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Demand-side approaches for limiting global warming to 1.5 °C

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Abstract The Paris Climate Agreement defined an ambition of limiting global warming to 1.5 °C above preindustrial levels. This has triggered research on stringent emission reduction targets and corresponding mitigation pathways across energy economy and societal systems. Driven by methodological considerations, supply side and carbon dioxide removal options feature prominently in the emerging pathway literature, while much less attention has been given to the role of demand-side approaches. This special issue addresses this gap, and aims to broaden and strengthen the knowledge base in this key research and policy area. This editorial paper synthesizes the special issue's contributions horizontally through three shared themes we identify: policy interventions, demand-side measures, and methodological approaches. The review of articles is supplemented by insights from other relevant literature. Overall, our paper underlines that stringent demand-side policy portfolios are required to drive the pace and direction of deep decarbonization pathways and keep the 1.5 °C target within reach. It confirms that insufficient attention has been paid to demand-side measures, which are found to be inextricably linked to supply-side decarbonization and able to complement supply-side measures. The paper also shows that there is an abundance of demand-side measures to limit warming to 1.5 °C, but it warns that not all of these options are "seen" or captured by current quantitative tools or progress indicators, and some remain insufficiently represented in the current policy discourse. Based on the set of papers presented in the special issue, we conclude that demand-side mitigation in line with the 1.5 °C goal is possible; however, it remains enormously challenging and dependent on both innovative technologies and policies, and behavioral change. Limiting warming to 1.5 °C requires, more than ever, a plurality of methods and integrated behavioral and technology approaches to better support policymaking and resulting policy interventions.

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Introduction

The Paris Climate Agreement set an ambitious target of limiting global warming to 1.5 °C above preindustrial levels. However, national pledges to reduce emissions, so-called Nationally Determined Contributions (NDCs),

are insufficient to meet this goal, meaning wide-reaching policy action is urgently needed (Rogelj et al. 2016a; UNEP 2017). Carbon-budget studies that link cumulative CO_2 emissions to global mean temperature rise clearly show that if the target is to be met, emissions need to peak in the very near term and decline to net zero by mid-century following the implementation of deep decarbonization measures (e.g., Kriegler et al. 2018; Rogelj et al. 2015a). Available emission budgets defined by the 2 °C target were already challenging; the 1.5 °C goal and the lack of rigorous global action has made this all the harder to achieve: with each year that passes, the remaining budget shrinks by another ~ 40 $GtCO_2$ (GCP 2016) (Fig. 1). Although carbon budget estimates remain uncertain, the urgent need for decisive mitigation policies remains (Michaelowa et al. 2018; Millar et al. 2017; Xu and Ramanathan 2017). The challenge set by the Paris Agreement is enormous (Rockström et al. 2016) and requires profound social as well as technological change (Geels et al. 2017; Turnheim et al. 2015). Meeting this ambitious target will need a marked departure from historical rates of change and current policy (Knutti et al. 2016; van Sluisveld et al. 2015). Against this backdrop, there is a vital need for robust scientific research to inform policymakers of mitigation actions across the *entire* energy system, building on NDC commitments.

The current scientific evidence base on long-term system transformation to meet the 1.5 °C ambition is dominated by global scenarios based on Integrated Assessment Models (IAMs),[1] which emphasize supply-side technologies and carbon dioxide removal (CDR) options.[2] From a methodological point of view, an important reason for the dominance of IAMs in the 1.5 °C literature is their unique ability to link mitigation strategies and technology portfolios to cumulative emission budgets and, consequently, warming outcomes. As a result, they have become "gatekeepers" of research in the domain. IAMs outcomes tend to heavily rely on CDR and storage technologies, particularly bioenergy with carbon capture and storage (BECCS) (Clarke et al. 2014; Fuss et al. 2014; Millar et al. 2017; Minx

et al. 2017). These options are even more apparent when energy-intensive and temperature-overshoot pathways are analyzed (Kriegler et al. 2017).

In comparison, demand-side options tend to be neglected in IAMs (Kriegler et al., 2018), even though deep decarbonization pathways rely on low-energy demand or low-energy intensity (Rogelj et al. 2015a). Modeling studies consistently show that demand-side measures play a critical role in meeting ambitious mitigation targets (Clarke et al. 2014; Riahi et al. 2015). Creutzig et al. (2016) argue that a better understanding and integration of demand-side mitigation strategies may help to reduce or remove reliance on large-scale CDR options or (even more controversial) solar radiation management technologies. Moreover, demand-side portfolios have potentially wider benefits and encompass fewer risks than supply-side options: they are closely associated with synergistic co-benefits for health, pollution, security, equity, living standards, and system costs (von Stechow et al. 2016; Ürge-Vorsatz et al. 2016). Furthermore, demand-side options reduce risks by introducing greater flexibility into the choice of energy-system transitions (Lucon et al. 2014). These aspects raise important questions about the options, measures, strategies, sectors, services, timing, and feasibility of demand-side mitigation pathways to limit warming to 1.5 °C. Furthermore, we do not yet fully understand the implications of stringent, demand-side policy instruments in the 1.5 °C context. Emerging literature stresses the importance of demand-side measures and call for substantial new research advances in this area (e.g., on policy issues, modeling, mitigation costs) (Creutzig et al. 2016, 2018; Grubler et al. 2018).

Purpose of the special issue and editorial

The purpose of this special issue is to broaden and strengthen the evidence base on the role of demand-side policies, measures, and corresponding mitigation pathways to limit global warming to 1.5 °C. First, it addresses the knowledge gap regarding how demand-side mitigation options can contribute to achieving the 1.5 °C goal. Second, it aims to raise the profile of demand-side options in the current policy and academic discourse focusing on the 1.5 °C goal. Third, it seeks to bring together diverse research communities through a

[1] Two main types of IAMs are identified in the literature (Weyant 2017): Detailed Process IAMs provide disaggregated and detailed regional and sectoral mitigation analyses, while Cost-Benefit IAMs generate a more aggregated view of impacts and climate mitigation economics by region or sector.

[2] For a detailed review of CDR approaches see Minx et al. (2018).
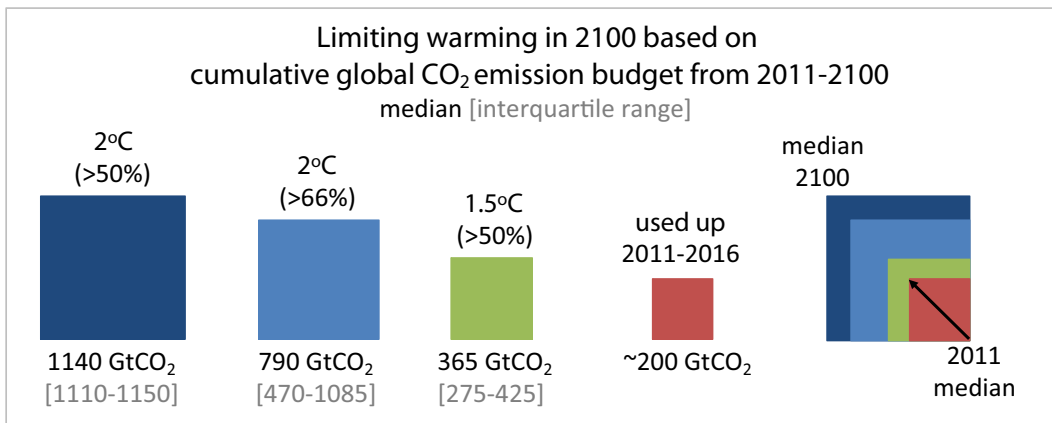
Fig. 1 Cumulative emission budgets for limiting warming to 2 °C and 1.5 °C. Notes: Areas of boxes are proportional to cumulative total CO_2 emission budgets from 2011 to 2100 consistent with limiting warming to 2 °C and 1.5 °C (with 50–66% and >66% probability) based on data from Rogelj et al. (2015b). Historical annual emissions of ~40 $GtCO_2$ from 2011 to 2016 are estimated from GCP (2016). Note that cumulative emission budgets vary depending on the methodology and assumptions (Rogelj et al. 2016b). Budgets for limiting warming to 2 °C given in the IPCC Fifth Assessment Report (Clarke et al. 2014) are slightly higher at 960–1430 $GtCO_2$ (50–66% probability) and 630–1180 $GtCO_2$ (> 66% probability). Budgets for limiting warming to 1.5 °C, reported in Rogelj et al. (2015a) are slightly lower at 200–415 $GtCO_2$ (> 50% probability)

collection of deep decarbonization studies that provide a starting point for cross-disciplinary discussions of demand-side approaches.

Energy Efficiency has consistently addressed climate mitigation and demand-side issues since its inception. The journal provides critical analyses of demand-side issues in the transition to more sustainable energy systems. This special issue is consistent with this practice in bringing together a collection of articles that explore demand-side approaches and address the following research questions: Are deep decarbonization pathways in the transport sector compatible with the 1.5 °C target? How can 1.5 °C pathways be pursued through (radical) changes in household consumption? What is the role of potentially disruptive low-carbon innovation to limit warming to 1.5 °C? What is the gap between national, bottom-up studies, and European (aggregated) 1.5 °C scenarios? Which policy options will encourage deep decarbonization pathways in the building sector? What is the role of the sectoral policies for triggering an immediate peak in global emissions to keep the 1.5 °C target within reach? To what extent can minimum performance standards complement carbon pricing? Will policies to promote energy efficiency help or hinder in achieving the 1.5 °C climate target? What are the impacts of carbon pricing and energy-efficiency policies on electricity supply and demand in the USA? What policy interventions would foster near-zero carbon emissions in the residential heating sector? Taken as a whole, this special issue reflects the emerging knowledge on demand-side options and provides policy-relevant insights to complement the existing IAM literature.

These articles scrutinize a wide variety of demand-side topics that underpin the Paris Agreement and the 1.5 °C discourse. This breadth of vision is very much consistent with *Energy Efficiency*'s philosophy. In this editorial, we introduce the special issue's contributions "horizontally" through three shared themes: policy interventions, demand-side measures, and methodological approaches. For each theme, we summarize the key insights from each article, supplemented by insights from other relevant literature on 1.5 °C mitigation and/or demand-side measures. In the final section, we draw out the lessons learnt and present our concluding thoughts as editors of this special issue.

Stringency and the role of demand-side policies to limit global warming to 1.5 °C

As a whole, the set of papers in this special issue emphasize the importance of ambitious and coordinated policy efforts to drive the speed and direction of a 1.5 °C transition. A wide variety of policy instruments are assessed or modeled. Following the sectoral policy interventions contained in Bruckner et al. (2014), Fischedick et al. (2014), Lucon et al. (2014), and Sims

et al. (2014), we highlight various policy insights that can be derived from the collection of papers as a whole.

Sectoral targets and emission peaks

Ambitious sectoral targets are needed to drive deep decarbonization pathways. Gota et al. (2018) highlight the need to set long term, ambitious sectoral-mitigation targets to decarbonize the transport sector. This includes targets for absolute greenhouse gas (GHG) emission reductions, vehicle CO_2 standards, modal split, technology (e.g., electric vehicles), and renewable energy (e.g., the electrification of transport and the fuel mix). Establishing very ambitious targets for the transport sector is critical to avoid or reduce trips, encourage a change towards highly efficient travel modes, and improve the performance of vehicles and fuels.

Wachsmuth and Duscha (2018) compare reductions in energy and carbon intensities across different end-use sectors, and stress the importance of sectoral mitigation targets, particularly at the national level. They assess target-oriented national scenarios and show that conceivable emission reductions in end-use sectors can be more stringent than aggregated (IAM) scenarios suggest.

Méjean et al. (2018) highlight the importance of global emission peaks across end-use sectors. Their modeling approach assumes a global carbon price to meet emission targets, and the authors highlight that ambitious, near-term sectoral policies are needed to drive rapid decarbonization of the electricity, industrial, and transport sectors. Brown and Li (2018) adopt indicative targets for the US electricity sector—ranging from 14.2 GtCO$_2$ (based on population) to 74.3 GtCO$_2$ (based on GDP)—until 2040, which they then use as a benchmark to analyze the extent to which a combination of carbon pricing and dedicated demand-side policies can contribute to meeting the mitigation target.

Building codes

Several papers argue that stringent building codes are a critical way to implement systems that define minimum technical conditions for energy performance. An implicit and significant assumption in this area is that such codes can be effectively enforced.

In their modeling approach, Brown and Li (2018) assume ambitious state building codes will lead to high-shell thermal efficiencies for single-family homes, apartments, and mobile homes. Similarly, Méjean et al. (2018) highlight the importance of rigorous building standards (including energy labelling) in fostering energy-efficiency improvements and reducing energy demand in the residential sector. Building codes are also addressed by Wachsmuth and Duscha (2018), who demonstrate plausible national emission reductions based on the assumption that both new buildings and retrofits meet the highest available thermal-efficiency standards. Consistent with the available literature (Lucon et al. 2014; Seto et al. 2016; Ürge-Vorsatz et al. 2013), the authors argue that stricter building codes in the near term are a necessary condition to avoid carbon lock-in in the sector. This, in turn, is consistent with Kuramochi et al. (2018) who identify various key benchmarks to limit warming to 1.5 °C, including: higher renovation rates (5% in 2020) and all new builds to be fossil-free and near-zero energy in 2020.

Chen et al. (2018) devote considerable attention to ambitious building codes in their modeling of mitigation pathways for the Chinese building sector. Their approach is based on an annual increase in the efficiency rate of building shells by 1–1.5%. The authors argue that such improvements could be comparable to those studied in Germany. Chen et al. conclude that stringent building codes combined with technology standards and carbon pricing, are critical in achieving energy (and resulting cost) savings in the building sector.

Performance standards

Sonnenschein et al. (2018) offer a new analysis of the important question of whether energy-efficiency standards are necessary if economy-wide carbon pricing is in place. The authors model the effect of "Minimum Energy Performance Standards" (MEPS) on the lifecycle costs of four home appliances including the CO_2 externality. They found that fairly modest MEPS could achieve the same result as the (considerably more stringent) carbon prices that are evident today (e.g., equal to or above 100 US$/tCO$_2$). The authors conclude that MEPS for appliances are a cost-effective, complementary policy to carbon pricing in the long term.

Chen et al. (2018) consider stricter MEPS in various scenarios. The authors assume a 0.75% annual rate of

efficiency improvements for a variety of technologies associated with heating, cooling, lighting, cooking, and hot water services. Combined with a carbon tax, they find that more ambitious performance standards are central to triggering deep decarbonization pathways in the Chinese building sector. The authors conclude that national performance standards should be significantly improved. Similarly, in the transport sector, Wachsmuth and Duscha (2018) and Gota et al. (2018) highlight that stringent fuel-efficiency standards should be put in place to lay the foundations for a meaningfully contribution to the 1.5 °C goal.

Behavioral policies

As mitigation pathways require both technical and social change, both dimensions must be addressed in combination (Eyre et al., 2018). While most of the 1.5 °C literature has focused on technology policy and the need to address market failures, growing attention is being given to behavioral anomalies (e.g. heuristics, limited attention) and the need to address them with (innovative) policy interventions (e.g. Bager and Mundaca 2017; Frederiks et al. 2015; Gillingham and Palmer 2014; Pichert and Katsikopoulos 2008).

Sonnenschein et al. (2018) argue that, in addition to performance standards and carbon pricing, further (mixes of) policy interventions that address behavioral anomalies should be studied (e.g., labelling programs, green defaults). Likewise, Gota et al. (2018) stress that current mitigation measures rely heavily on assumptions of behavioral change. Knobloch et al. (2018) find that the potential impacts of modeled policy instruments are highly dependent on assumptions of behavioral decision-making (cf. Kolstad et al. 2014; Mundaca et al. 2010; Worrell et al. 2004). The authors argue that a failure to acknowledge behavioral issues (e.g., bounded rationality) in modeling can lead to misguided policy recommendations and thus misleading outcomes. Consistent with the literature addressing demand-side issues in the domain of climate mitigation (Creutzig et al. 2016; Lucon et al. 2014; Sims et al. 2014), Gota et al. underline that not only do optimistic mitigation scenarios require greater behavioral change but also that mitigation potential due to behavioral options may be higher than is often assumed in modeling studies (see also Creutzig 2016). In line with the literature that addresses human behavior, climate mitigation, and modeling tools (e.g.,

Jochem et al. 2000; McCollum et al. 2017; Mundaca et al. 2010), the papers in the special issue implicitly (or explicitly) acknowledge the challenges associated with the parameterization of behavioral change in modeling tools.

Moberg et al. (2018) devote considerable attention to behavior and policy. Analyzing different end-use segments across four European countries in a deep decarbonization context, the authors conclude that existing behavioral-oriented policies that address consumption are limited and rely heavily on self-governance and nudging. They stress that voluntary options are insufficient and that only "forced" policy scenarios will lead to necessary lifestyle changes. Their results show that individuals are willing to embrace climate responsibility; however, (further) policy interventions—beyond economic incentives—are needed to encourage behavioral change. The authors conclude that there is high potential for regulatory approaches targeted at high emission domains (e.g., mobility and food).

Carbon pricing and complementary policies

Carbon pricing mechanisms (cap-and-trade schemes or carbon taxes) are often cited as a key part of the policy mix in 1.5 °C (or 2 °C) mitigation pathways (e.g., Bertram et al. 2015; Riahi et al. 2017; Rogelj et al. 2018; Rogelj et al. 2013; Stiglitz et al. 2017). In this particular case, stringent policy takes the form of carbon prices that are considerably higher than today. For example, in the building sector, Chen et al. (2018) model an economy-wide carbon tax ranging from 70 US$/$tCO_2$ in 2020, 300 US$/$tCO_2$ in 2050 to 1265 US$/$tCO_2$ in 2100. Combined with other policy assumptions related to ambitious minimum performance standards and building codes, the tax regime accelerates the implementation of mitigation measures, both on the supply side and in the building sector. The authors conclude that a combination of carbon pricing and technology-oriented policies is needed if the Chinese building sector is to meet the 1.5 °C goal.

Méjean et al. (2018) model emission constraints and corresponding peaks based on a uniform carbon price, ranging from nearly 150 US$/$tCO_2$ to 450 US$/$tCO_2$ in 2030. Results show that higher carbon prices are required in high-energy demand scenarios (e.g., ~360 US$/$tCO_2$ in 2030) than low-energy

demand scenarios (e.g., ~ 250 US$/tCO$_2$ in 2030). High-energy demand scenarios are characterized by slow energy-efficiency improvements in end-use sectors and energy-intensive lifestyles. On the other hand, and especially when combined with sector-specific demand-side management policies, the level of carbon pricing that is required to reach the temperature target is reduced by between 25 and 50% in 2030. The authors stress that their model implies a relatively limited set of mitigation technologies compared to other IAMs. Thus, the carbon price needed to meet a given mitigation goal is higher than in other IAMs, which implies higher mitigation costs.

Modeling deep decarbonization pathways in the residential heating sector, Knobloch et al. (2018) use a sectoral carbon tax to drive mitigation measures. In this case, a carbon tax increases the price of fossil fuels relative to their carbon content. Different scenarios are modeled using a tax in the range of 50 US$/tCO$_2$ to 100 US$/tCO$_2$ in 2020 and from 200 US$/tCO$_2$ to 400 US$/tCO$_2$ in 2050. Carbon taxes are either implemented in isolation or combined with technology subsidies, a procurement scheme and building codes. Their results show that it is this combination of policies that is most effective in driving market uptake of fuel-efficient low-carbon technologies.

Brown and Li (2018) analyze mitigation scenarios based on a carbon tax in the US electricity sector, either implemented in isolation or combined with other policies (e.g., MEPS). Carbon prices are relatively lower than those modeled by Chen et al. and Méjean et al. and range from 10 US$/tCO$_2$, 20 US$/tCO$_2$, and 40 US$/tCO$_2$ in 2020 to 26 US$/tCO$_2$, 53 US$/tCO$_2$, and 59 US$/tCO$_2$ in 2040. Results show that a mix of energy-efficiency policies and a carbon tax that increases from 10 US$/tCO$_2$ in 2020 to 27 US$/tCO$_2$ in 2040 delivers net savings. Interestingly, a higher tax (ranging from 20 US$/tCO$_2$ in 2020 to 53 US$/tCO$_2$ in 2040) is shown to deliver the same emission reductions and keep the sector within the 1.5 °C target; however costs are much higher in the absence of complementary demand-side policies. This emphasizes that increased energy efficiency (or lower energy intensity) reduces mitigation costs (Grubler et al. 2018; Luderer et al. 2013; Riahi et al. 2015; Rogelj et al. 2013).

The modeled or optimal carbon prices presented in this special issue need to be compared with real-life observations. In 2016, nearly 15% of global GHG emissions were priced directly via a tax or emissions trading system (ETS) (World Bank et al. 2017). However, almost three quarters of emissions currently addressed by carbon pricing mechanisms are below 10 US$/tCO$_2$ (World Bank et al. 2017), which is significantly lower than pricing levels consistent with the Paris Climate Agreement: 15–360 UStCO_{2-eq}$ in 2030, 45–1000 UStCO_{2-eq}$ in 2050, and 140–8300US$/tCO$_{2-eq}$ in 2100 (Stiglitz et al. 2017). Wachsmuth and Duscha (2018) conclude that the European Union's ETS is very unlikely to provide the economic incentives for decarbonizing the industrial sector unless substantial reforms are undertaken. The authors argue that although the ETS innovation fund[3] may offer better incentives, complementary demand-side policies are still urgently needed across end-use sectors.

Coordinated and effective policy mixes

Finally, ambitious policies often take the form of increasing the stringency of existing measures while simultaneously implementing new, bold interventions. This process needs to be coordinated, and policy evaluation is crucial. In addition to the implementation of carbon pricing alongside demand-side policies, various papers underline the need for comprehensive and integrated policy mixes.

Analyzing emission peaks and dynamics across various sectors, Méjean et al. (2018) discuss low-energy demand scenarios in terms of making current policy instruments (e.g., building codes, standards) more stringent, while at the same time implementing novel regulatory and market-based interventions (e.g., financial products for retrofits, aggressive investment in public transport, incentives for teleworking)—in addition to carbon pricing. Policy-driven scenarios show that a rich mix of stringent sectoral policies, particularly for transport and industry, are critically needed in the near term. The authors conclude that this approach helps to lower energy demand and reduce the level of carbon pricing needed to meet the temperature target. Similarly, Chen et al. (2018) highlight the need for a coordinated policy mix, comprising a carbon tax, ambitious building codes, and stricter technology standards to drive deep

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[3] For further information see https://ec.europa.eu/clima/events/articles/0115_en

decarbonization pathways in the Chinese building sector. Moberg et al. (2018) conclude that a policy mix that goes beyond market-based incentives and voluntary agreements is more likely to drive deep decarbonization pathways across various end-use segments. The authors stress the need for command-and-control policy initiatives to drive behavioral change and sustainable consumption patterns.

Wachsmuth and Duscha (2018) show that national mitigation scenarios based on bottom-up exercises open up opportunities for carbon emission reductions in end-use sectors that are more stringent than those observed in more aggregated scenarios. From a policy perspective, the authors conclude that emissions can be reduced by targeting specific areas, namely sufficiency, energy efficiency, electrification, and fuel switching. In line with other studies (e.g., Darby 2007; Princen 2003), they argue that sufficiency in energy services in the building sector can be addressed via stringent building codes (e.g., that can approximate passive house standards), retrofitting targets, MEPS, energy use quotas, or progressive electricity tariffs (cf. Wilhite and Norgard 2004).

Knobloch et al. (2018) explore policy mixes and their interactions. Carbon taxes, technology subsidies, a procurement scheme, and building codes are explored in a variety of scenarios. Assuming coordinated and effective policy efforts, the results show that policy mixes are more effective than carbon taxes in isolation to drive the nearly full decarbonization of the residential-heating segment. Modeling outcomes show that carbon taxes (from 50 to 200 UStCO_{2\text{-eq}}^{-1}$) combined with subsidies and renewable energy procurement policies can trigger mitigation measures that deliver near-complete decarbonization.

In contrast to calls for stringent and coordinated policy mixes, Patt et al. (2018) argue that demand-side policies (and measures) could compete with decarbonization measures. In their "thought experiment," the authors argue that the limited political capital for tackling climate change may be used up by energy-efficiency policies—at the expense of policy support for renewables and other decarbonization measures. They also argue that investments in energy efficiency may crowd out investments in the supply of low-carbon energy, as both are capital intensive and compete for the same, limited, pool of finance. Moreover, renewables offer increasingly cost-effective

abatement opportunities due to learning effects, while the marginal abatement in the cost of energy-efficiency measures may be lost once the low-hanging fruits are picked. Patt et al. (2018) conclude that these political, institutional, and investment barriers to rapid decarbonization—if they materialize in practice—could mean that demand-side measures do not contribute as much to the 1.5 °C mitigation target as the other empirical, analytical, and modeling studies presented in this special issue suggest.

Sectoral decarbonization pathways and corresponding measures

This section provides a crosscutting or horizontal overview of the demand-side measures resulting from the policy interventions described in the "Stringency and the role of demand-side policies to limit global warming to 1.5 °C" section. This overview is grouped by end-use sector. Where relevant, it includes energy supply issues. To frame the discussion, we follow the IPCC (Working Group III) definition of (sectoral) measures, understood as "technologies, processes or practices that contribute to mitigation, for example [energy efficiency measures], renewable energy (RE) technologies, waste minimization processes, [and] public transport commuting practices" (Allwood et al. 2014, p. 1266).

Buildings

The articles that analyze demand-side measures in the buildings sector stress the critical need for rapid improvements in energy efficiency if the 1.5 °C target is to remain viable. Consistent with previous IPCC Assessment Reports (Levine et al. 2007; Lucon et al. 2014), their findings confirm the value of several mitigation measures and opportunities.

Méjean et al. (2018) analyze global emission peaks intended to meet the 1.5 °C goal and the resulting dynamics across various sectors, including the residential sector. First, they show that a post-2030 peak makes the 1.5 °C goal unachievable but, if it is reached earlier (in 2020), direct emissions in the residential sector peak at nearly the same time. This finding indicates the need for a high degree of policy coordination between international climate policy and specific sectoral interventions. From a global perspective, the study finds that the residential sector

contributes relatively less to an earlier peak than others. However, these results are sensitive to assumptions about energy-demand patterns and corresponding policies, which critically affect the timing of peaks.

Wachsmuth and Duscha (2018) analyze the feasibility of 1.5 °C and 2° targets under various mitigation scenarios for the European Union (EU) and European countries. In the building sector, national scenarios (e.g., France, Germany, Italy) show deep decarbonization pathways resulting in emission reductions ranging from 94 to 100% in 2050. Using a decomposition analysis, the authors reveal a substantial difference between these national scenarios and an aggregated IAM scenario, which only finds reductions of up to 46%. They attribute this gap to the reduced contribution of per capita energy use to emission reductions in the IAM. In contrast, in national scenarios these contributions are the result of moderate lifestyles changes and higher levels of energy efficiency. The study also finds evidence of a gap between national scenarios and an aggregated EU bottom-up scenario, which indicates reductions up to 85%. However, the fact that this gap is considerably smaller than the IAM scenario, illustrates the more detailed analytical potential of bottom-up approaches (Lucon et al. 2014). National deep-decarbonization scenarios include a high level of electrification in energy end-use across the building sector, a reduction in fossil carbon intensity due to a shift to natural gas, a slow increase in house size (per capita m^2), and highly efficient appliances and lighting. Stringent thermal standards for both new buildings and retrofits also play a critical role.

Chen et al. (2018) analyze the implications of the 1.5 °C target for the building sector in China. Policy-driven scenarios show that direct emissions need to peak before 2030 and the sector must approach net-zero emissions by the end of the century. Key measures facilitating the transition include massive efficiency improvements in building shells, together with space heating and cooling. Other contributions include much slower growth in energy demand and an increase in the supply of decarbonized power.

Wilson et al. (2018) focus on the building sector in cities in the UK and identify various potentially disruptive innovations, which are grouped into three generic strategies: (a) interconnectivity for optimized usage (e.g., smart appliances), (b) improved thermal performance (e.g., smart heating controls), and (c) reduced demand for space and materials (e.g., flexible use or shared space). Innovations that are perceived by experts to be both disruptive and emissions reducing include home energy-management systems (HEMS), the internet of things, and LED lighting with smart controls. Two innovations are analyzed in detail to explore potential annual reductions. Estimates range from 0.1 MtCO$_{2-eq}$ (for smart appliances) to 2.6 MtCO$_{2-eq}$ (for smart heating controls). The authors argue that these estimates are conservative, and further research is needed regarding the potential contribution of HEMS and other disruptive innovations to the 1.5 °C goal.

Brown and Li (2018) model mitigation pathways in the USA electricity sector (upstream), which result in significant efficiency improvements in the building sector (downstream). Policy-driven measures include highly efficient air conditioners, refrigerators, freezers, geothermal heat pumps, electric water heaters, dishwashers, air source heat pumps, and gas and electric clothes dryers. Assuming stringent building codes, shell-thermal efficiencies in single-family homes, apartments, and mobile homes also play a key role in emission reductions consistent with the 1.5 °C goal.

Knobloch et al. (2018) focus on deep decarbonization pathways for residential heating. Their results show that near-zero decarbonization in 2050 is feasible, provided that stringent, integrated policy frameworks are put in place. The study highlights the critical importance of high-thermal insulation for new houses, extensive retrofitting of existing buildings, and the expansion of small-scale renewable energy technologies. Technology portfolios feature a move away from fossil fuel technologies. The rapid deployment of ground source heat pumps, solar thermal and modern biomass is a feature of all stringent mitigation pathways. An important assumption underlying the study's results is that the residential sector converges to an average heating intensity (e.g., 45 kJ per m^2 per heating degree day by 2050 under "rapid retrofitting"). The authors also note that their technology choice decision framework relies upon specific behavioral characteristics.

Transport and mobility

Transport, as an end-use sector, has often been seen as "hard-to-decarbonize", with a high degree of lock-in to

fossil fuel-powered private vehicles (Creutzig et al., 2015). Several articles in this special issue challenge these findings and identify a range of approaches for deep decarbonization. Wachsmuth and Duscha (2018) analyze mitigation scenarios and show that emission reductions of 90–100% are possible by 2050 in various national scenarios (e.g., France, Germany, the UK). Their decomposition analysis indicates that carbon emissions in national scenarios are much lower than those projected by aggregated EU scenarios based on bottom-up or an IAM. Reasons for this difference include, for example, the higher resolution of transport activity, the greater diffusion of electric vehicles, and the larger share of biofuels. Specific mitigation measures characterizing national pathways include, for instance, the electrification of the sector (including electrically driven heavy-duty vehicles via trolley tracks), marked modal shifts, and the use of biofuels or synthetic fuels.

From a global perspective, Méjean et al. (2018) also identify clear decarbonization pathways for the transport sector. Bringing forward the global emission peak from 2025 to the present results in an earlier peak in the transportation sector. This reduces peak emissions by around 2 $GtCO_2$ and the stringency and pace of decarbonization efforts (after the peak). However, unlike other sectors, their findings reveal that a global emissions peak in 2020 could lead to a relatively late peak in direct emissions (around 2035) in the transport sector. This is mostly driven by lock-in effects due to existing infrastructure, suboptimal urban planning, and the coupling of GDP growth with demand for mobility. On the other hand, emissions decrease at a faster rate than other end-use sectors after the global peak. The authors acknowledge that further studies are needed to better understand these trends.

Gota et al. (2018) provide an extensive analysis of deep decarbonization pathways in the transport sector. Their review covers up to 1500 low-carbon measures in 81 countries, which are grouped into three main categories: (a) "avoid" measures that aim to decrease the need for transport trips, (b) "shift" measures that aim to move trips to more efficient modes, and (c) "improve" measures that aim to increase the fuel efficiency of vehicles. Their study reveals that two thirds of these measures address fuel efficiency or decarbonization, while nearly one third address changes in travel behavior. Using three low-carbon scenarios (conservative, optimistic, and average) the authors show that an optimistic scenario (stringent, intensive measures in the near term,

continuing until 2050) can decrease emission levels to 2.5 $GtCO_2$. In this scenario, the transport sector meets the indicative 2 °C target, and puts it very close to a sectoral 1.5 °C goal.

Wilson et al. (2018) explore the role of potentially disruptive innovations in passenger mobility and consider four generic strategies: (a) alternative fuel or vehicle technologies (e.g., electric vehicles), (b) alternative forms of auto-mobility (e.g., car clubs), (c) alternatives to auto-mobility (e.g., mobility-as-a-service), and (d) reduced demand for mobility (e.g., telecommuting). Innovations in all four categories include both business model and technological innovations. The authors find that mobility-as-a-service and electric vehicles are relatively more disruptive. Estimated annual emission reductions for the UK range from a lower bound of 0.04 $MtCO_{2\text{-eq}}$ (for e-bikes) to an upper bound of 0.9 $MtCO_{2\text{-eq}}$ (for car clubs). Consistent with other studies in this special issue, Wilson et al. highlight the potential for mobility-related measures to deliver significant emission reductions.

Industry

Brown and Li (2018) study the situation in the USA, and model many highly efficient measures within the industrial sector. Such measures include combined heat and power, electric motors, and specific measures to reduce energy use by 2030 in bulk chemicals (18%), cement and refining (23%), pulp and paper (40%), and iron and steel (57%) subsectors.

Like the building and transport sectors, Wachsmuth and Duscha (2018) find deeper decarbonization pathways in national scenarios than aggregated EU scenarios. In national scenarios, emission reductions by 2050 range from 93 to 103%, compared to 61% (in IMAGE) or 74% (in PRIMES). Their decomposition reveals that low per capita energy use, high electrification, resource efficiency, and increased penetration of renewable energy fuels (biomass and biogas) all play an important role in decarbonized national scenarios. Reductions in per capita energy use are partially driven by improvements in the manufacturing of energy-intensive products (e.g., the substitution of cement clinker by cleaner alternatives, and recycling in the iron and steel and aluminum subsectors).

Méjean et al. (2018) emphasize the need for industry to implement robust mitigation measures in the near term if the 1.5 °C goal is to be achieved. Like the

residential sector, their results show that if a global emission peak is reached in 2020, direct emissions in the industrial sector peak at nearly the same time. Like the transport sector, an earlier global peak (very close to the present time) reduces both peak industrial emissions (by approximately 2 $GtCO_2$, from 10 to 8 $GtCO_2$) and the pace of decarbonization efforts after the peak. The authors acknowledge that their results are sensitive to assumptions about high- or low-energy demand. Under low-energy demand, short-term emission reductions are high due to rapid improvements in energy efficiency, which, in turn, delay emission peaks in other sectors (such as transport).

Food and dietary choices

The importance of food consumption and dietary choices in climate mitigation has been clearly identified in the literature (see e.g., Hedenus et al. 2014; Weindl et al. 2017; Wynes and Nicholas 2017). Two articles in this special issue consider food-related measures and resulting emissions. Moberg et al. (2018) identify significant potential for emission reductions based on a so-called sustainable diet, which encompasses an increase in organic, locally produced foods combined with a vegetarian diet. Wilson et al. (2018) identify various disruptive innovations related to food, grouped into four strategies: (a) alternative dietary preferences (e.g., reduced meat consumption), (b) urban food production (e.g., vertical farming), (c) producer–consumer relationships (e.g., food-link schemes), and (d) reduced demand for food (e.g., food-waste reduction). Scaling up evidence of emission reductions from early adopters to similar segments of the UK population, they conservatively estimate that consumer-related innovations could reduce direct and indirect emissions in the agriculture sector by up to 7.1%.

Supply side and distribution

Various papers analyze the link between end-use sectors and supply. Confirming findings from other whole-system analyses of 1.5 °C mitigation, Méjean et al. (2018) conclude that an early peak in global emissions entails accelerated emission reductions in demand sectors together with the rapid decarbonization of the electricity sector.

Wachsmuth and Duscha (2018) analyze energy supply in the context of indirect carbon emissions that are excluded from end-use sectoral analyses at the national level, and reveal interdependencies between electricity demand and supply. The authors argue that across the EU, and in selected European countries, there is a critical need for a greater share of renewable energy sources in the supply mix, which is identified as an important complement to demand-side efforts. Their analysis shows that energy-use reductions make a greater contribution to emission reductions in national (bottom-up) scenarios than international or EU mitigation pathways. One important reason for this is the exclusion of carbon capture and storage (CCS) measures in national scenarios, which means that demand-side options reach their technical limits in deep decarbonization pathways. At the same time, the authors acknowledge that national scenarios only consider mitigation options close to their market maturity.

Similarly Chen et al. (2018) emphasize the need for accelerated low-carbon electrification in the construction sector in rural and urban areas of China. A common element is the phasing out of traditional fossil fuels (coal and petroleum). In rural areas, traditional biomass is completely replaced by modern fuels in two or three decades and, under a 1.5 °C scenario, the fuel mix is nearly identical to that of urban residential areas. The authors also find that fossil fuel-based district heating is displaced by geothermal heating. Solar energy overtakes natural gas and plays a major role in the hot water and heating segments. Despite these far-reaching changes, the authors stress that their projected increases in solar and geothermal energy are still lower than indicative national targets.

Knobloch et al. (2018) also stress the links between demand and supply. For instance, improved building shells combined with solar thermal and ground source heat pumps are shown to considerably reduce electricity demand (by up to 50% in certain scenarios). However, scenarios that envisage the complete electrification of residential heating would require substantial additional capacity, equivalent to nearly half of currently installed global-power capacity. In addition, the full electrification of the heating sector results in indirect emissions that cancel out up to 80% of direct CO_2 reductions. These results strongly suggest that the direct electrification of the heating sector might be ineffective and expensive compared to more efficient, cost-effective alternatives.

Wilson et al. (2018) analyze various potentially disruptive innovations that lie at the interface between end-

users and energy supply. These are categorized as follows: (a) new service providers (e.g., energy aggregators, such as when municipalities or market intermediaries enable energy users to collectively bargain for low-carbon investments), (b) the integration of consumers into grids (e.g., time-of-use pricing), and (c) decentralized energy supply (e.g., community energy, peer-to-peer electricity trading). In line with the literature that explores potential conflicts between business models, centralized supply systems, and energy efficiency (see e.g., Bachrach et al. 2004; Blumstein et al. 2005; Eyre 1997), Wilson et al. underline that consumers might become less passive and move towards the active production, organization, and management of small-scale energy systems. This development is a potentially disruptive threat to the core business of centralized networks and utilities.

Brown and Li (2018) highlight synergies between stringent energy-efficiency policies across end-use sectors, and a carbon tax in the power sector designed to shift the fuel mix away from coal and towards wind and solar. They argue that emission reductions and slower growth in electricity demand are key elements in stringent mitigation pathways. On the demand side, increased energy efficiency can also decrease investment in installed capacity and fuel expenses, which in turn significantly lowers utility resource costs.

Methodological approaches

This section explores the different methodological approaches referred to in this special issue, including their strengths and limitations. As stated earlier, a significant challenge for the analysis or evaluation of demand-side policies and mitigation pathways concerns the existence of robust, consistent links with the temperature target. In this respect, the choice of analytical tools and methodological approaches is of prime importance. Despite inherent uncertainties, complexities, and caveats, the papers in this special issue map out various analytical avenues that can complement or strengthen existing knowledge. They are grouped into four main categories.

System modeling (including IAMs)

As noted in the introduction, global integrated assessment model (IAM) analyses of 1.5 °C mitigation pathways emphasize the importance of demand-side measures.

Some IAMs specialize in developing a detailed representation of end-use technologies (Hibino et al. 2003). Other IAMs run specific studies in which model variants with more demand-use detail are developed to answer specific research questions (McCollum et al. 2017). But it is neither possible nor desirable for IAMs to capture the full richness of demand-side approaches to mitigation. Modelers face a trade-off between elaboration and elegance (Held 2005): increased complexity can reduce transparency and interpretability. This is necessarily so for parsimonious and tractable models trying to capture the entire global energy and land-use systems.

As a result, the resolution of demand-side technologies and measures in global IAMs is generally quite coarse. Particularly in models from a macroeconomic tradition, sectoral energy demand is given as a function of income growth based on historical calibrations. In other words, energy demand in future scenarios is commonly defined exogenously based on assumed GDP growth and parameterized income elasticities (together with limited responsiveness to changing energy prices). This leaves little scope for exploring demand-side strategies that could rapidly and dramatically reduce emissions. Ultimately, global IAMs can try to capture stringent demand-side approaches to mitigation in four broad ways: endogenously or exogenously; and explicitly or implicitly. Table 1 summarizes this 2×2 grid and gives an example of each combination. Exogenous representations are derived from scenario narratives or storylines, which IAMs interpret quantitatively.[4]

As an example, the potential for demand reduction is analyzed under the awkward rubric of "lifestyle change," which—in model speak—conflates arbitrarily selected behavioral changes with assumed shifts in social norms and institutions. Lifestyle change is hard to model endogenously in global IAMs; but it is also hard to parameterize or quantify by mapping storylines to model inputs and assumptions (Schwanitz 2013). Nevertheless, some IAM studies do specifically set out to analyze the system outcomes of lifestyle change. As an example, van Sluisveld et al. (2015) find that assumed reductions in demand for heating, cooling, residential floorspace, appliance ownership, and private vehicle use can reduce global CO_2 emissions by up to 35% by

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[4] A coherent and internally consistent storyline is what distinguishes a scenario from a model (where inputs and parameters are set or varied to test behavior or answer a specific research question).

Table 1 Ways of analyzing demand-side approaches in global IAMs. Note: Arrow from top left to bottom right shows direction of improved "resolution" of energy end-use

	Implicit (represented as being part of a more general process or phenomenon)	Explicit (represented as a discrete, identifiable process or phenomenon)
Exogenous (externally specified)	Feature of scenario narrative interpreted into modelling assumptions (or used to interpret modelling results *ex post*) *e.g., rising GDP drives rising demand for energy services (Bauer et al. 2017)*	Feature of scenario narrative mapped into specific model input or parameter *e.g., strong policy and innovation emphasis on reducing transport-sector emissions implies a high learning rate for alternative fuel vehicles and so costs reduce rapidly as a function of experience (McCollum et al. 2016)*
Endogenous (internally generated)	General relationship between energy end-use and internal model variables but without resolving specific causal mechanisms *e.g., stringent climate policy implemented as a high carbon price increases the cost of energy carriers and so reduces demand through parameterised price elasticity (Pye et al. 2014)*	Specific relationship between determinant of energy end-use and internal model variables based on a specific causal mechanism *e.g., social influence effects reduce perceived risk of alternative fuel vehicles and so accelerate adoption rates by making lifecycle costs more competitive with conventional vehicles (Pettifor et al. 2017)*

2050. But such studies tend to lack an underlying narrative that can explain why lifestyles are changing in the first place (Geels et al. 2016).

In sum, global IAMs have significant limitations. First, they tend to be anchored on currently available mitigation options, particularly on the energy supply (although BECCS is a notable exception). Second, they tend to have relatively aggregated representations of energy end-use technologies and the contexts in which they are deployed, and so have limited capacity to analyze energy-demand transformation or the emergence of novelty in energy services. Third, they do not capture the broad range of socio-technical energy demand drivers, such as social norms, culture, institutions, and lifestyles (Schwanitz 2013). Consequently, insights from IAM analyses are increasingly limited by the failure to reflect the rapid, real-world transformations that lie outside the scope of a tractable model (Geels et al. 2016).

Two articles in this special issue build on this basic insight and aim to provide a better understanding of the implications of 1.5 °C mitigation pathways at the sectoral level. Méjean et al. (2018) apply the IMACLIM-R model to assess the worldwide transition across demand sectors (transport, residential,

industry). The authors analyze global emission peaks, and the pace and dynamics of deep decarbonization pathways. They find that in the short term, ambitious demand-side policies are crucial in supporting a global emission peak and maintaining the likelihood of meeting the 1.5 °C goal. From a national perspective, Chen et al. (2018) apply an IAM (the GCAM-TU) to the building sector in China. Both studies confirm the high degree of uncertainty about future energy use, which is often driven by complex relationships between economic development, technological progress, population growth, behavioral patterns, and policy assumptions (cf. Kriegler et al. 2014; O'Neill et al. 2017; Riahi et al. 2017).

It is important to acknowledge the findings of an earlier paper using two IAMs (MESSAGE and REMIND) to explore a range of 1.5 °C scenarios: "in line with what was found for 2°C [...] targeted measures to stimulate energy-efficiency improvements are a key enabling factor for achieving a 1.5°C target" (Rogelj et al. 2015a, p. 523). Subsequent analysis using six IAMs and the "Shared Socioeconomic Pathway" (SSP) scenario framework used in the IPCC reinforced this earlier finding. By adding stringent climate policy assumptions to

each of the five SSP[5] baseline scenarios, a range of 1.5 °C mitigation pathways were identified (Rogelj et al. 2018). All such pathways were found to strongly limit energy-demand growth, although the study also found that: "Energy conservation is a common strategy in stringent mitigation scenarios, but it also has limits" (Rogelj et al. 2018, p. 327). These limits refer to the need for full decarbonization of the energy supply to reach net-zero emissions around 2050 or soon thereafter.

A recent IAM study posed the question: Can the 1.5 °C target be met without relying on BECCS, or indeed, any CCS? The study found that it can, but only by unprecedented transformation of end-use services to reduce total global energy demand by around 40% from 2020 to 2050 (Grubler et al. 2018). Importantly, although this study used a global IAM to quantify the optimal energy supply mix, the analysis of energy-demand reduction potentials was done "off model" using bottom-up estimations of activity levels and energy intensity for each energy service and end-use sector. This methodological innovation was necessary to overcome the inherently limited endogenous representation of energy demand in the IAM.

Decomposition analyses

Decomposition approaches are also used to explore the challenges and implications of meeting the 1.5 °C mitigation target. Departing from, or building upon, the IPAT equation (Ehrlich and Holdren 1971; Holdren & Ehrlich 1974), the Kaya Identity (Yamaji et al. 1991) or the Logarithmic Mean Divisa Index (Ang and Zhang 2000), studies that apply a decomposition approach pay particular attention to changing energy and carbon intensities as critical drivers of CO_2 emission reductions.

Patt et al. (2018) reflect on the potential competition between policies and investments in energy efficiency on the one hand, and clean energy technology on the other. As part of this "thought experiment" and assuming carbon budgets consistent with a 1.5 °C target, the authors use the Kaya Identity to assess substitution rates between improvements in energy intensity and carbon intensity from initial values of 1.6 kWh per US$ and 300 gCO_2 per kWh respectively. Like many Kaya Identity analyses, they do not consider policies designed to reduce population or economic growth. Based on several, highly stylized, assumptions regarding learning, diffusion, and abatement costs, Patt et al. argue that substantial and unprecedented energy-efficiency improvements may have only marginal effects given the timeframe needed to decarbonize the energy supply.

Wachsmuth and Duscha (2018) use an index decomposition analysis (IDA) to analyze and compare reductions in energy and carbon intensities in various stringent mitigation scenarios applied to the EU and selected European countries. Their approach evaluates ambitious bottom-up scenarios for France, Germany, Italy, and the UK, and estimates sectoral mitigation rates, and assesses them against European scenarios contained in global 1.5 °C (or 2 °C) mitigation pathways. The use of IDA helps to understand the development of sectoral energy and carbon intensities and reveals the gap between national bottom-up studies on the one hand, and European and IAM scenarios generated by the PRIMES and IMAGE models respectively.

Like any methodology, decomposition approaches have their limitations. Concerns about collinearity, causality, and the reliability of significance statistics (p values) have been stressed in the literature on the drivers of CO_2 emissions (Mundaca and Markandya 2016; Raupach et al. 2007). In addition, an IDA becomes mathematically complicated if the dataset includes zero values (Ang and Zhang 2000). As Wachsmuth and Duscha correctly point out, this can be an important issue in CCS scenarios where zero or negative carbon intensity values are possible. Furthermore, Wachsmuth and Duscha underline the intricacies of carbon and energy intensities in a 1.5 °C context: the approximation of independence of these intensities is valid for marginal changes, while variation in 1.5 °C mitigation pathways is considerable. It is also important to take into account sectoral specificities regarding the (in)dependence of energy and carbon intensities. Wachsmuth and Duscha note that the assumption of independence may not hold—even in the short term. For example, priority dispatch rules in markets may mean that lower electricity demand may not reduce the use of renewably generated electricity.

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[5] The Shared Socioeconomic Pathways (SSP) framework "provides a basis of internally consistent socio-economic assumptions that represent development along five distinct storylines: development under a green-growth paradigm (SSP1); a middle-of-the-road development along historical patterns (SSP2); a regionally heterogeneous development (SSP3); a development that results in both geographical and social inequalities (SSP4); and a development path that is dominated by high energy demand supplied by extensive fossil-fuel use (SSP5)" (Rogelj et al. 2018, p. 325).

Bottom-up approaches

In this special issue, we define "bottom-up" approaches in broad terms, as disaggregated characterizations and analyses (including quantitative modeling) of end-use sectors, services, or technologies that aim to provide policy-relevant knowledge. By their nature, these bottom-up approaches are less concerned with systemic effects (e.g., on the energy supply or wider macroeconomy effects) than IAMs.

Gota et al. (2018) use a bottom-up approach to analyze the extent to which the transport sector can meet a sector-specific mitigation goal consistent with the 1.5 °C target. Relying extensively on available mitigation studies, the authors first translate the 1.5 °C target to an indicative 2050 sectoral target (equivalent to 2 GtCO$_2$). They then compare this target with mitigation potentials resulting from the aggregation of bottom-up estimates, including comparisons with IAM scenarios. Finally, they compare the sectoral target with low-carbon scenarios that are aggregated at national and global levels. Their evaluation is based on a metanalysis comprising over 500 bottom-up modeling estimates from 81 countries that account for nearly 92% of global transport emissions. The authors acknowledge that there is a high degree of uncertainty in the transport-mitigation potential and emphasize that their results must be taken with due caution. A key area of improvement for comparative studies lies in the consistency of key assumptions (e.g., growth in transport demand) and the inclusion of wider mitigation measures, notably those that address behavioral change.

Brown and Li (2018) use the National Energy Modeling System (NEMS) model. The authors combine NEMS with various policy-driven scenarios and an indicative 1.5 °C target for the US electric sector. The target is derived in three steps: (a) the adoption of a global carbon budget consistent with a 1.5 °C goal, following estimates presented in Millar et al. (2017), (b) the estimation of a national 1.5 °C carbon budget as a percentage of the global carbon target based on GDP and population, and (c) the determination of a 1.5 °C target for the electricity sector as a percentage of total US emissions generated by the overall power sector in 2016. An important methodological element lies in the type of foresight used in the model. Future price increases are based on the assumption that utilities consistently engage in integrated resource planning to meet least-cost operations resulting from future policies (see also Hourcade et al. 2006; Mundaca et al. 2010; Worrell et al. 2004). This drives carbon emission and electricity-demand reductions ahead of policy implementation. The paper notes two important limitations. One relates to the timeframe of the analysis (until 2040) and the potential underestimation of mitigation costs if they are not rooted in a much longer perspective (e.g., until 2100). The authors also highlight that the analysis does not take into account leakage or additional emissions that may arise during deep decarbonization transitions.

Knobloch et al. (2018) use the Future Technology Transformations model (FTT): Heat model to explore deep decarbonization pathways for residential heating given various policy scenarios (e.g., carbon taxes, technology subsidies). The FTT: Heat model provides a bottom-up simulation of technology diffusion and aims to forecast technology portfolios for residential heating systems up to 2050. Despite the difficulty of parameterizing behavioral change in modeling tools, the authors implement a stylized heterogeneous, decision-making approach to understanding the choice of household technology. The study explicitly addresses various limitations and uncertainties, and the authors stress that the inclusion of behavioral features means that the results are more realistic and, unlike optimization models, provide more valuable insights for policymakers. Finally, they argue for much closer collaboration between behavioral scientists and modelers.

Wilson et al. (2018) apply a simple quantitative approach to estimate potential emission reductions from a set of disruptive low-carbon innovations (DLCIs) currently available for adoption by consumers. Building upon the method of Dietz et al. (2009) for quantifying realistically achievable emission reductions from household measures, the authors follow a four-step approach using the UK as a case study. These steps are: (a) identify existing early adopting DLCI niche, (b) quantify emission reductions based on observed activity by early adopters, (c) match DLCI niche to equivalent segment of the UK population, and (d) estimate potential annual reductions if DLCI niche was scaled up to the UK population. Based on available behavioral, energy, and emissions data, the authors estimate emission-reduction potentials for 11 DLCIs across three domains: mobility (e.g., car clubs), food (e.g., urban farming), and buildings (e.g., smart heating controls).

They stress that the key assumption in their approach is that diffusion is limited to population segments that match the sociodemographic characteristics of early adopters. However, they argue that evidence from other diffusion studies suggests that this assumption is conservative and that the estimated emission reductions represent a lower bound.

Sonnenschein et al. (2018) use a life cycle costs (LCC) approach to analyze the potential effectiveness of MEPS. MEPS set minimum levels of efficiency, and often ban underperforming products from the market (Lucon et al. 2014). According to the authors, MEPS are often defined by determining which efficiency requirement minimizes LCC for end users. First, their approach considers the relationship between annual units of energy consumption and the market price of home appliances (e.g., refrigerators, dishwashers) with different efficiency classes. Then, optimal LCC are calculated based on purchase price, operating costs, and a high-end estimate of the social costs of carbon (SCC) emissions (equivalent to 150 US$ per tCO_2). The latter is used as a proxy of near-term shadow carbon prices for 1.5 °C scenarios. LCC optima (with and without carbon prices) are calculated for different appliances and the price of switching between inefficient and efficient appliances following the implementation of MEPS incentives is analyzed. Sonnenschein et al. acknowledge that modeling LCC with SCC may be overly simple and that various limitations and requirements need to be considered. These include statistically sound relationships between high-market prices and efficient products, the difficulty of forecasting product improvements based on an ex post market approach, and alternative functions in the LCC optimization method.

Stakeholder approaches

Methodologies that generate and analyze data collected from the public, experts, policymakers, and other actors are an important part of the analytical toolkit. Wilson et al. (2018) use a survey of low-carbon innovation experts (firms, investors, market intermediaries, policymakers, and researchers) to assess potential emission reductions from selected DLCIs. The survey was distributed to experts prior to two workshops addressing innovation, markets, and research needs. It spanned a set of 40 innovations in four domains: mobility, food, homes, and energy supply. Experts were asked to score the potential of these innovations in terms of both disruptiveness and emission reductions. The authors acknowledge that their results are based on a small sample, and emphasize that their findings are illustrative. Nevertheless, experts perceived that potentially disruptive innovations were either dependent on technological progress or behavioral change, and that potential emission reductions were dependent on market proximity and current market size, rather than the potential for long-term transformation.

Moberg et al. (2018) explore how to achieve 1.5 °C mitigation pathways via transformations in household consumption. Combined with other tools (e.g., simulation game to explore emission reductions of 50%), the authors use in-depth interviews held in four European countries to evaluate household behavior and responsibility across various domains (food, housing, mobility). Their approach focused on a single, overarching question: "Who do you consider responsible for climate mitigation?" A content analysis of the data revealed two main areas of discussion: responsibility and systemic barriers to (individual or collective) mitigation actions. No significant variations were found between countries but the sample size needs statistical considerations. The results suggest that there is consensus regarding individual responsibility in implementing mitigation actions, and the role of public policy to steer behavioral change.

Conclusions

The objective of this special issue is to strengthen the evidence base on the role of demand-side policies, measures, and corresponding mitigation pathways to limit global warming to 1.5 °C. Three themes recur: policies, measures, and methods. What are the main lessons learnt? Where does this leave us?

From a policy point of view, this special issue underlines the crucial role of demand-side solutions for keeping the 1.5 °C target within reach. It emphasizes the importance of policy portfolios in driving the pace and direction of deep decarbonization pathways and reducing mitigation costs. Overall, authors argue that stringent and well-coordinated policy mixes are required to remain on a path leading to a 1.5 °C target. Shifts in investment patterns are critically needed. Sectoral targets, building codes, performance standards, behavior-oriented interventions, and carbon pricing are all seen as important policy options that are already available to

policymakers. Carbon pricing is found to be particularly important, albeit insufficient to drive mitigation pathways compatible with the 1.5 °C goal. End-use behavior is characterized by non-financial preferences; therefore, path dependency and a variety of barriers and anomalies need to be targeted more specifically. In addition, concerns about sufficiency, rebound effects, and changes in social welfare resulting from (potential) additional energy use need to be addressed indicating that policy interventions cannot be reduced to technological innovation, substitution, or purely market-based approaches.

Meeting the goals of the Paris Agreement is an enormous challenge for societies and policymakers, and trade-offs go well beyond the technological (supply) dimension. A key issue is the ongoing management and evaluation of a diverse portfolio of policies. Experimentation must go hand-in-hand with assessment to improve the design and implementation of interventions. The papers presented here show that demand-side mitigation in line with the 1.5 °C goal is possible; however, it remains immensely challenging and reliant upon both innovative technologies and policy, and behavioral change.

This special issue also highlights an abundance of demand-side measures to limit warming to 1.5 °C. Low-carbon innovations offer transformative potential by integrating technologies with new business models. Some measures are specific to sectors, segments, products, or energy services, while others are generic (notably technical-efficiency improvements). But not all of these demand-side measures can be "seen" or captured by current quantitative tools or progress indicators, and some measures remain poorly represented in the literature and policy discourse. Demand-side measures and supply-side decarbonization are inextricably linked, and rapid action is needed on both fronts. This is consistent with the basic idea that downsizing the energy system (by tackling ever-rising demand) makes it more feasible to decarbonize the energy resource mix via renewables and other measures (Grubler et al. 2018).

A careful analysis cautions against single-solution approaches (e.g., the potentially adverse effects of heat pumps on the electricity system, and the crowding out of renewable energy investments by energy-efficiency investments). At the same time, measures that address consumption are very reliant on self-governance. However, and contrary to prevailing thinking, this special issue shows that sector-specific deep decarbonization pathways are possible. Ambitious and sustained implementation of demand-side measures reduces mitigation

costs and the need for CDR options. Overall, the papers presented here suggest that there could be a kind of "triple dividend" from increased energy efficiency, encompassing environmental, social, and economic aspects. Further research should systematically assess the multiple co-impacts and welfare effects of demand-side measures in a 1.5 °C context.

Finally, and from a methodological point of view, the articles in this series underline the notion that there is no single best method that can comprehensively capture the dynamics, complexities, and potentials of deep decarbonization pathways. The range of methodological approaches in this special issue clearly illustrate that analyzing demand-side measures requires a plurality of tools, methods, and datasets that are applied to diverse sectors, services, and domains. Forward looking, scenario-based analyses yield different insights depending on the approach or tools used. Comparing and contrasting these insights underlines the strengths and weaknesses of particular approaches. Whole systems models are useful and important tools for analyzing systemic effects, trade-offs and interdependencies between demand and supply-side issues. Global IAMs play an important role as gatekeepers in 1.5 °C analyses by linking long-term energy transformation pathways with cumulative emission budgets and global warming outcomes. These powerful tools can simulate or optimize energy and land-use transitions and are particularly useful in evaluating resource, supply side or upstream transformations. On the other hand, they provide fewer details when assessing services, final energy demand, or living standards.

An important challenge in modeling studies relates to the integration, parameterization, and assessment of behavioral (or lifestyle) changes. In line with the literature, authors highlight the need for unambiguous references to norms and values whenever behavioral change or related policies are analyzed. Furthermore, given the growing evidence that cognitive, motivational, and contextual factors affect technology choice and energy use, much more effort needs to be devoted to the inclusion of behavioral anomalies and deviations from rational choice theory, which can lead to systematic differences between decision and experienced utility. The multiple challenges of limiting warming to 1.5 °C require, more than ever, a plurality of methods and integrated behavioral and technology

approaches to better support policymaking and resulting policy interventions.

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