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Innovation and climate change: A review and introduction to the special issue

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ABSTRACT

While innovation is expected to play a major role in decarbonization, the development and diffusion of low-carbon technologies are too slow in most sectors and countries to stabilize the climate. In this introductory paper to a Special Issue on “Innovation and climate change”, we review selected innovation studies literature, reflect on historical trends and insights, and cast light on future research on innovation and climate change. To set the stage for this Special Issue we present an analysis of key research topics, most influential papers and innovation journals, highlighting contributions across four interrelated themes: fostering climate action, shaping policy, promoting experimentation and learning, and examining effectiveness. While past studies and this special issue made significant contributions, we suggest that research on innovation have not sufficiently engaged with three important topics: i) blending behavioural change with technological innovation; ii) the socio-technical drivers of accelerated low-carbon transitions, and iii) the role of digital technologies as new venues of solutions to managerial challenges in addressing climate change. The nexus of climate change and innovation calls for different disciplines and coevolutionary views, as opposed to a traditional disciplinary focused approach. It also may require the need for broader, more inclusive and interdisciplinary research teams.

1. Introduction

With the effects of climate change growing more apparent, innovation is expected to play a major role in enabling national and subnational decarbonization processes. Recent developments present both private and public sectors with different technological approaches from low or non-carbon technologies to mitigate sources of greenhouse gases (GHG), to carbon capture and storage innovations to address the consequences of global warming (Sovacool, 2021b; UNGC-Accenture, 2015). Yet, the field of innovation studies, and its broad range of approaches including technology and innovation management and innovation policy, has acknowledged that, in addition to technological progress, addressing global challenges through innovation also involves organizational, social and economic changes. For example, studies have shown that moving a novel technology from the lab to the living room consists of a complex co-evolving process among technology, regulations, infrastructure and consumer behaviour (Geels, 2002, 2004; Verbong and Geels, 2007; Rip and Kemp, 1998). Given that research is expected to help turning challenging problems into manageable solutions (George et al., 2016), this is an opportune moment to reflect on past insights and cast light on future research on climate change and innovation.

Recent events show examples of contextual factors that favour or at least create strong incentives for climate change innovation. In 2015 during the United Nations Climate Change Conference in Paris, twenty countries including the UK, the US, China and India, committed to double their public investment in low-carbon technology as part of the ‘Mission Innovation’ agreement (Sanchez and Sivaram, 2017). In addition, the European Commission has developed a greener carbon-free Europe strategy to support related innovation. At the same time, NGOs and climate activists such as Greta Thunberg, have influenced

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political agency around the globe and challenged economic structures and governmental policies grounded in economic growth at the expense of environmental impacts (O'brien et al., 2018; Sabherwal et al., 2021). Policy push for low-carbon technologies is also coming from the newly elected Biden administration. At the private sector level, Bill Gates's Energy Breakthrough Coalition has mobilized investors on breakthrough innovations to address climate change (Adam and Thornhill, 2015). Finally, for decades academia has been engaged in the development of new technologies (Burchardt et al., 2018; Carayannis et al., 2012; Lefsrud and Meyer, 2012). Yet, low-carbon technological progress has been too slow to achieve the temperature goals set by the Paris agreement (OECD, 2017; Höhne et al., 2020). A key challenge is thus to understand what combination of factors will help the acceleration of low-carbon innovations and the discontinuation of carbon-intensive ones.

In what follows, and as part of this Special Issue, we discuss key topics in research on "Innovation and Climate Change". To do that we look back by exploring key research themes addressed in previous studies, and look ahead by discussing main challenges, opportunities and future research agendas. We start with a descriptive analysis of key research topics, most influential papers and journals. Then we discuss key contributions, highlighting four key interrelated themes: fostering climate action, shaping policy, promoting experimentation and learning, and examining effectiveness. This is followed by an overview of this special issue papers. Next, we present an outlook of future research opportunities and challenges.

In line with the co-evolving process of complex systems mentioned above, we apply a co-creation methodological approach (De Koning et al., 2016; Sovacool et al., 2020), where authors from different disciplines act as co-creators and engage in active form of interacting and sharing as opposed to modular contributions. More specifically, the lead authors interacted with prominent experts during the paper development process to jointly draft, revise and refine the paper. We aim to offer timely insights to future of innovation studies and climate change. We approached the nexus of climate change and innovation as interdisciplinary and coevolutionary, as opposed to a traditional disciplinary focused approach. The resulting topography, albeit imperfect due to limitations in considering all available information, provides an alternative to 'flat terrain' landscape, which tends to influence actors to 'stay fixed' or 'wander aimlessly' (Levinthal and Warglien, 1999).

2. Contextualizing climate change and innovation studies

Insights from energy policy and the broad business literature help us appreciate the interrelatedness of sociotechnical factors in the context of climate change and innovation. One insight is that the feasibility of innovative technologies such as renewable energy (especially solar photovoltaics and microinverters), smart grids, and distributed energy storage has improved in recent years because increased deployment has led to substantial cost reductions (IRENA, 2021; Viardot et al., 2013). Another insight is that investments in low-carbon innovation are still too low and that substantial increases are unlikely without more support from policymakers (Reid and Toffel, 2009). This is because companies may still find it difficult to invest in innovations that require long development timelines without an existing large market and are thus reluctant to bear the costs of an innovation such as clean energy (Ghisetti and Pontoni, 2015). Despite such challenges, many large companies are directing part of their research and development (R&D) investments to climate change.

At the governmental policy level, many countries have developed incentives for research and innovation, especially renewable portfolio standards (popular in North America) and feed-in tariffs (popular in Europe) (Alizada, 2018; Zhou et al., 2019). Other "supply side" incentive include R&D subsidies and tax credits, which reduce innovation costs and support for collaborative innovation activities. For example, the European Union has recently offered billions of euros of co-funding to companies willing to develop cheaper, more efficient solid-state batteries. So far, four large groups - Saft, Siemens, Solvay and Manz, and more than 260 smaller firms responded positively to the incentive (Toplensky, 2018). In China and Germany, the government has played a key role in stimulating demands for renewable energy leading to a dramatic increase in the production of solar panels (Arantegui and Jäger-Waldau, 2018; Jäger-Waldau, 2021). The resulting economies of scale translated into significant price reduction, which simultaneously accelerated the adoption of solar panel while trouncing the competition. Similar governmental incentive strategy has been successfully applied in wind energy and more recently in batteries for electric cars in China (Sanderson, 2021). While such incentives have also significantly influenced research, more support is needed to accelerate the adoption of cleaner technology innovations through for example, procurement policies, carbon taxation, environmental and safety regulation, and tax rebate or price subsidies to the consumers to compensate for the market power of incumbent technologies offering less eco-friendly alternatives (Polzin, 2017).

Consumer perceptions has long been recognized as playing a key role in influencing companies to develop sustainable new technologies. According to Wang et al. (2018), product information about energy savings, material decrease, and carbon dioxide emission reduction positively influences users' perception of the value of a given product. However, there is a large diversity in consumer preferences for low-carbon innovative products such as the electric car and not all consumers can have access or afford "decarbonized" products (Shabanpour et al., 2017; Zhao et al., 2018).

Most innovations aiming at addressing the causes or the impacts of climate change are technologically complex and associated with higher degree of risks and uncertainties (Wu et al., 2020). These technologies often rely on knowledge from different fields and are embedded in innovation ecosystems that involve many different organizations (Cecere et al., 2014). As expected, one consequence of such complexity is the rise in risk and uncertainties to succeed as the need for coordination from all partners within the system are increased (Levinthal and Warglien, 1999).

Radical technological innovations are increasingly seen as necessary in order to limit climate change to less than 2 °C of temperature change, the goal of the Paris agreement (Pooler, 2021), or to more aggressively limit climate change to a 1.5 °C (IPCC et al., 2018). The mitigation of global warming has driven some large companies to initiate important process innovations in manufacturing by adopting lean carbon and energy-efficient processes and technologies (Lee, 2013). Some firms, such as BMW or Fiat, have even instituted entirely new supply chains or materials (such as carbon fibre or the inclusion of battery manufacturing capabilities) into their business models or joint ventures (Sovacool et al. 2019). In the building sector, companies are working on smart interconnected appliances using Internet of Things, as well as smart heating controls and energy management systems for home energy efficiency (Wilson et al., 2018). Finally, in the food sector, in addition to the rise of plant-based burger market, urban food production ("vertical farming") has been explored to limit emissions associated with the storage and transport of food from fields to large cities (Wilson et al., 2018).

3. Exploring technology and innovation research

In this section, we present an overview of innovation and climate change research, but first we explain our approach to the selection of journals in this review, which is grounded on the disciplinary connections that exist within the innovation studies field.

Since early studies on technology and innovation research, such as Liker (1996) and Chen (1999), the field was recognized as highly interdisciplinary and created a list of specialty journals. They based their work on citation analysis and expect surveys with journal editors and members of the Academy of Management technology and innovation management division. The disciplinary connections within the field have been further explored in studies such as Linton and Thongpapanl (2004), Ball and Rigby (2006), Linton and Embrechts (2007) and more recently in Hall (2018) and Pitt et al. (2021). Together, these studies show that innovation has a very wide and pervasive area of application and involves broader consideration of the relations between journals and disciplines (Table 1). We limited our review to such list of journals, which albeit not comprehensive, it offers a solid proxy for research rigor and influence, as measured by citation, and provides full transparency of the scope of our review and the steps we followed during the process of charting innovation studies related to climate change.

While the contents of these journals differ substantially, Linton and Thongpapanl's (2004) analysis of the interdisciplinarity of the field provides insights into the different focus of the journals. For example, they explain that the *Journal of Product Innovation Management* draws much more heavily from the marketing literature than the other journals. While *Research Policy* often deals with the front-end of the innovation process, *Journal of Product Innovation Management* addresses the entire innovation process. *Technological Forecasting and Social Change (TFSC)* tends to focus on forecasting technological and social changes and implications for business and policy (Table 1).

We start with an analysis that identifies influential papers (measured by number of citations), top journals in number of publications on related theme (measured by number of papers published on related topic) and key topics of study. We used Scopus database with search terms including "climat* change" OR "global warming" OR "climate warming" OR "climate mitigation" OR "energy" OR "low-carbon transitions" OR "low-carbon innovation".

Search process included title, keywords and abstracts and involved several rounds of papers selection, based on examination of abstract and keywords. Our initial search returned 921 papers (from 1990 to 2021), of which we excluded reviews and papers with peripheral alignment with climate change, leading to a total of 877. In addition, we used a bibliographic software tool, *VOSViewer* (Waltman et al., 2010) that develops data networks for visual interpretation.

Table 1
Disciplinary approach and focus of selected innovation journals.

Journal	Disciplinary approach to innovation studies
Technological Forecasting and Social Change	It focuses on the co-evolution of technology and society, often with a forecasting orientation.
Research Policy	It is likely to be the vehicle of choice for researchers with disciplinary approaches to innovation studies from an economics and policy perspective.
IEEE Transactions on Engineering Management	It is oriented toward operations and management information systems. It appears to be an attractive outlet for innovation researchers from an organizational behaviour discipline base.
Technovation	It frequently draws on economics and science and technology, cites heavily Research Policy and International Journal of Technology management.
International Journal of Technology Management	It is likely to be a vehicle of choice for researchers focusing on managing with technology. Draws on economics and science and technology literatures.
Journal of Product Innovation Management	It draws heavily from the marketing literature addresses the entire innovation process.
Research Technology Management	It draws heavily from other innovation journals and practitioner-oriented sources.
Technology Analysis & Strategic Management	It is influenced heavily by the organizational behaviour and strategy fields.
Journal of Engineering and Technology Management - JET-M	It is likely to be the vehicle of choice for researchers who approach innovation studies from an organizational behaviour perspective.
R&D Management	It draws from economics and behavioural disciplines.

Based on: Linton and Thongpapanl (2004), Ball and Rigby (2006), Linton and Embrechts (2007), Hall (2018) and Pitt et al. (2021).

From the discussion on contextualization presented in section 2, we identified prominent experts to invite as contributors to this paper. Our selection criteria included high impact on climate change academic and policy debate in recent years and a diversity of representation that would include Europe, the US, Asia, Africa and Latin America. High impact was measured by number of citations, number of publications in top academic journals in the fields of innovation, policy and science, an active role and influence on policy panels such as IPCC and taking a leading institutional role and strong public and media engagement, to name a few. The lead authors interacted with experts during the paper development process to jointly draft, revise and refine the paper.

3.1. Descriptive overview of past and current key research themes

To begin, some broader context of the theoretical approach adopted by climate change related studies published in innovation journals is helpful. The multidisciplinary line of inquiry focusing on innovation, policy, as well as technology management that sit within it, has been heavily influenced by major conceptual approaches. One notable stream of research focuses on innovation systems, with innovation-activities of firms at the centre stage of economic and innovation processes and related systemic contexts supporting, or hindering, innovation capabilities (Lundvall, 1992; Nelson, 1993; Edquist, 1997; Watanabe et al., 2000; Tukker et al., 2008).

Another stream of research has taken a different approach and examined innovation as a transformative process that involves the concurrence of systems of innovation, production and consumption (e.g., Geels, 2002, 2004; Verbong and Geels, 2007). This approach analyses the emergence and diffusion of new technologies as involving struggles between radical niche-innovations, existing regimes, and macro-contextual 'landscape' developments across techno-economic, socio-political and cultural dimensions (Geels et al., 2018; Weber and Rohracher, 2012). Such stream of research, known as socio-technical transition studies, has evolved from 'end-of-pipe technologies' to 'clean tech' to system change and socio-technical transitions (Smith et al., 2010). Transition studies are framed by four core theoretical strands - transition management, strategic niche management, multi-level perspective on socio-technical transitions and technological innovation systems (for a detailed account of the emergence and delineation of the transition studies field see Markard et al., 2012). As we will show later, researchers have used such approaches as framework of analysis for their studies on innovation and climate change, including some of the most cited papers.

Fig. 1 shows the volume of related papers published from 1990 to 2021 suggesting a significant rise in interest in the topic after 2005 and a sharp increase since 2015. Although such an increase is due to an overall growth in number of publications across all areas of research in the last

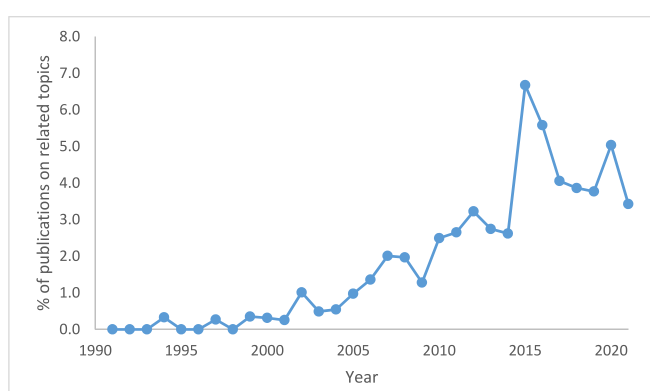


Fig. 1. Number of papers related to search terms in top ten innovation journals (1990–2021).

decades (To and Yu, 2020), it may reflect researchers' response to special issues in related themes in the 2000s, which in general tend steer related studies after special issue is done. For example, we found eight special issues in *Technological Forecasting and Social Change* on topics such as sustainable development goals, grand challenges, climate stabilization, climate implications of GHG and energy efficiency.

In Table 2 we list the top ten journals in number of related published papers, which is led by *Technological Forecasting & Social Change* followed by *Research Policy*. Unlike the other journals in the list, these two journals organized special issues on topics that drew researchers' attention to related submissions. Ten out of the twenty most cited papers shown in Table 3 were published in *Research Policy*, followed by *TFSC* with eight papers. The number one cited paper was published in *TFSC* by Riahi et al. (2007), which examines GHG emission scenarios for climate change mitigation technologies and finds that the energy sector is clearly the largest source of GHG emissions and thus the prime target of emissions reduction. The second most cited paper by Weber and Rohracher (2012) deals with policy legitimization processes for long term strategic challenges. The latter adopts a transitions approach to better capture the complexities of transforming systems of innovation, production and consumption. Many highly cited papers explore the transitions literature and the role of governance, policy, innovation pathways and strategic management.

Fig. 2 shows a network visualization of main research topics related to climate identified by authors' keywords. Circles indicate the degree or frequency of the node and the strength of the line, the co-occurrence amount. Here we refer to these clusters of keywords as key research themes. The data suggests that, excluding generic terms such as innovation, climate change, economics, technology development and sustainable development, three major research clusters stand out, *Climate change mitigation* (orange) with links to studies related to China, environmental impacts and industrial structures; *Empirical analysis* (Blue) linked to studies on innovations such as full cells and alternative vehicles and to stakeholders and *Sustainability transition* (Purple) which connects to studies involving innovation policy and systems, social aspects, etc.

Outside the main clusters represented by coloured bubbles, we observed significant increase in fragmentation of research topics related to climate change in the field of innovation studies over the years. For example, while during the ten-year period of 2003–2013, we identified 81 different keywords, between 2014 and 2021 this number increases to almost 400. Single or small groups of papers deal with topics that have few linkages to major themes in the field.

3.2. Thematic overview of past and current key research themes

Building on the above main clusters of research papers, keywords and the sample of highly cited papers since 1990 (Table 3), we explore some of the key themes emerging in the field of innovation studies. Although many studies clearly belong to more than one cluster, here we focus on how most relevant studies have addressed key challenges related to climate change and innovation. Inductive themes are summarized in Table 4.

Table 2
Innovation journals and published papers related to search themes.

Journal	Number of publications
Technological Forecasting and Social Change	603
Research Policy	104
IEEE Transactions on Engineering Management	58
Technovation	51
International Journal of Technology Management	20
Journal of Product Innovation Management	14
Research Technology Management	12
Technology Analysis & Strategic Management	6
Journal of Engineering and Technology Management	5
R&D Management	4

Table 3
Sample of highly cited papers since 1990 (Scopus database).

Paper	Focus	Scopus citation
Riahi, K. et al. (2007)	GHG emissions scenarios of different socio-economic and technological developments.	754
Weber, K.M., Rohracher, H. (2012)	Policy legitimizing framework for transformative change.	447
Kivimaa, P., Kern, F. (2016)	The concept of 'motors of creative destruction' – extending the concept of Technological Innovation Systems (TIS).	384
Rogge, K.S., Reichardt, K. (2016)	The concept of policy mixes for sustainability transitions and related analytical framework.	382
Nemet, G.F. (2009)	Demand-pull policy measures influence on non-incremental technical change	381
Geels, F. W. et al. (2016)	Transition pathways typology and transitions shifting between pathways.	375
Hekkert, M.P., Negro, S.O. (2009)	Functions of innovation systems framework for technological change processes.	265
El-Kassar, A.-N., Singh, S.K. (2019)	Green innovation drivers and influence on competitive advantage, environmental and organizational performance.	248
Späth, P., Rohracher, H. (2010)	Ways to analyse regional discourses on socio-technical futures.	247
Herring, H., Roy, R. (2007)	Consumers rebound effects and how innovative technology might be designed to promote environmental benefits.	245
Verbong, G.P.J., Geels, F.W. (2010)	Possible transition pathways for sustainability transitions in the electricity system and implications for (grid) infrastructures.	238
Riahi, K. et al. (2015)	Implications of the near-term pledges for the feasibility and costs of long-term targets.	223
Costantini, V., Mazzanti, M. (2012)	Public policies and private innovation patterns influence on production process higher efficiency	213
Foxon, T.J. et al. (2010)	Transition pathways development approach for a low carbon electricity.	213
Wardekker et al. (2010)	Resilience as an approach to climate change adaptation under uncertainty.	213
Johnston, B. et al. (2005)	The challenges to moving to a hydrogen-fuelled economy and how to proceed.	205
Veugelers, R. (2012)	Mission oriented green innovation policy.	199
Hess, D.J. (2014)	Sustainability transitions as a political process and the role of industrial power to support pro-ST political coalitions.	190
Geels, F.W., Verhees, B. (2011)	The role of cultural legitimacy in technical innovation journeys.	182
Hoppmann, J. et al. (2014)	The influence of technological change interdependencies and uncertainty on policy interventions in socio-technical systems.	178

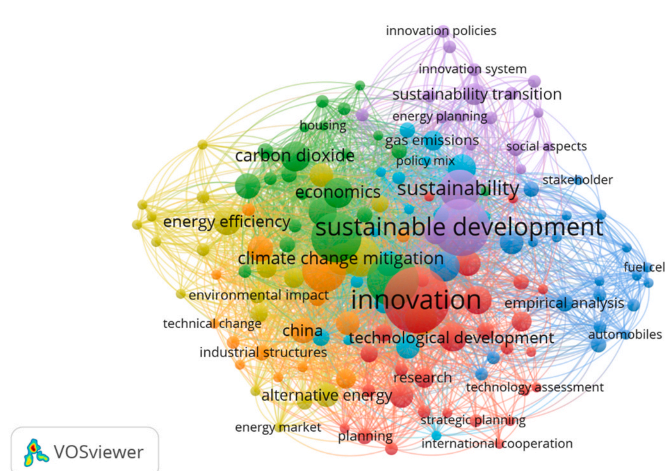


Fig. 2. Overlay Visualization of authors' keywords listed at least 5 times.

Table 4
Overview of key themes within the innovation and climate change literature.

Theme	Description
Utilizing innovation to foster adaptation and mitigation and involve stakeholders	Harnesses insights about the interplay between technology, organizations, regulations and user practices influence, or are influenced by, the adoption of alternative sources of energy technologies to describe or accelerate climate action, or involve a broader set of actors and stakeholders
Shaping transition processes via *policy and management*	Draws from empirical or conceptual work about how to inform local, national, or global policy and/or improve transition processes and management
Promoting social experimentation, learning and adoption	Investigates functions of technological innovation systems or social experiments, expectations, learning patterns or diffusion rates of transitions
Examining the efficacy or effectiveness of technologies or transition processes	Evaluates often in a more normative manner whether a given transition or technology is better or worse for the climate or effective compared to other technologies or some sort of baseline

3.2.1. Utilizing innovation to foster adaptation or mitigation and involve stakeholders

Innovations on climate change mitigation include energy efficiency as well as low-carbon and non-carbon technologies, carbon reduction technologies, carbon capture, and storage technologies (Newell, 2009). More controversial technologies include "geoengineering" options, which seek to slow or reduce global warming through the intentional, large scale modification of the climate (Sovacool, 2021b; Winter, 2014). Geoengineering proposals involve inflecting reflective particles in the atmosphere, carbon capture and storage into the ground, or building giant mirrors in space to deflect the sun's rays (Sovacool, 2021b; CB Insights, 2019).

These distinct climate pathways or approaches can even be visualized in Fig. 3. Essentially, mitigation and geoengineering options seek to "avoid the unmanageable" by directly lessening carbon dioxide or equivalent emissions or enhancing the ability of natural and technical sinks to store them; adaptation seeks to "manage the unavoidable" by building resilience and adaptive capacity to account for climate changes already underway, given previous levels of emissions and likely future outcomes. Thus, each pathways involves divergent underlying management logics, business markets, and incumbent actors. Mitigation is often perceived as a public good with little to no market value other than the direct sale of energy technologies or services, with a business model focused on fuel substitution or pushing low-carbon alternates to take the place of fossil-fuel systems. Main actors here include emerging renewable energy and electric vehicle companies, the extractive industries and mining sector, the hydrocarbon industry, retrofit firms, and energy service companies. Climate adaptation is often perceived as having strong local co-benefits and a market value connected to improving resilience, making investments in infrastructure, or diversifying other local assets such as agriculture or buildings; incumbent actors here include those already pushing large development or community benefit projects. Geoengineering has the weakest but also newest business model, with no set of established actors but the potential to disrupt the underlying logics and market structures of both mitigation and adaptation.

Most innovation literature focuses on mitigation and adaptation, rather than geoengineering. As evidenced by our review, innovation studies within the mitigation theme have often examined how the interplay between technology, organizations, regulations and user practices influence, or are influenced by, the adoption of alternative sources of energy technologies. For example, Stephens et al. (2008) explored socio-political influences (e.g. regulations, institutions, public

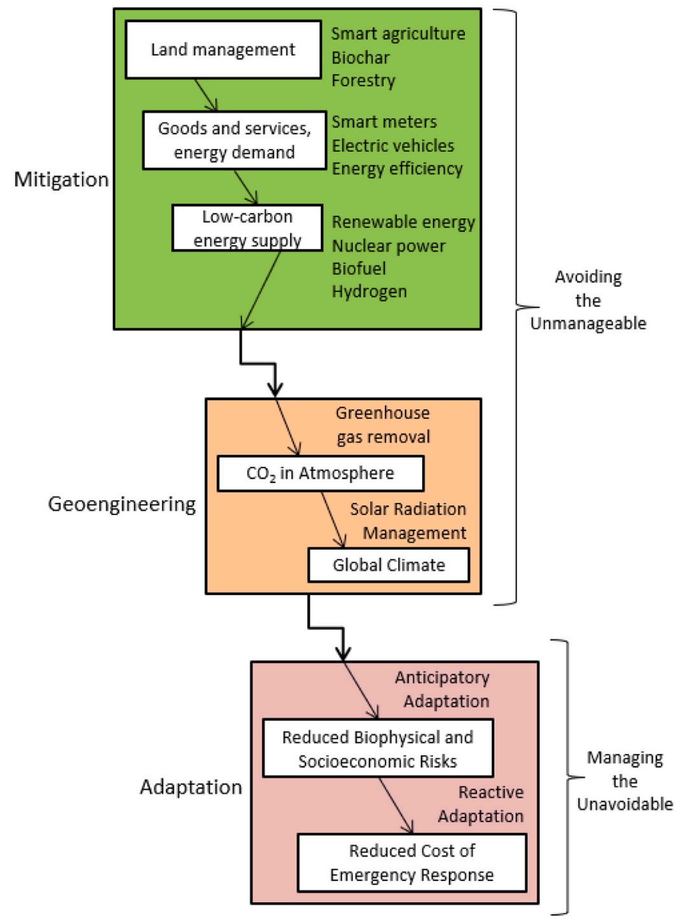


Fig. 3. Conceptualizing climate change mitigation, geoengineering, and adaptation.
Source: Modified from Sovacool (2021a).

perception) that can accelerate the deployment of alternative emerging energy technologies. Consistent with van de Kerkhof and Wieczorek (2005), they highlight the need to adopt an integrative analysis that considers the perceptions of key stakeholders but add the importance of also integrating policy review and media for more effective strategies to accelerate the deployment of emerging energy technologies.

Other studies within this cluster explore how to promote more stakeholder inclusion. The importance of both interstitial factors (interplay) and stakeholder influence is also investigated by Paschen and Ison (2014) examining how perceptions of a particular problem or challenge influence our understanding of local socio-ecological systems. They suggest that narrative investigatory approach of human cognition process of an issue, such as climate change, can play an important role in building governance approaches that are more transformative from the stakeholder side. The message here is that local environmental knowledge, lay perceptions and socio-cultural and affective-emotive factors can add fundamental information to the design of adaptation policies and public engagement strategies. van de Kerkhof and Wieczorek (2005) argued that stakeholder engagement framework needs to be adopted in dealing with the complexities of transitions management effectively. They suggest a learning process in which the participants distance themselves from their immediate interests and consider new viewpoints, while still raising any issues and questioning assumptions on which these viewpoints are based.

Together, the above studies indicate that climate action must intertwin a broad, sociotechnical set of issues. As the combination of influences among landscape and socio-technical regime factors shape technology change, attention must be also devoted to potential, yet expected, unintended outcomes of so many interactions (Latour, 1988).

3.2.2. Shaping transition processes via policy and management

Another cluster of studies published in innovation journals focus on what elements count for informing policy, how policies should be developed and how transition management processes can be improved. For example, some studies investigate how well-designed policies include coordination among consistent carbon pricing, performance-based regulations and public funding (Veugelers, 2012). These findings indicate that consistency issues and long-term nature of regulations and taxes are crucial to the policy interventions influence. Longevity of governmental incentives was also identified in a previous study by Nemet (2009) as a key shortcoming of 'demand-pull' approaches. Using the case of wind power technology, he showed that although demand-pull policies have created a multi-billion dollar market for mitigation technologies, lack of policy consistency partially explain why investors did not react positively. A later study by Kriegler et al. (2015), takes a different approach to the analysis of policy influences by examining the effect of front runner coalitions, such as the EU and China, and follower countries, to forecast the climate mitigation policy landscape. They found that early action in China has a measurable impact on warming outcomes by reducing pre-2050 excess emissions by 20–30% thus increasing the likelihood of staying below 2°. For the follower countries, technology responses to front runner tend to be limited, thus requiring dedicated policy instruments for innovation diffusion. The delayed action from follower countries may lead to larger transitional mitigation challenges in the medium term (Kriegler et al., 2015).

Taking a different perspective, Verbong and Geels (2010) suggest scenario building approaches as systematic exploration tools of transition pathways and policy goals and strategies. They show that such tools can provide an in-depth assessment of the dynamics of transitions and even unravel possible hidden strategies. Foxon et al. (2010) also use scenario approach to add that transitions pathways need to consider integrating technological and social science analyses.

Other studies within this cluster look at styles of transitions and transition management. Innovation studies such as Wardekker et al. (2010) have taken a resilience approach as managerial solution to enable "*… a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks*" (p. 988). Under this perspective, participatory evaluation of adaptation options is used to allow making resilience sufficiently operational for local actors to translate a concept into concrete actions. On a related study, Walker et al. (2010) emphasize the complementary, yet crucial, role of policies that are context sensitive, as opposed to 'top-down' and more rigid regulations, in supporting and promoting resilience.

3.2.3. Promoting social experimentation, learning and adoption

This cluster of literature emphasize the social aspects of transitions via experimentation or diffusion and adoption. Some studies engage with real life data to identify and codify lessons learned from current green technologies development and adoptions issues, especially insofar as they can be considered social or governance experiments. For example, biomass energy technologies have been used to examine what functions of a technology innovation system (i.e., interacting network of agents under an institutional infrastructure) work well (Hekkert and Negro, 2009), indicating that the key is to coordinate the interplay between guidance through policies, market formation and entrepreneurial activities.

Other lessons have been drawn from analysing consumer adoption issues of alternative vehicles technologies, such as battery-electric and fuel cell vehicles. van Bree et al. (2010) for example, use Multi-Level Perspective to explain that there are dynamics between manufacturers and consumers, which are affected by pressures created by climate change regulations and rising fuel prices. On a related study, Eggers and Eggers (2011) demonstrate key critical adoption factors for all-electric vehicles include purchase price, timing of the market entry, or the progressing of a set structures (i.e., network of repair shops and charging stations) that fosters alternative technologies. A later study, by Huenteler et al. (2016), suggests that in order to stimulate the necessary innovation process through policies, these need to be tailored to different patterns of innovation life-cycle, i.e. product-process innovation or system-component shifts, because these cycles involve very different innovation and learning processes.

3.2.4. Examining the efficacy or effectiveness of technologies or transitions

A final cluster of literature examine the efficacy or effectiveness of particular technologies or transitions (in terms of achieving carbon targets or engendering rapid and sustained transitions). Su and Moaniba (2017) found that the number of climate-change technologies has increased as the changes in levels of carbon dioxide and other greenhouse gas emissions worsen. However, this is only true if carbon dioxide emissions come from coal and natural gas. The authors also found negative relationship in green technology development if emissions mostly come from petroleum and other greenhouse gases. While they found a positive correlation between major GHG countries and technology development, government investments in energy, telecom, transport or water/sanitation joint public-private projects seem to have limited contributing factor to the development of climate-change technologies.

Du et al. (2019) draw on Su and Moaniba (2017) and their patent analysis to examined whether green technology development has decreased carbon emissions. Although they found that green technology innovations play a vital role in climate change mitigation, these only take effect when the economy reaches a high-income level. This is in part because green technology is typically expensive for individuals in low-income economies, suggesting that support mechanisms such as intellectual property protection, green finance, and governmental support are need for accelerating diffusion and application of green technology in emerging economies (Su and Moaniba, 2017). In another empirical study using zero-energy buildings, Brown and Vergragt (2008) show that green innovation is about technology as much as it is about people's perceptions, and their learning interactions with organizations and the technology. An earlier study by Herring and Roy (2007) calls the attention for unintended outcomes of energy efficiency improvements in consumer behaviour. They found that lower energy price may lead to greater consumption and reducing energy costs through efficiency can increase purchase of larger and more powerful product models.

4. Contributions of the papers in this issue

Driven by an array of challenges, and opportunities, to enable decarbonization technologies, this Special Issue aimed to acknowledge and motivate relevant innovation research. As we recognize that business, economic, social pressures in responding to climate change influence future innovation, we sought to provide a deeper and wider understanding of how, why and when organizations respond to the effects of climate change either as a stimulus or as a deterrent of innovation. In doing so, we focused on showcasing how to exploit the former and overcome the latter.

In total 25 papers were submitted, of which one third were from China, another third from Europe and the remaining from various countries. We received one from Brazil, one from Pakistan, and one from Africa. Most of the topics addressed regulations and policies issues affecting technology innovation, followed by financing and investment, then business model innovation. Only one paper involved digital innovation. The contributions of the four papers that survived the review process, including their focus and methods are listed in Table 5 and discussed next. Two of them, Zhang et al. (2021) and Greco et al. (2020) are closely related to shaping transition process theme discussed above. The other two papers, Elahi et al. (2021) and Nylund et al. (2021), focus on utilizing innovation to foster adaptation or mitigation.

Table 5
Summary of the four studies published in this special issue.

Study	Focus	Methods	Key Implications
Zhang et al. (2021)	Low-carbon technologies and investment decision-making	Dynamic modelling	Low-carbon adoption investment decisions need to consider consumers' perceptions and government interventions simultaneously
Elahi et al. (2021)	Technology innovation and global warming adaptation in South Asia	Survey of 1232 wheat growers from Pakistan	Education and experience are positively associated with adaptation strategies. Information technology benefit all (whether large or small farmer).
Greco et al. (2020)	The effectiveness of different sets of policy instruments	Cross-sectional data and longitudinal data from surveys in 2009 and 2015.	Coordinated design, implementation and environmental innovation policies are more likely to survive in the long run. Additional support to firms benefiting from innovation policies does not positively affect environmental innovation development.
Nylund et al. (2021)	Patterns of eco-innovation emergence for climate change mitigation	Climate change mitigation technologies patent citations	Dominant designs strongly influence enabling global warming mitigation technologies Financing radical innovations with strong enabling capacities brings better benefits.

The paper titled "Enterprises' decisions on choosing low-carbon technology by considering consumer perception disparity" adds to our understanding of the difficult challenges large companies are facing when considering investing, or not, in innovation for mitigating global warming (Zhang et al., 2021). The paper analyses how consumer perceptions and government subsidy policies are both critical in the decision of a firm to adopt low-carbon technology. They note that in China, companies need to consider consumers' perceptions before investing in low carbon innovation for new product development, especially if there are various competing options. This is because consumer low-carbon preference plays a significant role in affecting the types of products in the market. The study suggests considering simultaneously the impact of consumers' perceptions and government interventions on adoption processes. As we discussed above, given that the Chinese government plays an important role in promoting low carbon technology innovation, understanding their investment decision processes may help foster mitigation technology adoption around the globe.

The paper by Elahi et al. (2021) investigates how technology innovation can contribute to the adaptation to the consequences of global warming in South Asia. It concerns with the agricultural sector in an emerging country as indicted in its title: "Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk: A retrospective survey of rural Punjab, Pakistan". The study addresses a widely acknowledged concern over the detrimental impact of global warming on agricultural production especially in emerging countries (IPCC, 2014). While Africa has often been pointed out as a vulnerable area of the world, few studies have examined climate change issues in South Asia, especially Pakistan. Yet, the country is the eighth most affected by climate change according to the Global Climate Risk Index (Eckstein et al., 2021). The authors found that farmers who adopted climate smart management strategies had higher wheat yield than farmers who did not practice these measures with a positive association between education (and experience) and adaptation strategies. While large farmers are more likely to adopt innovative management strategies, due to access to more resources compared to small/medium farm holder, information technology played an important role for all. This is because access to weather forecast information helps adjusting irrigation schedule more frequently and effectively. The paper also offers detailed recommendations to governments to help farmers to mitigate the consequences of global warming not only with education and preparation but also with financial and technical support. The authors advocate for a more systematic implementation of climate-smart strategies that have been practiced in other parts of Asia, such as efficient drainage systems in India, agroforestry in Viet Nam, and the use of stiff-stem wheat variety in Japan.

The paper by Greco et al. (2020) explores the effectiveness of different sets of policy instruments used by the German government to stimulate environmental innovations and general innovations. The study discusses issues related to situations where governments have separate programs to invigorate environmental innovations that are designed and managed by different ministries, even though sometimes they are using the same kind of tools such as R&D subsidies. The authors highlight that while interaction between different programs may lead to positive results (i.e., policy mix) there is also the risk that lack of overall coherence and alignment turns into poor results (i.e., 'policy mess'). Thus, the research analyses if the effectiveness of a cross-instrumental policy mix is greater than the effectiveness of individual innovation and environmental. The study comes at an interesting time given that in September 2019, a comprehensive climate policy package was introduced by the German government. The results show that cross-instrumental policy mix have better effects than individual programs run independently, both in the short and the long term. Interestingly, the authors find that providing general support for innovation to firms already benefiting from environmental policies does not create any additional effects to develop environmentally friendly innovations. One possible reason being the lack of coordination amongst the public agencies responsible for implementing innovation and environmental policies. The authors conclude that policymakers should coordinate their efforts in designing and implementing innovation and environmental policies; with positive effects likely to persist in the long term. This is an interesting point to make considering longstanding nature of global warming issues and the need to continuous actions from governments notably to stimulate clean-air innovations as pointed out by previous studies discussed above (Nemet, 2009; Veugelers, 2012).

Finally, the study developed by Nylund et al. (2021) identifies enabling technologies and study the patterns of emergence of new fields of eco-innovation in sectors or categories of climate change mitigation. Following Autio and Thomas (2014), they define enabling technologies as those that create platforms or stimulate ecosystems that build other innovations. As environmental technologies in general are complex and relied on other technologies to be fully developed and effective, eco-innovations, and more specifically low-carbon innovations, are developed within ecosystems of different entities. Within these ecosystems, some technology innovations are more crucial than others and have the potential to serve as the basis of complementary innovations in other related application areas. The authors build a conceptual framework around how complementary, complex, and collaborative technologies contribute to the generation of enabling technologies. Then they apply it to global warming related sectors to study those enabling technologies and their trajectories. Their findings indicate that building on previous enabling technologies is helpful and that a dominant design has in general a high influence on enabling technologies when it comes to mitigate global warming. Another implication is that it is better to finance radical innovations with strong enabling capacities for the development of induced technologies and the capacity to become a market standard. This may probably comfort the view of investors such as Bill Gates who prefer to fund innovative start-ups that are emulating the strategy of Microsoft to turn a new product in a *de facto* standard.

While the four accepted papers present clear contributions, they also open other avenues for future research. For instance, following the perspective of Elahi et al. (2021), further research is need in examining how innovations may help to adapt to the consequences of global warming in the agriculture in other emerging countries in Africa, Asia, or South America, including Brazil. Similarly, the research presented Nylund et al. (2021) underlines the necessity to better understand the role of digital innovation, both intended and unintended, in developing effective technological to mitigate the impacts of climate change and explore its consequences.

5. Challenges and research opportunities

To both contextualize and ground the Special Issue, but also chart critical research frontiers within the field, this section details multiple perspectives on climate change and innovation from the expert contributors and presents a discussion on topics relating to the challenges and opportunities for future research.

5.1. Blending behavioural change with technological innovation

Much of the innovation literature supposes that policy action (often from the top-down) can steer and shape sociotechnical change in ways conducive to sustainability transitions, a theme already mentioned above in section 3.2. An implicit argument here is that policy can effectively shape technology and innovation patterns. This includes a distinction between technocratic solutions – e.g. technology standardisation and licensing (e.g. Kamp and Forn, 2016) – and socially oriented user-based engagement which can enable tinkering and localized innovation (e.g. Hargreaves et al., 2013; Raven et al., 2008; Browne et al., 2012). Tsoutsos and Stamboulis (2005) even suggest three key policy aims: (1) the development of focused learning mechanisms, (2) the encouragement of new types of players and (3) flexible financing mechanisms, adapted to the characteristics of individual applications and environmentally consistent academic evaluation.

Nevertheless, in focusing so aptly on policy and technology, some of the innovation literature glosses over a key debate within the climate change and energy policy literature concerning the potential emissions reductions to be achieved by technology (and further improvements in innovation and technical performance), but also those that may be achieved by behaviour (or an alteration of practices and social dynamics). Behaviour change of consumers can be influenced by individual elements such as emotional factors and cognitive biases in the decision-making process, and external factors such as socio-economic inequality, cultures of energy consumption, fiscal instruments such as carbon pricing, etc. (Creutzig et al., 2018; Dubois et al., 2019; Moberg et al. 2021).

For example, as much as 72% of global greenhouse gas emissions can be ascribed to household consumption, the remaining share being related to public consumption. This makes decarbonation as much about household decision-making, demand and behaviour as technology. Technical energy efficiency solutions essentially reduce the emissions per unit of production (e.g. reduce emissions from producing private cars) and/or offering products or services with lower emissions per unit of consumption (e.g. private cars with better mileage). For this to result in absolute reductions of emissions – and not merely reducing the relative emissions - we need to obtain control over or abate rebound effects. The extent of non-mitigated rebound effects is thus an important reason why technical improvements do not always create net reductions in emissions. Behavioural solutions on the other hand involve an active effort in changing the nature – in some cases also the amount - of consumption. This can be – presented in order of qualitative changes to take place – (1) renouncement (e.g. giving up owning a car), (2) reduction (e.g. reducing your mobility), (3) substitution (e.g. using public transportation instead of a private car), and (4) efficiency -improvement, e.g. continue using your private car, but buying a more efficient one (Høyer, 1999).

Even if both the technical and behavioural categories of change reduce the overall footprint of a household directly and indirectly, technical energy efficiency solutions target typically the production side (car-makers in our example), whereas behavioural solutions target households (the buyer and driver of the car). As an example of the large and robust potential individual behaviours hold, Fig. 4 simulated a technical energy efficiency versus behavioural approach towards household carbon reductions between 2015 and 2050. Assuming a 2 percent annual reduction rate "technical energy efficiency" solutions could in theory - given that we can mitigate rebound effects - still only halve global emissions, while a combination with behavioural shift would in theory diminish emissions significantly further by almost 76 percent. Although a combined pace of 1 percent per annum would lead to a halving of emissions in 2050, a combined pace of 3 percent would reduce emissions almost by a factor 10 in 2050. The bottom panel of Fig. 4 also underscores the sheer magnitude of emissions reductions that behavioural change in theory can accomplish—far more than low carbon infrastructural supply or the pledges under the Paris Accord.

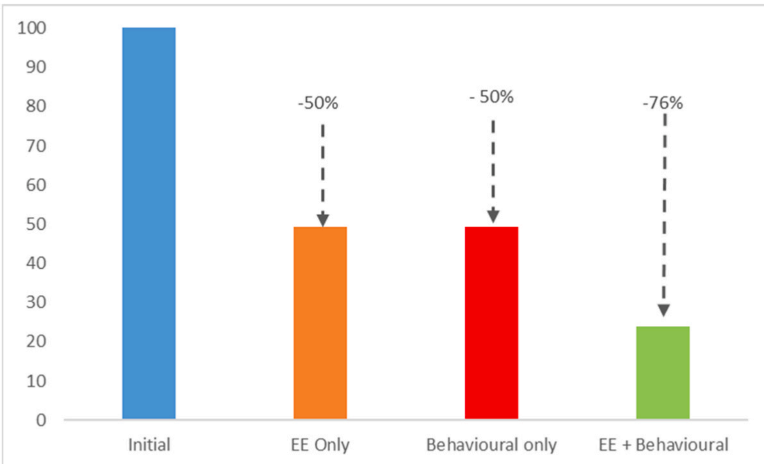
Thus, policymakers and other actors need to focus more on stimulating sustainable behaviours and lifestyles. The research community also needs data and knowledge that can address this nexus of demand-side options, lifestyles, barriers and required behavioural change to decarbonize lifestyles (Moberg et al., 2021).

Nevertheless, we also need to continue to harness innovation as a means to achieve decarbonization. Technologies (and the financing behind them) will play a key role in the successful transition of the energy system in reaching carbon neutrality by 2050 and beyond. As the top panel of the Fig. 5 below suggests, promoting technological innovation and diversity involves not only maintaining and perhaps phasing out typical, aging, and often inefficient equipment. It also involves promoting currently commercialized best practices such as energy efficiency measures in buildings, wind and solar power, combined heat and power, post combustion CO2 capture, electrification of industrial processes, LED lighting, biofuel cars, and improved pollution controls on power plants as well as investing in state-of-the-art options such as fuel cells, advanced fuels, and offshore wind farms. It lastly involves steering investment in future frontier or breakthrough technologies such as fusion or algal fuels that could revolutionize how we supply and use energy in the far future. The International Energy Agency underscored this point when they noted that in their scenarios, technologies at prototype or demonstration stage today in 2021 are expected to contribute almost 35% of emissions reductions up to the year 2070; they also noted a further 40% can come from technologies only at the earliest stages of adoption (IEA, 2020).

Ultimately, then, more research is needed on how we can continue to make deep emissions reductions on the demand and behaviour side, but also on the technology side; to ensure that these actions do not displace or trade-off with each other; and also to ensure that such reductions are permanent, and have little risk of leakage or failure. One recent study framed this in terms of technological and behavioural "disruption," and it plotted a set of 98 distinct climate actions distilled from a meta-analysis of 538 proposed policies across multiple decarbonization scenarios. One implication from their fundamental argument was that more extreme behavioural disruption (see Fig. 6, y axis) and extreme technological disruption (see Fig. 6, x axis) achieved less effective carbon abatement than the middle ground of options (reducing heating, reducing waste, decarbonizing industry, etc.). This implies not only that behavioural and technological disruption are needed, but that they must be *balanced* against each other.

5.2. Socio-technical drivers in the acceleration of low-carbon transitions

Another important research topic for innovation studies is the *a. Top panel : Effect of a 2% annual reduction of GHG emissions due to Energy efficiency only (orange), Behavioral only (Red) and cumulated (Green), between 2015 and 2050*



b. Bottom panel: Total gigatons of carbon displaced by behavioural change (in green) compared to INDC pledges (orange) and low-carbon infrastructure (blue)

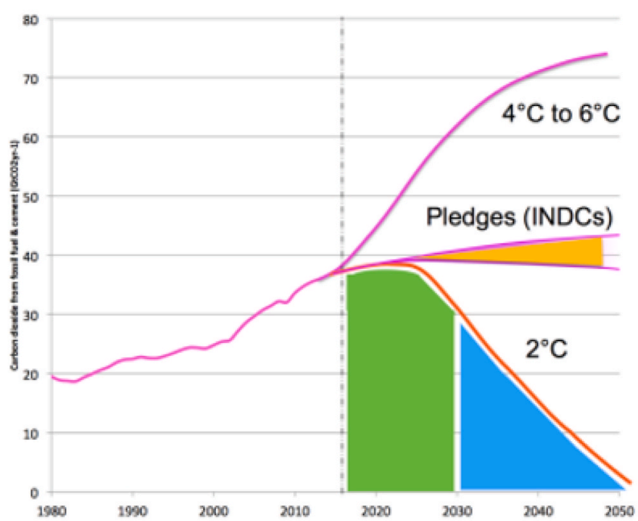


Fig. 4. The magnitude of behavioural changes in mitigating greenhouse gas emissions a. Top panel: Effect of a 2% annual reduction of GHG emissions due to Energy efficiency only (orange), Behavioral only (Red) and cumulated (Green), between 2015 and 2050
b. Bottom panel: Total gigatons of carbon displaced by behavioural change (in green) compared to INDC pledges (orange) and low-carbon infrastructure (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Authors. Note: EE = Energy Efficiency. Data derived from the HOPE project (Dubois et al., 2019) as well as the Tyndall Center (Anderson and Bows-Larkin, 2016).

acceleration of low-carbon transitions, which is essential to keep climate change 'well below' 2 °C. In the widely used Multi-Level Perspective (Fig. 7), this topic is about the shift from the second to the third phase in socio-technical transitions, when radical innovations move from small niches into mainstream markets.

While the special issue papers make important contributions, their focus on the adoption of low-carbon technologies (by firms or farmers) or the effects of policy instruments on environmental innovations do not sufficiently engage with the processual and co-evolutionary characteristics of low-carbon innovation that are essential to understand the endogenous drivers of accelerated innovation and diffusion. The socio-technical transitions and innovation studies fields already offer partial insights about these drivers, but stronger conceptualisations and rigorous empirical investigations of their feedbacks and interactions are yet to be developed. They suggest that endogenous drivers include both techno-economic ones and actor-related drivers:

- technological performance improvements, resulting from R&D activities, knowledge flows within sectoral innovation systems (Malerba, 2002), and complementary innovations that enhance the functionality of new technologies (Arthur, 1989).
- cost reductions resulting from scale economies in production (which spread initial capital costs over more units), improved manufacturing techniques and processes (through learning-by-doing, purchasing new machines, improving factory lay-outs, reducing inputs), or lower financing costs as confidence and experience increase (Arthur, 1989; Malhotra and Schmidt, 2020).
- increasing interests from consumers as new technologies become better or cheaper or because consumer preferences change (Rogers, 1996); increased market demand lowers cost, as noted above, and improves company confidence and investment, as discussed below.
- societal debates and changing social norms, which shape consumer preference (Bowles, 1998) and consumer purchases through contagion and imitation (Young, 2009).
- changing interpretations and increasing confidence by companies, as markets grow and technologies improve, leading to increased investments in R&D and manufacturing plants (Bolton et al., 2016), which help lower costs and further improve the technology.

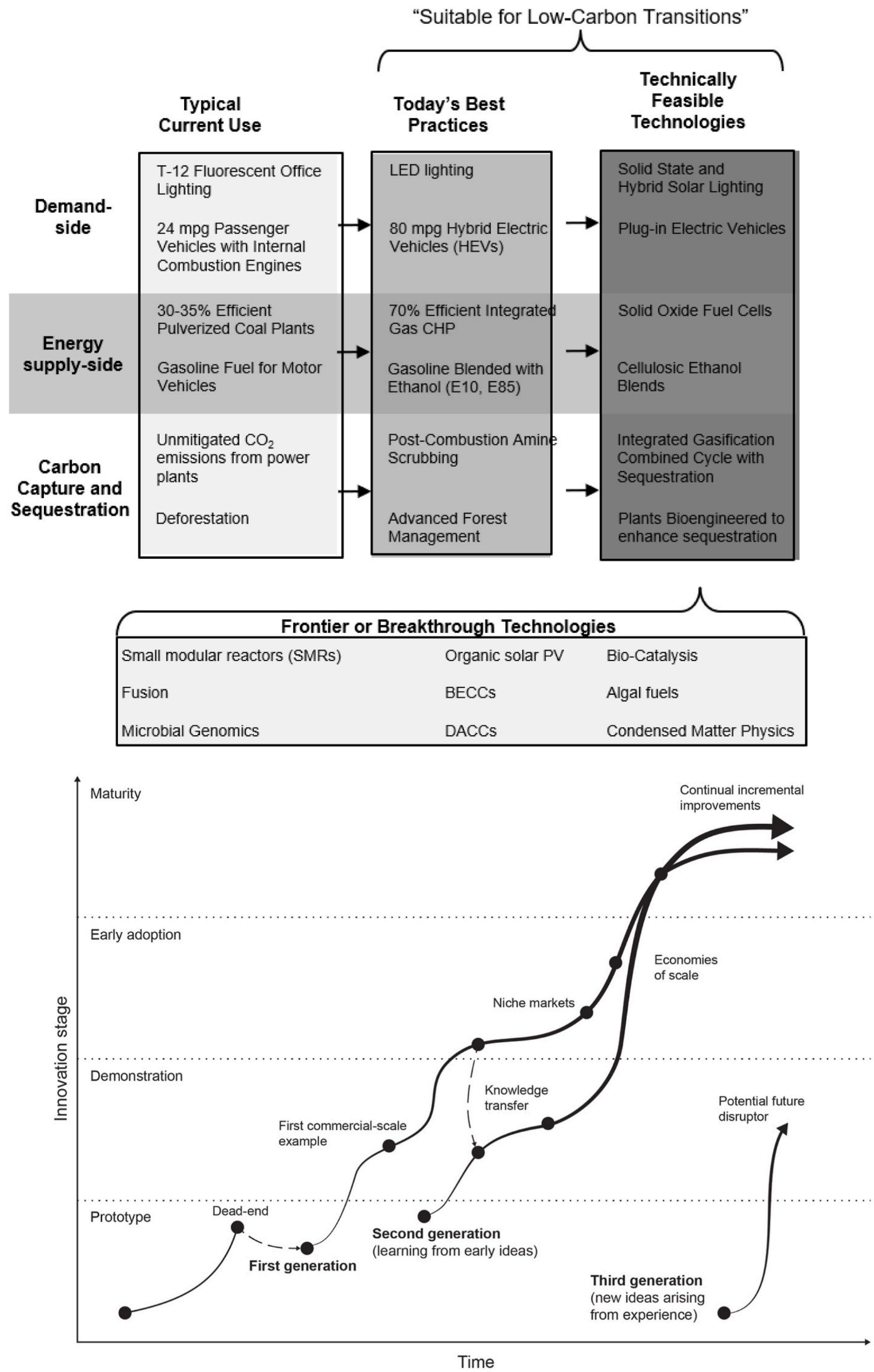


Fig. 5. Typical, current, feasible, and frontier low-carbon energy technologies (top panel) and their associated stages of innovation (bottom panel).
Source: Top panel modified from van de Graaf and Sovacool (2020), bottom panel from International Energy Agency (2020). Note: LED = light emitting diode. PV = photovoltaic. BECCs = bioenergy with carbon capture and storage. DACCs = direct air capture with carbon storage.

- stronger policy support for innovations through R&D subsidies, purchase subsidies, regulations, direct infrastructure investment, often in response to public debates and industrial lobbies (Meckling et al., 2015).

Although comprehensive empirical analyses remain to be done, the few success cases of accelerated low-carbon innovation and diffusion, such as solar-PV, onshore and offshore wind, and electric vehicles, all seem to have involved interactions between these drivers, with positive discourses, sustained policy support and gradually increasing consumer demand boosting company investment that improved technical performance and lowered costs faster than economists and computer modellers had anticipated (Nemet, 2019; Bohnsack et al., 2020; Strauch, 2020; Sharpe and Lenton, 2021): between 2010 and 2020, cost decreased by 85% for utility-scale solar-PV, 56% for onshore wind, 48% for offshore wind (IRENA, 2021), and 90% for Li-ion battery packs (BNEF, 2020).

While different literature strands offer insights into one or more of these drivers, a synthetic understanding of their interactions has not yet been developed. Furthermore, while these interactions can create

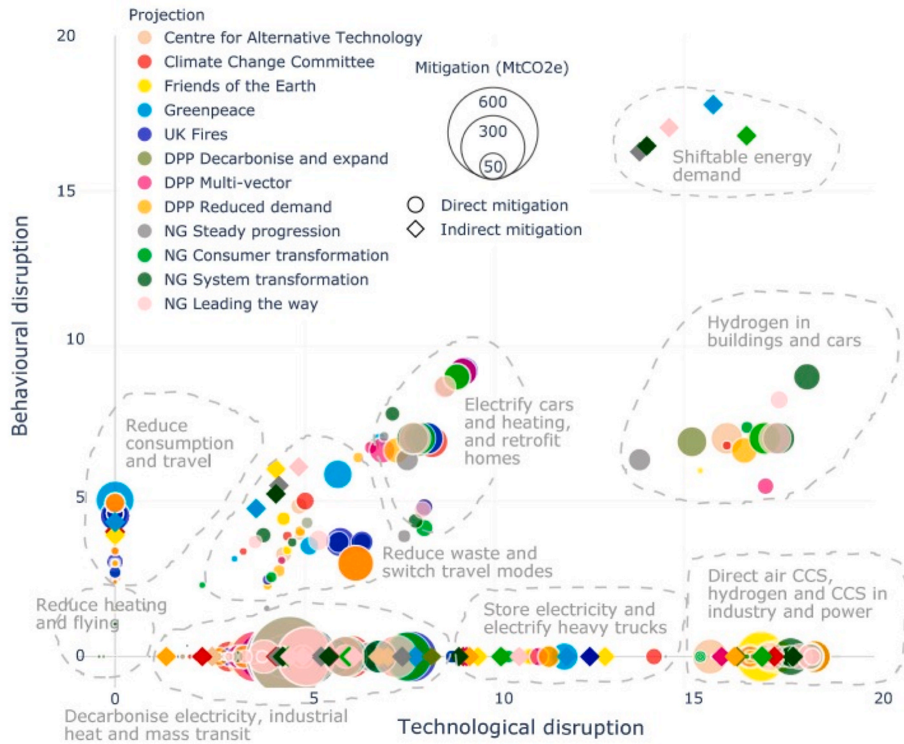


Fig. 6. Technological and behavioural disruption in 98 decarbonization options.
Source: Nelson and Allwood (2021). Note: bubble size represents the relative mitigation potential.

positive, amplifying, feedback loops in later transition phases, they can also generate negative, dampening feedback loops in early phases, when actors are reluctant to invest, develop and adopt new technologies because of inertia, high switching costs, and high technology costs (David, 1990; Aghion et al., 2019). But because they do not invest, low-carbon technologies remain high in costs and low in performance, which hinders and delays the transition. Radical low-carbon innovations therefore first tend to emerge in small, peripheral niches or application domains, which offer protection from mainstream market selection and nurture the gradual development of new technologies (Schot and Geels, 2008)

The core research puzzle for accelerated transitions is therefore how low-carbon innovations can cross tipping points and move from their slow emergence in protective niches towards wider diffusion, which allow learning effects, cost decreases, enhanced confidence, increased investment, and other positive feedback loops to kick in and accelerate the pace of change: "Once they reach a tipping point, where expectations change rapidly, and technologies switch from one network to another, these [feedback] effects frequently go the other way (Krugman, 1991). Positive and reinforcing feedbacks derived from reduced technology cost accelerate further deployment and investment in supporting networks infrastructure, and institutions. Investments in enabling infrastructure spur technology tipping points through generating network externalities" (Zenghelis, 2019: 56–57). This research puzzle is not only interesting in itself, but also important because it offers plausible grounds for hope that low-carbon transitions can be accelerated to keep climate change below 2 °C (Victor et al., 2019; Sharpe and Lenton, 2021).

5.3. Managing solutions through digital technologies

Digital emerging technologies such as blockchains, additive manufacturing, Internet of things, autonomy, information and communication technologies (ICTs) and artificial intelligence can open new venues of solutions to managerial challenges in addressing climate change. For example, it is widely acknowledged that establishing and maintaining a low-carbon supply chain requires the difficult task of understanding issues occurring in the upper tiers of its supply chain (Kesidou and Sovacool, 2019). Monitoring and engaging with upper-tier suppliers in a global supply chain is challenging and requires extensive effort on a brand's part, and the associated resource requirements cannot be understated. Recently, firms have adopted supply chain traceability technologies, large-scale sensor-based measurements, and other data availability to help addressing these challenges (Casino et al., 2020; Tian, 2017).

Indeed, hyper-transparent supply chains can be achieved by digitizing the supply chain and incorporating technologies such as artificial intelligence, blockchain and Radio-frequency identification (RFID). For example, Nike is trying to gain transparency and visibility into the operation of its factories and inventory flowing across multiple countries by extensively adopting RFID and other technologies to 'reimagining' the supply chain infrastructure. What is needed is further research on how companies can find ways to either gain control of monitoring and engagement activities or formulate innovative ways to delegate them.

Despite the recognition of the many opportunities for improved services, one must plan and account for possible energy rebounds (Court and Sorrell, 2020). As illustrated in Fig. 8, ICT indirect impacts include both negative, such as increased packaging due to increase in individual delivery, and positive such as working from home instead of commuting, and do not necessary guarantee a less energy intensive outcome. Unintended outcomes, including increase in consumption due to cheaper service or product, also suggest that the net impact may be difficult to evaluate, and sometimes, to predict.

Yet, digital technologies can play an important role in influencing pro-environment behaviour of consumers. Analogous to the behavioural influence that builds on social norms, i.e. informal understandings about acceptable behaviour within a certain group of individuals, firms can harness the power of social influence to elicit pro-environmental

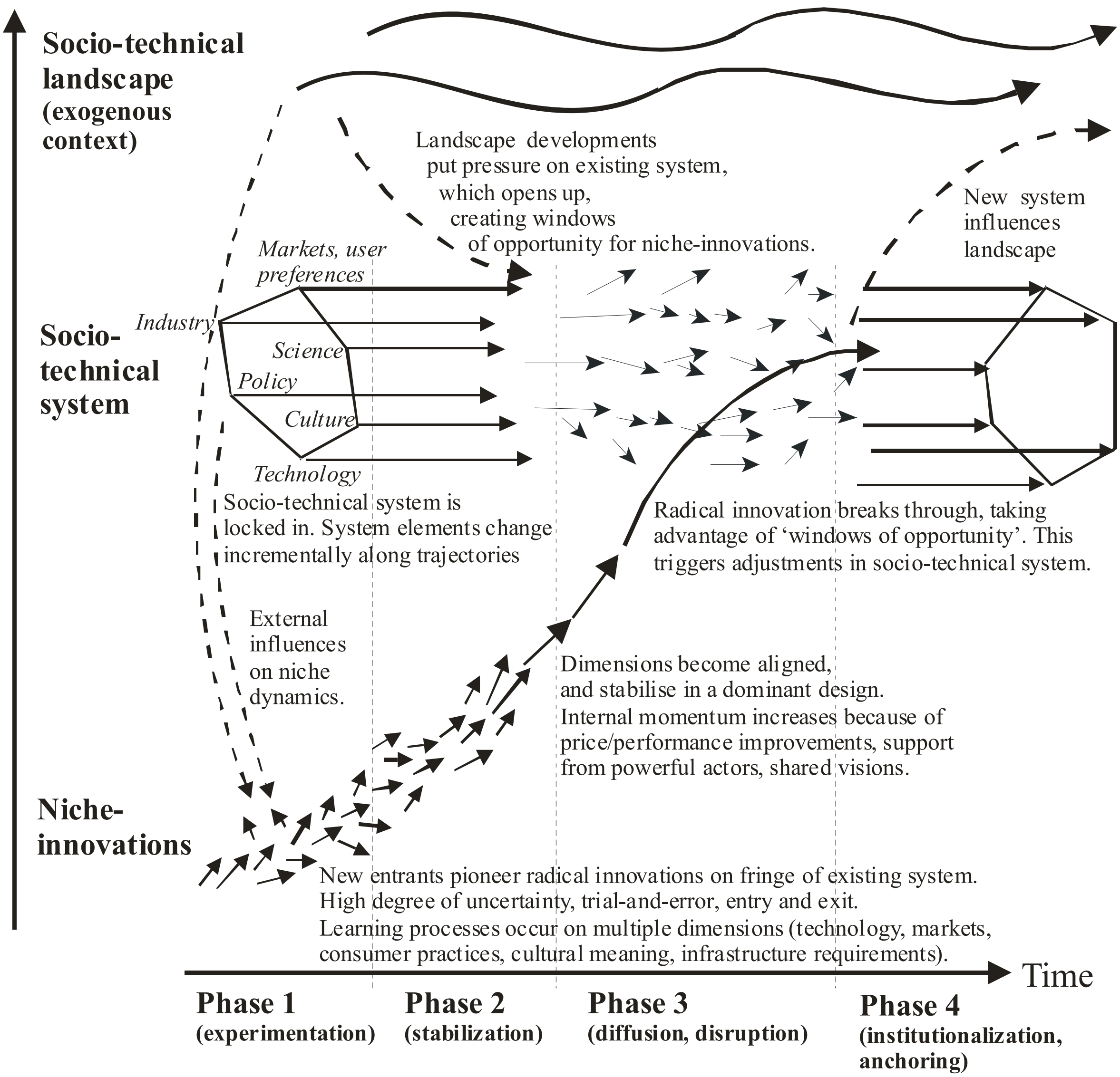


Fig. 7. Multi-level perspective on socio-technical transitions (substantially adapted from Geels, 2002: 1263).

consumption through digital technologies. For example, according to White et al. (2019), firms can influence sustainable purchase of online shoppers by showing on their webpage that others bought eco-friendly products. Yet, challenges still remain in understanding the gap between individual's intentions and behaviour. According IBM's recent study including 28 countries, although 80% of respondents pay great attention to sustainability, and over 70% would pay a premium of 35% on average, only few consumers who say they want to buy sustainable products actually do so. The reasons behind intention-behaviour discrepancies are still poorly grasped, which means that research in narrowing such a gap can be critical for, among other things, improving firms' payoffs from sustainable technologies and innovations.

In addition to the challenges and opportunities outlined above, the following research questions relating to the digital technologies have been not sufficiently explored in the innovation studies field:

- How to constructively use citizens' data to reduce carbon emission? For example, the "smart-city" concept is a technology-driven, data-rich area of research that involves collecting data from a wide range of sensors, so that cities can utilize their assets and resources more efficiently. But how does consumer participation in such data collection affect firms' goals related to climate change?
- How to accelerate the adoption of technologies like blockchain to improve supply chains' sustainability performance? As we mentioned above, digital technologies can help developing a transparent supply chain, improving visibility and alignment with the UN sustainability goals. In addition, these technologies have the potential to increase a firm's agility and improve its response to incidents and enhance a firm's ability to adapt and innovate supply chain processes. Yet, while digital technologies can bring such benefits, technology adoption within supply chains is often slow and incomplete and additional operational challenges are created by managing heterogeneous users (e.g., brands, farmers). Blockchain in particular and a correlated growth in cryptocurrencies have been shown to result in negative impacts to employment, energy consumption, air pollution, and community resilience in the United States and Venezuela (Rosales 2021; Goodkind et al. 2020; Greenberg and Bugden 2019).

Although digital technology research has received great attention in innovation journals, few studies have explored its links with climate change issues. Innovation scholars thus have a critical role to play in enhancing our understanding of the enabling decarbonization opportunities offered by such technologies. Such an understanding must

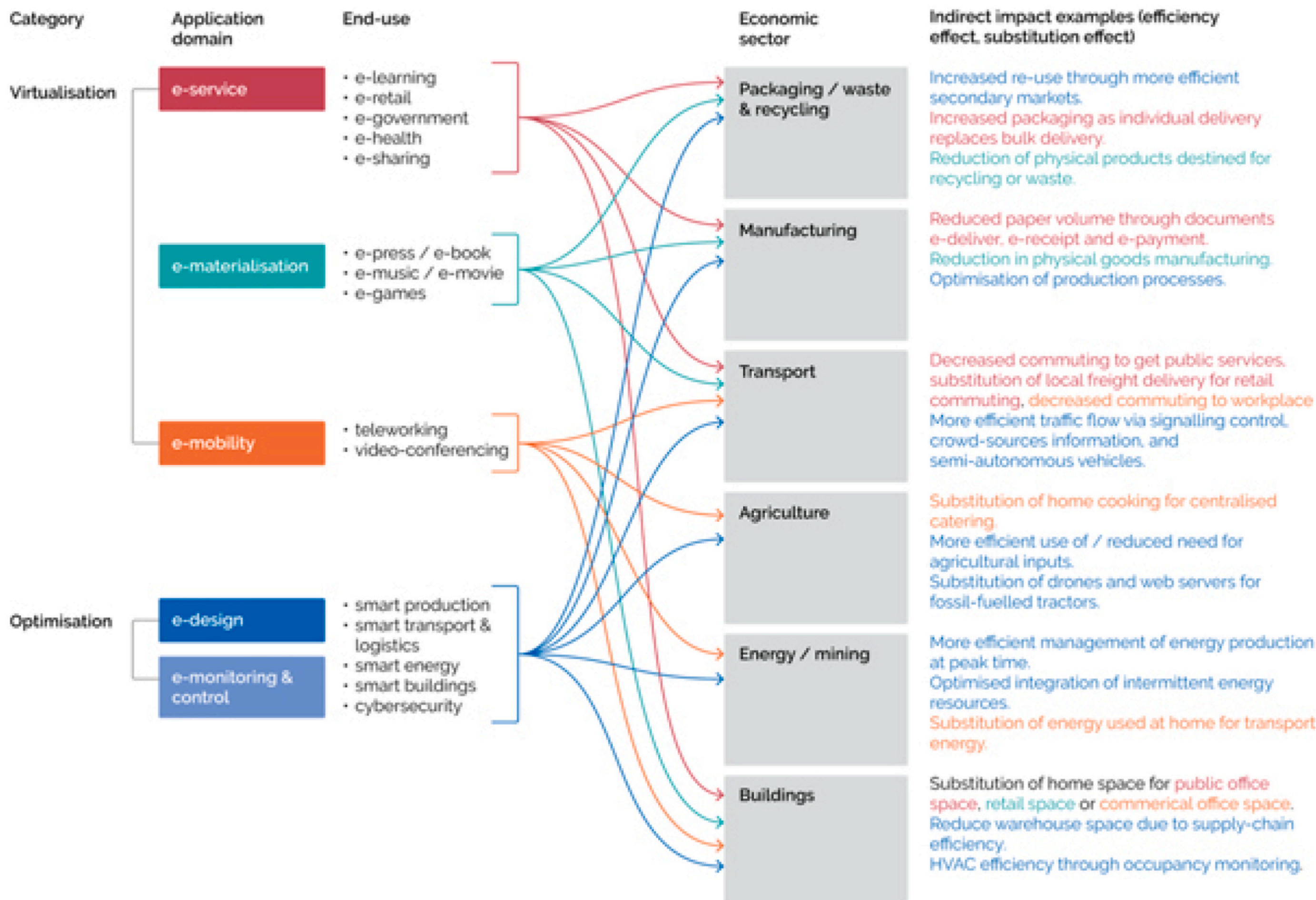


Fig. 8. ICT indirect impacts.
Source: Court and Sorrell (2020).

include theorizing, i.e., the why, the how and to what extent digital innovations can affect the deployment of climate change solutions, as well as its dissemination to developing countries – a concern that stems from the need to address climate change, taking into account economic development.

6. Conclusions and research frontiers

This paper examined research on climate change and innovation. We presented an overview of key research topics, most influential papers and journals, and four inductive themes. Overall, two major streams of theoretical approaches seem to dominate the related innovation studies literature, one based on innovation systems, and the other focused on innovation-based transition processes. The analysis of keywords using network visualization tools revealed that some of the main topic clusters include mitigation, energy efficiency, environmental impacts, industrial structures, technology development, sustainability transitions and empirical analysis of innovations such as full cells and alternative vehicles. Our analysis also indicated an increase in number of papers with few or no linkages to the main clusters, which may represent nascent research areas. Studies often possess a robust but thematically differentiated focus on areas such as accelerating decarbonization, informing technology or climate policy, promoting learning and experimentation, or assessing the effectiveness of technologies or pathways.

While we acknowledge that past studies and the papers selected in this special issue made significant contributions, we suggest that the innovation studies have not sufficiently engaged with three important topics: i) blending behavioural change with technological innovation; ii) the socio-technical drivers of accelerated low-carbon transitions and iii) the role of digital technologies as new venues of solutions to managerial challenges in addressing climate change (Fig. 9). The contributions of the invited experts substantiated the fact that the portrayal of innovation studies in the area of climate change lacks important further topics of research, as listed in Table 6.

Although we reflect on past studies and cast light on future research on innovation and climate change, this paper takes a broader perspective from the start and did not explicitly discuss conceptual issues in innovation studies debates. Future research should address such theoretical limitation in the context of, for example, the role of technological and dynamic capabilities, entrepreneurship, struggles between new entrants and incumbents, reorientation of incumbents, exploitation and exploration (including opening up new markets) and strategic management considerations including sense-making and resource allocation.

Our study is limited by using top innovation journals determined by citation analysis and reviews studies. The ranking may influence patterns of promotion and tenure, and where researchers choose to submit, which can perpetuate the position of these journals as leading research outlets. Most research is developed in Anglo-American contexts and contributions to the knowledge production on climate change and innovation from the Global South are rare, to the point in some cases where there is a complete absence of journals from such contexts. Building on Murphy and Zhu (2012), we suggest that the growing pressure from Global South home institutions to publish in leading

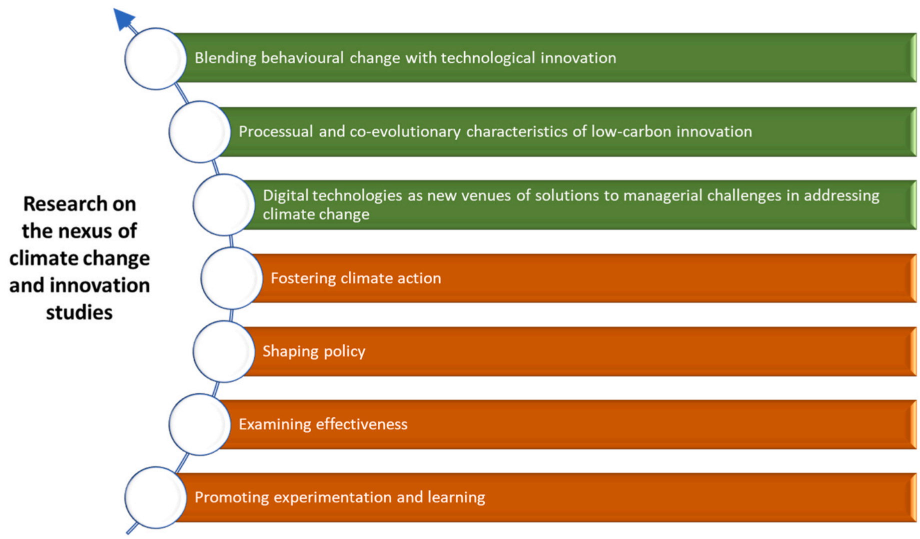


Fig. 9. Past/current research (brown bars) and new frontiers (green bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 6
Future research frontiers in need of an innovation studies perspective.

Blending behavioural change with technological innovation
• Management of demand-side options, barriers and required behavioural change to decarbonize lifestyles and new product development •Innovation ecosystems balancing deep emissions reductions on the demand, behaviour and technology side •Emerging digital innovations reducing non-mitigated rebound effects
The socio-technical drivers of accelerated low-carbon transitions
•Examining the shift from slow processes in protective niches (e.g., learning, coalition building, market creation) to rapid diffusion in mainstream markets •Conceptualisations and empirical investigations of feedbacks and interactions of between drivers of low-carbon transitions •Tipping points, accelerated diffusion across niches and regimes and implications for technology strategy and policy
The role of digital technologies as new venues of solutions to managerial challenges in addressing climate change.
•The role of global digital R&D in establishing and maintaining upper tiers low-carbon supply chains •Exploring the role of digital technologies in influencing pro-environment behaviour of consumers •Corporate governance, innovation and the use of citizen data to reduce carbon emission

journals, may supress knowledge authenticity so that the findings better align with contexts and cultures within which top journals operate (Ado and Wanjiru, 2018). In the Global South, there are some methodological constraints that may limit application of usual research methods such as interviews and surveys (Matos and Hall, 2020; de Lima, 2020). These include illiteracy issues, difficult to access and sometimes unsafe locations, lack of trust and freedom of speech. Yet, these challenges are seldom considered during the research design phases or explained in methodology or limitations of published articles. Instead, these are typically ignored, misrepresented or even hidden as authors fear it may be deemed as methodologically weak by leading journals. Consequently, their research may not be diffused due to failure to meet top journals standards, leading to a loss of important insights for global research, particularly for Grand Challenges like climate change. Innovation studies therefore need to become more inclusive, and more interdisciplinary, especially in a Global South context.

Instead of adopting a traditional disciplinary focused view, we approach the nexus of climate change and innovation studies as richly interdisciplinary and highly context dependent, i.e. being affected by sociotechnical factors, and as such calling for transdisciplinary and coevolutionary views. The importance of this broader and more inclusive perspective is that it avoids researchers not 'seeing' relevant issues because it is unfamiliar or non-obvious to them; or worse, not presenting the data they 'see', because is too obvious to them, but practically nobody else.

Acknowledgements

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