elements of neotraditional lifestyles and architecture. One approach is to use vernacular designs to provide comfortable conditions, successful examples of which are found, for instance, in Vietnam (126) and India (127). Another is to allow natural ventilation, with the use of part-time and partial-space indoor climate conditioning, using mechanical systems for the remaining needs only when passive approaches cannot meet comfort demands. Such pathways can enable energy use levels below 30 kWh (m^2·year) as a world average, as opposed to 30–50 kWh (m^2·year) when utilizing central air-conditioning (82).

Developing countries also present opportunities for integrated infrastructure and energy planning to be most effective at shaping development and emissions trajectories. For instance, an estimated 3 billion people worldwide rely on highly polluting and unhealthy traditional solid fuels for household cooking and heating (128), and shifting their energy sources to electricity and clean fuels could strongly influence building-related emissions reductions and provide significant socioeconomic development outcomes (129).

Finally, as economies shift from agriculture to industry to service, there is increased demand for, and emissions from, motorized two-wheelers and expansion of bus and rail public transport systems (130, 131). A major shift toward the use of mass public transport guided by sustainable transport principles, including the maintenance of adequate services and safe infrastructure for nonmotorized transport, presents great mitigation potential (132, 133). For example, Bogota, Columbia, and Addis Ababa, Ethiopia, have demonstrated that city transformations occur mainly as a consequence of investments in transport systems, entailing a modal shift to low-carbon modes. In Delhi, improved bicycle lane infrastructure led to greater uptake of cycling (134). Crucially, such modal shifts also reduce local air pollution. Supporting nonmotorized travel thus often supports development more effectively, more equitably, and with fewer adverse side effects to the environment and human health than providing for motorized travel (44).

Lifestyle changes can also have a significant impact on energy demand. Quantitative modeling of the impact of future lifestyle changes shows that the rate of growth of energy use (as opposed to absolute reductions) can be reduced by pursuing different consumption lifestyles, without compromising on quality of life (78, 79). Importantly, agriculture and land use account for a large proportion of the emissions from developing countries (96), and it is predicted that growing urban populations will demand more resource-intensive foods such as meat, reflecting the strong relationship between higher income and consumption of livestock products (135). It is important for all countries to reconsider these consumption patterns, and given that developing countries are in the early phases of the transition when animal and other resource-intensive product consumption per capita is very low, they have the chance to choose consumption patterns that bring development benefits to personal health and also reduce GHG emissions (136) (compare with Section 2.4).

As discussed above, the options for linked developed and climate benefits are plenty, especially within the context of large-scale country transitions. However, developing countries can also be marked by limited governance and low institutional capacity, resources, and skills, which is an obstacle to building resilient and integrated urban, agricultural, and land use management systems. In such instances, the capacity to strategically manage the trade-offs across development objectives is often limited. Poor governance can often stall the pace of policy uptake and lock in suboptimal technologies and infrastructure that result in high future costs (120).

For example, in Indonesia, institutional deficits, such as limited experience with urban planning and management, budgeting and accounting, and finance, have thwarted the decentralization of infrastructure programs from the central to local governments over the past decade (137). In China, silo-style planning, in which each municipal department makes decisions separately, is ubiquitous, rendering the achievement of cost-efficient environmental solutions infeasible (138). This limitation in local institutional capacity highlights the conundrum that rapidly urbanizing regions—often with the greatest potential to reduce future GHG emissions—are where a lack of institutional capacity can most obstruct mitigation efforts (139).

In sum, changing consumption trends in developed and developing countries implies changing habits and social norms that underpin unsustainable lifestyles and practices and their distributional consequences (140). Behavioral change and lifestyle choices can influence the use of infrastructures in developed countries, and structurally different infrastructure investments in emerging and least-developed economies could shape sustainable future energy use patterns. But bringing about changes in structures and behavior through norms is harder in the context of lower institutional and technical capacities, as is often the case in developing countries (140). This focus on social norms and habits is distinct from that of technological economic assessment, and thus necessitates a closer look into the framework for assessing demand-side solutions, the topic of the next section.

4. BEYOND TECHNOLOGY: FRAMEWORK FOR ASSESSING DEMAND-SIDE SOLUTIONS

We proceed by investigating an analytical framework for assessing demand-side solutions. Central to this framework are lifestyle changes that are commonly much more explicit on the demand side than on the supply side, and hence require a focus when assessing the solution space (Section 4.1; see also Section 2). But lifestyle changes also have overarching and important implications that change how a solution space can be assessed. An assessment of lifestyle solutions requires an explicit reference to values and normative positions taken (Section 4.2). Such an assessment would also expand the tight boundaries of analytical analysis, requiring a delicate approach in quantitative assessments (Section 4.3).

4.1. Lifestyle Changes

Demand-side solutions involve end users and hence lifestyle and behavioral change. For example, individuals might switch from personal, motorized transport to a flexible mode choice model, such as cycling and public transport for daily trips and car sharing services as needed for other purposes. It might also involve substituting a trip to remote islands by a trip to a local national park. In dwellings, savings could accrue from adjusting the thermostat. And a dietary shift would considerably reduce land demand, thereby helping to reduce GHG emissions. Altogether, these options can significantly reduce emissions compared to the baseline and, we argue, are an essential part of any realistic effort to achieve the highly ambitious 2°C target. Further, many of these options can be achieved at low costs, or even reduce costs for consumers. Nonetheless, most options are implemented only insignificantly or not at all. This points to culturally shaped preferences and the existence of strong default choices but also to significant difficulties in modifying behavior. Humans act and decide within societal structures according to well-established practices that are difficult to change because they are stabilized through routines, incentives, and institutions. Changes in practices are constrained by spatiotemporal and technological characteristics (139), in which cultural patterns, social inequality, and power relations are inscribed. These structures stimulate or underpin certain practices and discourage or prevent others. Political and economic institutions are the keys to explaining the stabilization or transformation of practices (141).

However, lifestyle changes have so far received only scarce attention in IPCC reports. The reason is twofold. First, lifestyle changes are normatively charged, with some reacting strongly against the very notion of lifestyle changes and others welcoming them as desirable. In other words, across countries, the very notion of lifestyle change opens the door for contentious debate over values. Second, as costs are rarely the issue with lifestyle changes, it becomes difficult to consistently evaluate and prioritize different options for such changes in terms of one consistent measure, such as US$/kg CO_2 eq. In a certain sense, cost-effectiveness studies of behavioral options and social norms are possible, as demonstrated for energy conservation by communicating their relative ranking in terms of electricity bills (105, 142). More of these studies are required. Yet, the overall welfare effects often remain elusive, as demand-side changes often have a normative whiff and also impact the supply side in general equilibrium frameworks. Lifestyle changes hence touch on questions about the boundaries of analytical frameworks and the usefulness of quantitative analysis. We discuss both points in turn.

4.2. Explicit Normative Frameworks

Technology-focused solutions assume that revealed preferences on issues like energy consumption are normatively applicable and will continue to exist in a manner similar to the current situation. In contrast, demand-side solutions assume to some degree a shift in preferences, underpinned by policies that encourage adoption of preferences compatible with broader welfare goals. This is apparently in contradiction to a revealed-preference approach within economics. But this contradiction can be partially reconciled.

A revealed preference approach assumes that actors have fixed exogenous preferences, hold correct beliefs about their environments, and make decisions by computing the maximal utility

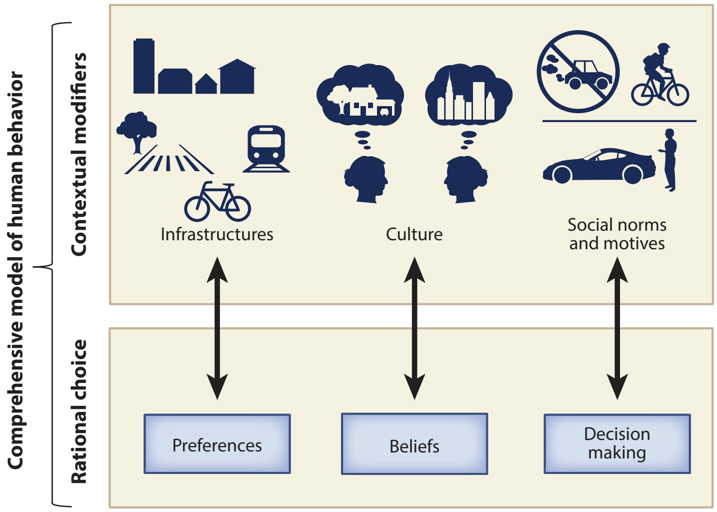

Figure 4

Comparing behavioral and rational choice approaches. Assessing mitigation solutions from a behavioral perspective implies taking a rich contextual perspective. Motivated by Mattauch et al. (49).

they can obtain. However, empirical literature in behavioral economics has demonstrated that this approach holds only under narrow conditions and cannot be applied to conditions in complex social and environmental settings. Crucially, although preferences have been shown to be endogenous to learning and the built environment, beliefs are often determined by cultural settings and more specific effects, like the availability bias; in addition, decision making is subject to habitual effects and social context (143–145). In other words, choices are socially, culturally, and environmentally contextualized. This is summarized in **Figure 4**.

The challenge with this broad contextualization is that the liberal approach of maximizing what people want, or what they state they want, comes into conflict with a perspective that aims to maximize subjective well-being. For example, some people may prefer to drive their car in car-oriented built environments, but they would likely experience health benefits from riding their bicycle in bicycle-oriented built environments. Under these circumstances, the question of lifestyle changes, at least in some instances, is subject to the specific normative position held. The consequences of a liberal perspective and a subjective well-being perspective for policies on transport-related choices are summarized in **Table 2**.

The lesson is that those taking a subjective well-being perspective, or those emphasizing public health, are more likely to embrace lifestyle changes than liberals. Liberals typically aim to satisfy revealed preferences; this can be strongly defended, for example, by specifying an equivalent-income approach that incorporates nonmonetary dimensions of well-being, such as health (146). In contrast, a subjective well-being approach would further extend the picture by also investigating how infrastructure and social norms influence behavior. A subjective well-being approach would then consider, for example, changing the built environment such that welfare is improved. Arguably this corresponds to the satisfaction of fundamental preferences. As a result, the most important policy space would relate to opportunity structures, or infrastructures, that incentivize behavior that reduces energy demand. Accepting this perspective, it then becomes clear that optimal infrastructure provision and carbon pricing become effective complements of each other, as has been shown in explicit urban spatial settings (23) and in economic theory (147).

Table 2 Normative positions and their influence on shaping policy decisions in transport-related choices[a]

Transport-related factor	Subjective well-being	Liberalism
Environmental awareness	Rewards for individual altruistic behavior	No particular rewards
Mode choice	Incentives for NMT, change in social norms, and cues against biases	Degree of incentivizing NMT depends on type of liberalism
Safety	Disincentives for risky behavior	No disincentives for risky behavior
Commuting	Disincentives	No disincentives
Car purchase	Vehicle tax according to car type	A status tax (according to type of liberalism)
Infrastructure	Prioritization: NMT, short commutes	Not directly applicable Alternative: elicit preferences in simplest context

[a]Table reproduced from Mattauch et al. (49).
Abbreviation: NMT, nonmotorized transport.

For assessments, however, it is practically and methodologically very difficult to evaluate such a change in welfare, as discussed in the next section.

4.3. Quantification and the Boundaries of Analysis

Any comprehensive analysis is plagued by substantial evaluation uncertainties. Commonly, discount rates are contested, and distributional effects play a major role in sensitivity studies. But the question of the boundaries of analysis remains too often undiscussed (14). A cost-benefit analysis should always specify the boundary of its framework. Technology-focused solutions can often work in a quantitative framework, specifying, for example, the amount of energy needed in any given year, under certain assumptions, underlying economic growth and demographic change, or the portfolio of evolving technological options and their cost profiles. Importantly, the underlying models implicitly assume constant preferences that are fulfilled by economic parameters. Demand-side solutions, in contrast, often need a more contextual specification in that they directly interact with lifestyle questions. As discussed above, demand-side solutions often translate into changing the opportunity space by offering different infrastructures, and ultimately by dynamically interacting with the formation of endogenous preferences. Clearly, then, a comprehensive assessment of demand-side solutions requires a different boundary of analysis. But the analytical framework for a changing infrastructure environment is not fully developed and poses hard challenges, especially when it comes to taking an explicit normative position (Section 4.2). In other words, existing analytical frameworks and their common boundaries pose a considerable barrier to the exploration of demand-side solution space.

5. CONCLUSION: AMBITIOUS CLIMATE CHANGE MITIGATION REQUIRES DEMAND-SIDE SOLUTIONS

Ambitious mitigation targets require making use of the complete solution space. Low-carbon energy technologies are central to reducing GHG emissions adequately. But demand-side solutions would facilitate and complement the task of technological solutions enormously.

This review synthesizes demand-side options for climate change mitigation. Two classes of demand-side options emerge. On the one hand, hard infrastructures, epitomized by the urban built infrastructure, provide a physical setting for shaping preferences, practices, and opportunity spaces. On the other hand, changing norms, practices, and nudges modify the opportunity space and can induce direct behavioral change. Reshaping urban forms and the urban environment provides ample opportunity to make car travel obsolete and save high amounts of energy in buildings. Both transport and buildings also offer significant opportunities for reduced energy demand by soft measures, such as providing targeted information on sustainable mobility for specific groups of people. In agriculture, demand-side action, in particular, dietary shift, could reduce emissions by more than 70% compared to the trend in 2055, thereby surpassing the potential of technological options.

Approaching the demand side in the context of development provides both challenges and opportunities arising from impending structural transitions and their opportunities to shape hard and soft infrastructures for the long term. In many cases, demand-side solutions will mitigate the rate of energy-demand growth rather than reduce absolute energy use or GHG emissions. And although emerging economies offer significant low-cost potentials when building new infrastructures and cities, they also face the serious implementation challenges arising from low administrative or institutional capacities.

This review also investigates the specific nature of assessing demand-side solutions. To date, demand-side solutions have been less systematically assessed than the technological supply-side solution space, especially as part of comprehensive cost-effectiveness analysis. The challenge is indeed one of the boundaries of analysis. When investigating supply-side solutions, a rational-choice model with given preferences can be assumed. Demand-side solutions instead often require an understanding of preferences that are endogenously modified, for example, by different infrastructure settings—as has indeed been empirically substantiated. However, assessments then require explicit normative assumptions and a different, contextually richer framework of analysis, which has not yet been firmly established. This is a primary task for future research.

The next IPCC assessment report should, in our view, nonetheless aim to assess demand-side solutions systematically, both with cost-effectiveness frameworks and in the broader frame of behavioral economics.

FUTURE ISSUES

1. A meta-analysis of cost-effective demand-side solutions would be important input for the next IPCC report.
2. The categorization of optimal and/or adequate infrastructure solutions to climate change mitigation in both developed and developing countries would be useful.
3. A comprehensive evaluation of demand-side solutions in broader welfare settings, for example, with an emphasis on subjective well-being and psychological health should be made.
4. Investigators need to study the welfare effects (of demand-side solutions in particular) by relying on the complete portfolio of behavioral economics and making normative choices explicit.

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