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TOPICAL REVIEW

Reviewing the scope and thematic focus of 100 000 publications on energy consumption, services and social aspects of climate change: a big data approach to demand-side mitigation*

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Abstract

As current action remains insufficient to meet the goals of the Paris agreement let alone to stabilize the climate, there is increasing hope that solutions related to demand, services and social aspects of climate change mitigation can close the gap. However, given these topics are not investigated by a single epistemic community, the literature base underpinning the associated research continues to be undefined. Here, we aim to delineate a plausible body of literature capturing a comprehensive

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spectrum of demand, services and social aspects of climate change mitigation. As method we use a novel double-stacked expert—machine learning research architecture and expert evaluation to develop a typology and map key messages relevant for climate change mitigation within this body of literature. First, relying on the official key words provided to the Intergovernmental Panel on Climate Change by governments (across 17 queries), and on specific investigations of domain experts (27 queries), we identify 121 165 non-unique and 99 065 unique academic publications covering issues relevant for demand-side mitigation. Second, we identify a literature typology with four key clusters: policy, housing, mobility, and food/consumption. Third, we systematically extract key content-based insights finding that the housing literature emphasizes social and collective action, whereas the food/consumption literatures highlight behavioral change, but insights also demonstrate the dynamic relationship between behavioral change and social norms. All clusters point to the possibility of improved public health as a result of demand-side solutions. The centrality of the policy cluster suggests that political actions are what bring the different specific approaches together. Fourth, by mapping the underlying epistemic communities we find that researchers are already highly interconnected, glued together by common interests in sustainability and energy demand. We conclude by outlining avenues for interdisciplinary collaboration, synthetic analysis, community building, and by suggesting next steps for evaluating this body of literature.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) reports increasing risk of climate change to human health, livelihoods, water supply, food security, human security, and economic development already appearing with global warming of 1.5 °C, and more harmful impacts with 2 °C (IPCC 2018). Yet, pathways limiting global warming to 1.5 °C would require rapid and often far-reaching transitions in energy, land, urban infrastructure (including transport and buildings), and industrial systems. These system transitions are unprecedented in scale, and possibly also in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (Geels 2018, IPCC 2018, McMeekin *et al* 2019).

Avoiding the risk and harm associated with negative emission technologies, such as large-scale land-system domination by bioenergy with carbon capture and storage, seems only possible with rapid reductions in energy demand (Grubler *et al* 2018). Demand-side measures, including energy efficiency improvements, are considered as overall beneficial, and mostly associated with no or moderate risks of harmful side effects (Edenhofer *et al* 2014, Dubois *et al* 2019).

Specifically, lowering energy demand growth is key to managing trade-offs between Sustainable Development Goals (SDGs) and creating synergies instead (von Stechow *et al* 2016). While the Global Energy Assessment started to systematically cover consumption-based energy choices (Roy *et al* 2012), and some key contributions highlighted the relevance of energy end-use choices (Wilson and Dowlatabadi 2007, Wilson *et al* 2012), up to now, demand-side options have not yet been systematically covered and framed in IPCC reports (Creutzig *et al* 2016). Demand-side options are here understood as mitigation solutions that relate to end-user demand of services and products, and may include not only end-users as consumers, but also service recipients as political agents.

More precisely, demand refers to end-use demand for services, such as nutrition, mobility, thermal comfort and lighting. It emphasizes services rather than consumption as essential dimension to guarantee constituents of wellbeing. A focus on social aspects is equally warranted, emphasizing the importance of social dynamics and people in their various roles as agents driving climate change but also climate change mitigation. In response to the realization that demand-side and service solutions might be of high relevance and importance, the next IPCC report (AR6) will cover demand-side solutions in a new chapter (chapter 5 of the WGIII: 'demand, services, and social aspects of mitigation').

The social sciences need to play a core role investigating preferences, norms and infrastructures in individual and institutional decision making, and its relevance for policy making; the role of social practices in organizing societies; they will need to address ethical perspectives on the question of good living in the context of demand-side solutions; engineering and industrial ecology will provide portfolios of end-use technologies compatible with demand and service associated climate solutions; and global scenarios and development studies will need to locate these solutions as elements of climate stabilization pathways and within the context of SDGs (Creutzig *et al* 2018, Nerini *et al* 2019). These tasks may possibly be operationalized but are also very broad. Broad is also the literature base that could possibly underpin assessments of demand-side climate change mitigation. Nearly all social sciences have to contribute some aspects to these discussions. Even an exploratory study with a small survey pointed to 96 different theories of socio-technical change (Sovacool and Hess 2017). It is hence very challenging to gain safe grounds in, let alone synthesize, the bodies of literature relevant for substantiating an assessment on demand-side solutions.

Here, we aim to delineate a plausible body of literature capturing the whole spectrum of demand, services and social aspects of climate change mitigation. Pragmatically, we take the IPCC's government-mandated outline of the corresponding chapter as a starting point and strengthen it with expert assessment of relevant and specific subtopics. By this we obtain a bottom-up characterization of the literature space.

For this study, we use bibliometric methods and big data approaches applied to the literature. We accept the premise that learning on climate solutions can be crucially supported, albeit not achieved on its own, by systematic methods and literature searches (Minx *et al* 2017), and find encouraging support in systematic and bibliometrically supported reviews on the opposite end of climate change mitigation solutions, namely negative emission technologies (Minx *et al* 2018, Fuss *et al* 2018, p 2, Nemet *et al* 2018). We also build on a systematic topography of the overall climate change literature (Callaghan *et al* 2020). Our specific contribution is a mapping of academic papers identified by systematically scoping the literature on demand-side, service-oriented, and social aspects of climate change mitigation.

Box 1. Key issues provided by the governments to address in chapter 5: Demand, services and social aspects of mitigation

(a) Mitigation, sustainable development and the SDGs (human needs, access to services, and affordability)
(b) Patterns of development and indicators of wellbeing
(c) Sustainable consumption and production
(d) Linking services with demand, sectors, systems—implications for mitigation and sustainable development
(e) Culture, social norms, practices and behavioral changes for lower resource requirements
(f) Sharing economy, collaborative consumption, community energy
(g) Implications of information and communication technologies for mitigation opportunities taking account of social change
(h) Circular economy (maximizing material and resource efficiency, closing loops): insights from life cycle assessment and material flow analysis
(i) Social acceptability of supply and demand solutions
(j) Leapfrogging, capacity for change, feasible rates of change and lock-ins
(k) Identifying actors, their roles and relationships
(l) Impacts of non-mitigation policies (welfare, housing, land use, employment, etc)
(m) Policies facilitating behavioral and lifestyle change
(n) Case studies and regional specificities

2. Research design: a mixed methods approach

We approach the bibliometric exploration of the literature bodies relevant for demand- and service-side solutions to climate change mitigation in two steps: (a) Top-down searches, and (b) Expert queries. We supplemented this with expert elicitation and a survey (SI) (available online at stacks.iop.org/ERL/16/033001/mmedia).

The UN member states mandated the IPCC with following an approved government outline for all chapters (box 1, IPCC 2017). Here we follow this outline and code it into 17 queries for each bullet point (see SI), thus scoping what governments consider be the relevant literature for demand, services and social aspects of climate change mitigation. These 17 queries identify 57 131 unique papers as of May 2020.

Some issues are translated into search queries nearly verbatim, such as 'sustainable production and consumption', others require more interpretation to become operationalized as search query. For example, 'Culture, social norms, practices and behavioural changes for lower resource requirements' is translated into TS = (('culture' OR 'social norm' OR 'practice' OR 'behavioral change') AND ('resource' OR 'energy')). Here TS is the Web of Science abbreviation for 'topic'. Search queries are tabularized in tables S1 and S2.

To constrain results to those relevant to climate change mitigation, we also add the following term as logical AND operation to the specific queries:

TS = (('CO2' OR 'carbon' OR 'GHG' OR 'greenhouse gas' OR 'climate change' OR 'global warming' OR 'climate crisis') NEAR/3 ('trading' OR 'tax' OR 'control' OR 'regulation' OR 'mitigat*' OR 'decarbon*' OR 'reduc*')) NOT TS = ('catalyst*' OR 'distill*' OR 'chemicals' OR 'super-critical' OR 'foaming' OR 'pore')

We call this the 'mitigation query'. It is further developed from the query used by (Lamb *et al* 2018). (NEAR/3 required the words to be not more than three words apart within the same document). The

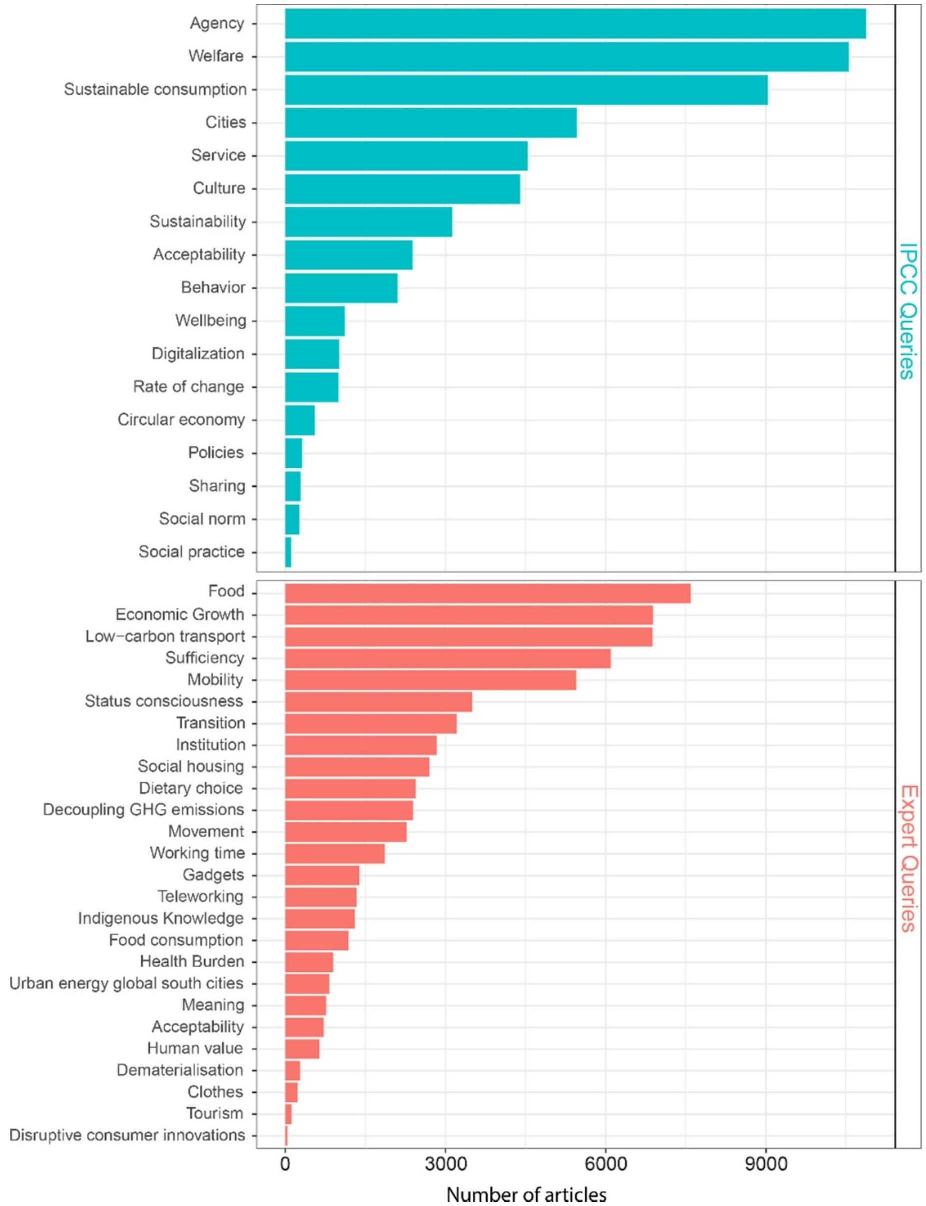

Figure 1. Number of articles resulting from specific queries. As some articles are found by more than one query, the total count includes doublets or triples. Queries are all detailed in the SI.

mitigation query alone yields ∼30.000 results in Web of Science as of 21 December 2018. The yields in response to combination with the specific queries are summarized in figure 1, and the specific queries can be found in the supporting information. In the result section, we evaluate the results of this query and reveal the shortcomings of this approach.

Second, we asked domain experts in our team to identify subjectively five of the most important papers in their specific field relevant to demand, services and social aspects of mitigation (see figure 1, and SI for query details). We cross-checked whether these papers were discovered by our top-down search query. Over 50% were not discovered by the top-down query.

Hence, we developed 27 search queries that are investigating aspects of the issue list in much more detail. These involve search queries that expand on the search query for a specific issue and that may be related to specific end uses. In particular, each topic-related search query had to be associated with at least one item from the government-provided issue list, and possibly one end-use or more. As a general rule, we dropped the mitigation query here, but instead refined the issue-related part of the query to derive a targeted set of queries (see supporting information). We find 63 847 documents. Among those 34% (21 913 documents) were also identified by the top-down search query. Expert queries hence identified by two thirds documents not yet obtained by IPCC queries, certifying the benefit of additional domain-expert derived search queries.

For example, we developed a search query for circular economy that involves synonyms, and that involves a process systematically capturing the highly relevant gray literature in this field. In other instances, we derived search queries that address a certain class of action, such as behavioral change, and combine it with certain end-uses, such as food consumption, to cover highly context specific examples.

The approach taken is comprehensive in relying on experts on all sectors, and on various different approaches. Nonetheless, bias is arising from possibly being incomplete and not having covered all topics that others might deem relevant. Another source of bias is that the experts involved may not cover geographical scopes and cultures completely. Our study is also biased by language, only querying English-language literature. Hence, there is certainly scope for improved and additional queries, and the results represented should be understood as a first attempt to define the literature base for demand-side solutions for climate change mitigation, not as a final result.

To explore the content of the studies in our queries, we apply topic modeling, an unsupervised machine learning technique that allows to explore the content in large collections of documents. Specifically, for the topic modeling, we use non-negative matrix factorization (Lee and Seung 1999), an approach that factorizes the term frequency–inverse document frequency matrix V with i items and μ documents into the matrices W (the topic-term matrix) and H (the document-topic matrix):

$$V_{i\mu} \approx (WH)_{i\mu} = \sum_{a=1}^{r} W_{ia} H_{a\mu}.$$

With each column a of W being topics. Each topic is represented by a distribution of words, in which the words with the strongest weights indicate the semantic content of the topic. Topics are calculated using the scikit-learn library, and are saved in a database and topic visualization system, as developed by (Chaney and Blei 2012). Code and additional information are published online at https://github.com/mcallaghan/tmv.

Topic models for the 99 065 publications are calculated for 20, 40, 60, and 80 topics. The relative usefulness of each model was assessed subjectively by the authors, based on inspection of the online visualization tool and the spreadsheet 'SI_topicmodels.xlsx' in the SI. The spreadsheet shows each set of topics in adjacent columns. Topics from each model are placed next to the topics with the largest number of each topic's ten highest-scoring words in common. This helps authors to find an appropriate level of granularity for the analysis, even as different choices are possible. We make a judgement based on subjective criteria, but the supporting data file 'SI_topicmodels.xlsx' can be inspected for the topic choices embedded in different models. While the main conclusions remain intact irrespective of model, we chose the topic models with 60 topics for further analysis as it provided for specific topics of interest for domain experts, such as tourism, without splitting up into redundant topics.

To compare IPCC and expert queries, we compare their respective topic models (figure S1). The results reveal that topic models are mostly matching well: one topic cluster usually corresponds to a model cluster in the other topic model (for example policy, social, research corresponds to policy, adaptation, research). However, there are some exceptions. For example, the core query emphasizes life-cycle assessment (LCA), a methodological term, which is not represented at the high-level topic presentation of the wider topic model. Instead, the wider model explicitly picks up 'China', the only geographical location in our topic results.

These results suggest that the generic search of the 'chapter' queries is good in identifying the overall topics. However, as expert domain queries find a high amount of additional literature (41 934 documents), expert search queries and knowledge remains important for identifying the in-depth literature.

Next, we used scoring by 20 experts to rank the 60 topics in terms of relevance as demand-side solutions for climate change mitigation (SI_topicgrading.xlsx). Each topics was scored by an integer number between 0 and 10, where 0 indicates zero relevance for climate change mitigation, and 10 indicates highest relevance for climate change mitigation. We calculated mean, median and standard deviation and ranked them according to median score. We then filtered out topics those were equal to or exceeded a median score of 7.0, thus guaranteeing that at least half of the experts scored the topic as highly relevant, resulting into 24 topics.

Finally, we aimed to understand the content messages by each of the 24 relevant topics. For each topic, we filtered out the ten papers that had the highest topic score, and the ten papers with topic score above 0.1 that had the highest citation count (adjusted for year since publication). We then read the 20 abstracts and evaluated them according to whether they contained relevant insights on demand-side solutions for climate change mitigation. We compiled these insights into table S3.

The overall workflow is reported in figure 2.

3. Results: disparate bodies of evidence but converging agendas

The literature on demand-side and service-related solutions for climate change mitigation is growing exponentially (figure 3). Compound annual growth rate, in average, is 16.4% from 1997 to 2018, with growth rates above 20% for 2009 until 2017. The overall literature on climate change grew by 13.7% in average between 1997 and 2018 (Callaghan et al 2020, figure S1). Growth rates of this body of literature is smaller than the overall growth in literature on climate change from 1997 to 2005, but higher from 2006 onwards (figure S2).

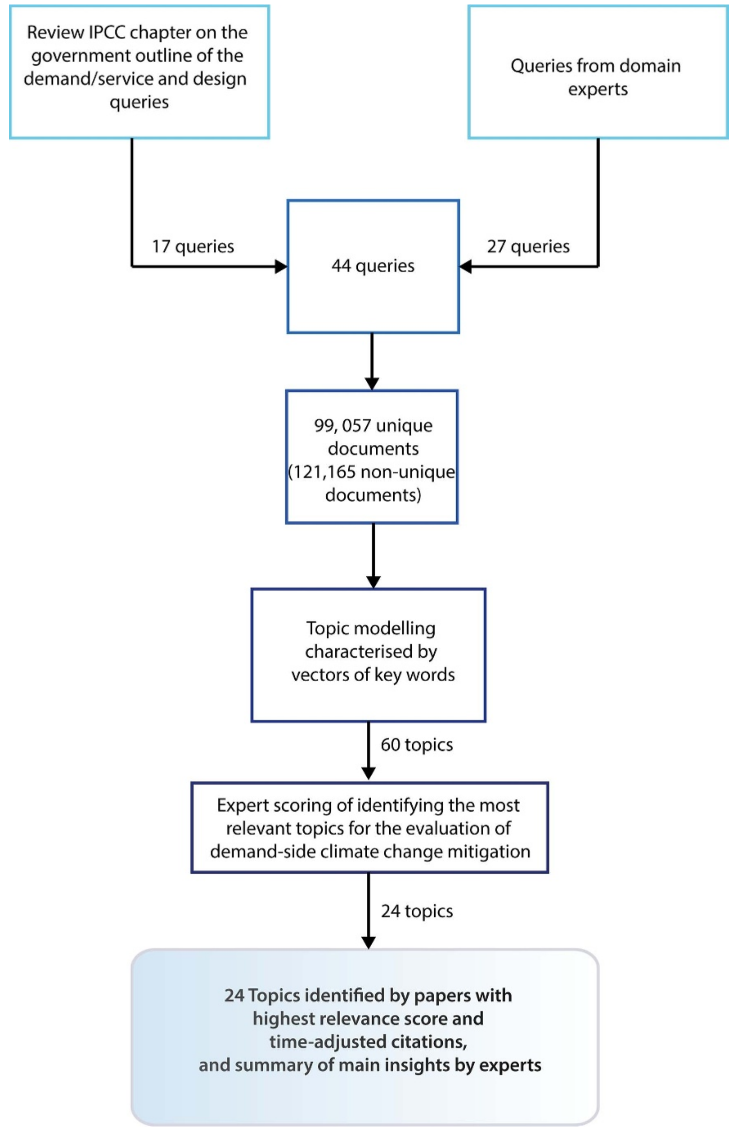

Figure 2. Flow chart of approach.

3.1. Mapping topic models overlaps and divergences

Locating the 99 065 results of the literature into a thematic map reveals a broad landscape of topics that provides orientation by mapping similarity as the inverse of distance (figure 4). Using non-negative matrix factorization, the 60 topic models was extracted from the abstracts (see Methods, and (Callaghan *et al* 2020)). The topic scores of each document are reduced to two dimensions (using *t*-distributed stochastic neighbor embedding (*t*-SNE)). This method seeks to preserve small distance between topically similar documents.

The map reveals that those topics deemed relevant by the expert judgment (relevance score $\geqslant$7) are more often occurring together than not and are mostly in the West of the topic map. As illustration how literature on specific topics is distributed over the map, we illustrated this distribution for the case of energy demand in figure S5.

We identify four clusters that are dominated by demand-related topics (figure 4). The policy cluster is located in the center and includes policy instruments, taxes, and cost-benefit analysis as topics, and related encompassing issues, such as GDP and low-carbon development. Located on top of the policy cluster, a housing cluster includes topics from buildings, to heat, community, rural households and cities, but also governance, thus specifying the multiple stakeholders involved in built environments, beyond policy makers. Also the topic of social housing and others clarify that the literature not only addresses mechanistic aspects of building and GHG emissions, but also the wider social context of energy use. Further to the right of the policy cluster, a food/consumption cluster summarizes issues on diet and waste, but also consumption. A surprising tourism topic is located further out to the left, related to overall consumption (footprints). Below the policy cluster, a cluster on mobility encompasses

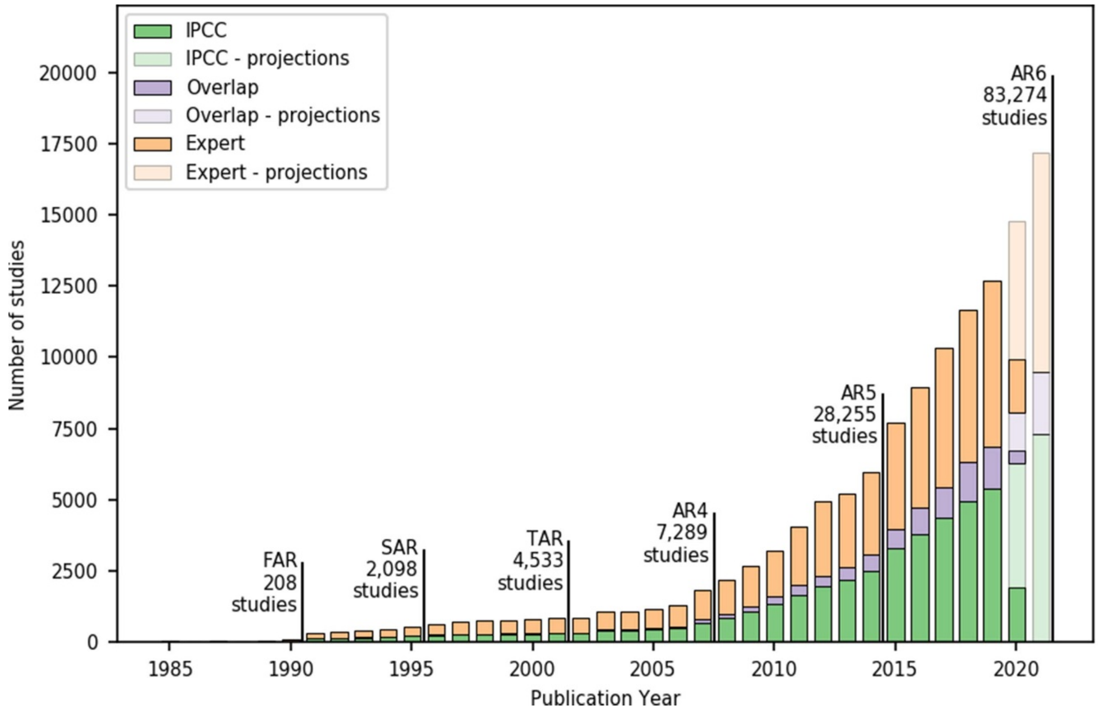

Figure 3. Growth of literature that underpins demand-side and service-related aspects of climate change mitigation. Numbers for 2020 and 2021 are extrapolated from the compound annual growth rate 2014–2019 (∼15%). The number of publications in the period of the 6th Assessment are projected to be nearly twice as high as the number of all publications before together.

topics like vehicles, travel, and transport. Electricity serves as a bridge between mobility and policy clusters, inter alia substantiated, content-wise, by the increasing importance of sector coupling for decarbonization.

The other parts of the thematic landscape are occupied by topics rated of less direct relevance to demand-side climate mitigation. They include nature related topics at the top right, such as soil, forests, and water, some of them connected to the food cluster via topics such as plant and crops. Another less relevant cluster of topics relates to supply side topics, such as wind, oil and gas that are connected to the central policy and the mobility cluster via energy demand and electricity, and also industry, located in the same region of the map (figure S6).

The overall map depicts an overall logical relationship between topics. Exceptions include tourism that is surprisingly disconnected to mobility and transport topics, even though aviation dominates the GHG emission footprint of tourism. Also the work topic is more difficult to localize and explain.

3.2. Expert synthesis of the key literature from topic models

Next, we summarize the key papers from the topic models, selected from the ten most cited of each topic model with topic score >0.1, and the 10 with highest topic score. We find a wide array of insights, ranging from the importance of consumption-based carbon footprints, to sectoral interventions, to policy instruments, and the key insight that demand and supply are interdependent and require joint consideration (table S3). We further condense these insights into headline statements in a clustered summary (figure 5).

While the statements communicate content and messages on their own, four important observations can be drawn from analysis of their relations.

First, the central role of policy instruments finds a specification in the wording of taxes as part of comprehensive evolution of policy packages and appropriate sequencing. Recent literature connects the effectiveness of policy instruments with fairness, achieved for example by payment of a climate dividend, thus guaranteeing impartiality and social support of market-based instruments. The policy literature also increasingly relates to behavioral and sociological insights, for example, showing that a price signal can trigger the development of social norms, which in turn leverage the otherwise possibly small price effect.

Second, the housing related messages reveal that buildings and cities are places where overall governance, including all societal actors, and collective action is advanced and investigated, emphasizing the social dimension of action. Surprisingly, in our literature base governance is more related to the housing cluster than to the policy cluster. This is possibly aligned to social housing and cities being places where

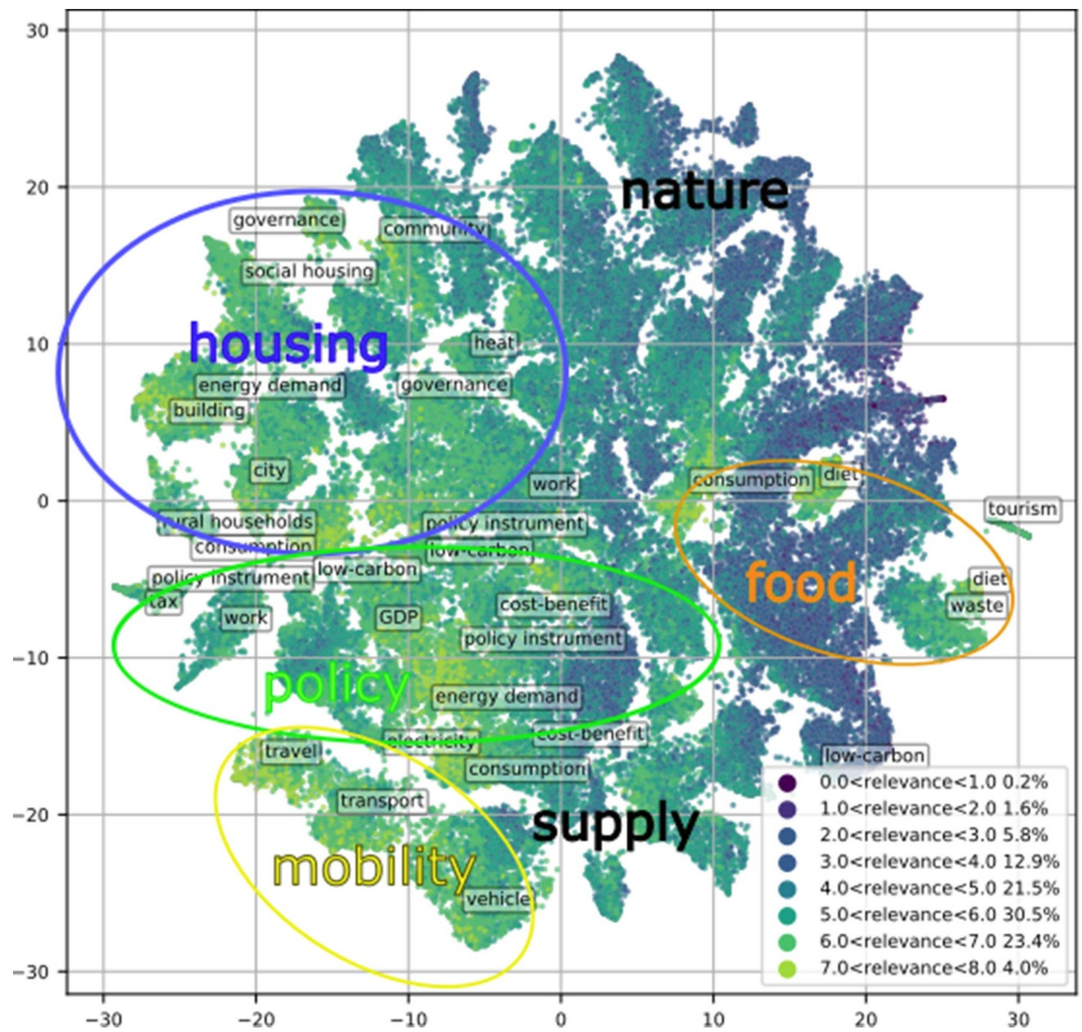

Figure 4. A map of the literature on demand, services and social aspects of climate change mitigation. Dots show document positions obtained by reducing the 60-dimensional topic scores to two dimensions aiming to preserve similarity in overall topic score. The two axes therefore have no direct interpretation, but represent a reduced version of similarities between documents across 60 topics. Documents are colored by query category. Topic labels of the 24 most relevant topics are placed in the center of each of the large clusters of documents associated with each topic. % value in caption indicates the proportion of studies in each 'relevance' bracket.

polycentric governance and a multitude of actors and perspective come together; or more generally, when specific places, urban and rural alike, are considered, people enter the picture, too.

Third, the consumption and food clusters puts relatively more importance on the individual character of action, emphasizing issues like diet shift but also tourism. Nonetheless, the literature also points to the role of choice architectures, infrastructures, and social norms, in addition to policy instruments, in changing the opportunity space for new consumption patterns.

Fourth, the role of thermal comfort in buildings, the role of active travel in transport, and the role of diets in consumption all point to a strong alignment of social and demand-side solutions for climate change mitigation with wellbeing and individual and public health, consistently acknowledged if not emphasized in the literature.

3.3. Mapping epistemic communities via citation patterns

What are the different epistemic communities researching climate change mitigation? To answer this question, we display papers clustered according to joint citation regimes (figure 6). In each cluster, manuscripts are related by joint citation patterns. Neighboring clusters are closer in terms of citation patterns than more distant clusters. Clusters which are cited by many other clusters can be interpreted as bridging topics, while for more isolated clusters we identify opportunities for interdisciplinary collaboration.

The bibliographic coupling network reveals that most of the literature is connected by citation patterns, directly or indirectly. Only small clusters are unconnected to the main body of literature, specifically those on metal and waste, but to some degree also that on social housing. The special role of waste

Figure 5. Cluster-oriented summary of key messages extracted from the highly relevant and highly cited academic publications of each topic model.

in the literature had also been identified in (Lamb *et al* 2018). The overall relation between the literature points to well-developed exchange between more particular epistemic communities.

Broadly, patterns of the thematic map are also reproduced in the bibliographic network. Policy instruments are found at the top and top left, with governance joining in on the top left. Building and heat appear more on the bottom right, transport and vehicles on the top right, and diet and food on the bottom left. This confirms high-level relationship patterns between different topics of the demand-side literature on climate change mitigation.

Some patterns of the bibliographic network are nonetheless also different to those of the thematic

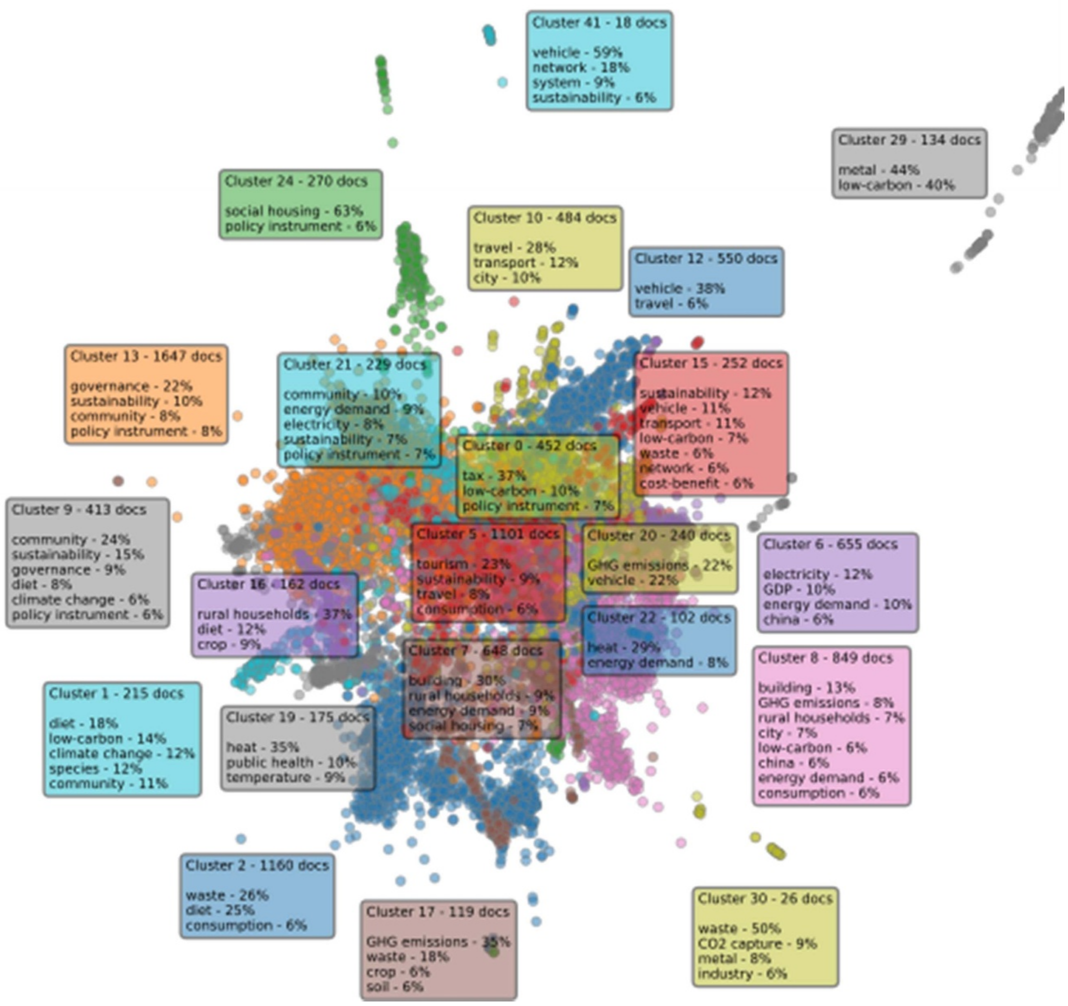

Figure 6. Bibliographic coupling network of demand-side solution topics. Nodes represent articles scaled by total citations. Proximity between nodes represents similar citation patterns. To identify communities, we specify clusters of proximate nodes using a community detection algorithm, representing resulting clusters in colours. All articles in one cluster add with their topic score to the cluster's topic score. Topics that exceed 10% of topic score in each cluster are shown in the labels. For background and similar approach, see (Lamb *et al* 2018).

map. For example tourism is rather marginal in terms of the specific topic vector. It is however central in terms of citation patterns, relating to similar bodies of literature as academic papers addressing other demand-side topics.

In epistemic communities, different topics appear together. The topic of sustainability appears as a glue relating policy communities to part of the mobility literature (clusters 5, 9, 13, 15, 21, 41). In turn, the building communities are glued together by the joint consideration of energy demand (clusters 6, 7, 8, 21, 22). This suggests that more abstract and encompassing topics serve as connection between different epistemic communities.

4. Discussion and conclusions

Our compiled and comprehensive list of references and abstracts includes more than 99 000 unique studies and reveals that social science, engineering, and environmental dimensions are all reflected in the wider literature on demand-side climate change mitigation. These involve, among others, a focus on energy services, such as housing and mobility, lifestyles, as well as a relationship to material and macro elements such as (urban) governance and infrastructure. It includes methods like life-cycle analysis, and a technological stock-oriented focus on issues like transport and buildings, representing engineering approaches. Finally, mostly via food/diet, also dimensions like agriculture, water and forests are explored in the literature. The complete literature can be found as CSV-file in the SI.

Admittedly, the literature on the demand-side reflects recent trends in the overall literature on climate change mitigation. In the overall climate literature published since 2014 (when the 5th assessment report of the IPCC was published), key topics

Table 1. Outlook on potential further studies, with key topics, their description and questions, and indicative studies listed. Topics identified by expert judgment, and are intended to bridge established topics and epistemic communities, thus connecting insights of different clusters identified in figures 4 and 6.

Topic	Description	Indicative study
Practices, time use, consumption and well-being	How do practices and household time use depend on both physical and social constraints and how do they impact carbon footprints, consumption and well-being?	(Jensen *et al* 2018, Wiedenhofer *et al* 2018, Smetschka *et al* 2019)
Political economy of urbanization	Who profits from what kind of urbanization patterns? How does political structure translate into different urban form and ensuing GHG emissions? What is the role of multilateral funding agencies?	(Gonzalez 2009, Mattioli *et al* 2020)
Paradigms of service provision systems	What kinds of market-based, public, and communal service provisioning systems and their institutions result in low-GHG emission patterns?	(Brand-Correa *et al* 2018, Rao *et al* 2019, Vita *et al* 2019, Fanning *et al* 2020)
(Re)designing cities for promoting shared goals of well-being and sustainability	How can urban design and policy choices shape and leverage more comprehensive views of individual and social well-being to promote sustainable urban transport modes?	(Creutzig *et al* 2012, Chapman *et al* 2016, Ramaswami *et al* 2016, Rodriguez *et al* 2018, Nagpure *et al* 2018, Ramaswami 2020)
Social norms and networks	Individuals are embedded in networks and heavily influenced by others in terms of what they consume. Social Network Analysis (SNA) can be used to integrate social, environmental sciences and humanities to intervene for action and respond questions such as, How effectively diffusion of norms through existing networks can foster demand-side solutions for climate mitigation?	(Centola 2010, Broadbent and Vaughter 2014, Zedan and Miller 2017, Javaid *et al* 2020)
Social status and energy consumption	Social contexts in energy consumption is key to understanding the potential of demand-side changes. How does perceived social status interact with household energy decisions that carry high potential for behavioral shifts?	(Lutzenhiser and Gossard 2000, Brooks and Wilson 2015, Wolske *et al* 2020, Ramakrishnan *et al* 2020)
Lifestyle typologies	Better understanding of lifestyles in different life stages (e.g. the silver economy) and cultures, and resulting opportunities for low-carbon innovations and sustainability transitions.	(Pettifor and Wilson 2020)

that gained currency included 'households', 'urban', and 'China' (Callaghan *et al* 2020). These topics are also dominantly reflected in the demand-side and service oriented climate change mitigation literature (figure 5).

Our results cover a broad spectrum of issues. We cover end-use sectors (transport, building, industry, waste), and their services (mobility, shelter, heating and cooling, nutrition, tourism, other energy services), governance and spatial scope (households, urban), macro-economics and resource use (growth). Queries were put forward by psychologists, urban scholars, technology innovation studies, industrial ecology, sociologists, and economists. We tried to cover blind spots by a third set of queries. Nonetheless, we certainly missed issues. Humanities, such as philosophy and history, and ethnographic and anthropological studies remain underrepresented, albeit this also reflects the relatively small number of publications from the humanities. Specifically, humanities have a lower tendency to publish in peer-reviewed literature. They instead publish in, for example, authored or edited books. Also, scholars in humanities publish in their original languages, rather than in English, more often than in social sciences or technical disciplines. Nonetheless, historical and ethical studies of low-carbon service provision systems deserve more attention and funding and are to a large extent invisible within climate change assessments.

The diverse presentation of disciplines covering broadly similar questions is intriguing. Studies approach the issue nearly always from one epistemic perspective. However, the value of these studies is of potentially high complementary value. Demand side transitions may require truly interdisciplinary collaborations or 'deep interdisciplinarity' across (a) sectors, e.g. by studying interrelationships between mobility, shelter and food demand; (b) training and expertise, e.g. relating behavioral, building and gender studies; (c) dimension, e.g. connecting discourses, markets, and technologies; and (d) disciplines, science and social science with the arts and humanities.

Resulting synthetic work, for example between social scientists studying lifestyles or time use, and industrial ecologists studying carbon footprints, have considerable potential. Deeply interdisciplinary studies will certify some conclusions of previous studies through different but complementary lenses, thus giving them more authority, while disapproving of other conclusions. Potential studies include data-based studies on GHG emissions, and data-based studies coding for various dimensions of lifestyles (table 1). Other studies can explore the upstream GHG emissions and resource and environmental implication of shifts in service provisioning systems, such as urban reconfigurations that enable high accessibility to health and education by active modes, such as walking and cycling.

Finally, investigations of governance would benefit from accurate understanding of existing lifestyles in different life stages and cultures, their associated GHG emissions, and trajectories and entry points for a shift. The resulting opportunities and corresponding examples are summarized in table 1. Together, such studies can help to establish a new epistemic community around demand-side solutions for climate change mitigation.

As a final note, we would like to raise a concern on the ahistorical approach in the research on social and demand-side solutions to climate change mitigation, also evident in this paper. We find that the majority of papers were published in the last 5 years, and in a self-enforcing process only highlight English language literature. The resulting impression is that of a highly innovative research field. However, age-old insights are neither adequately witnessed, nor is literature from historical studies comprehensively reflected. That may be a mistake. Already a local high culture 2500 years ago inscribed in what they regarded as the center of the world the maxim of 'μηδὲν ἄγαν'—nothing to excess[26].

[26] 'Nothing to excess' is one of the inscriptions on a column in the forecourt of the Temple of Apollo at Delphi, Greece.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://figshare.com/s/dc35e3ec7fd748378347.

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