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Expert perceptions of game-changing innovations towards net zero

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A R T I C L E I N F O

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A B S T R A C T

Current technological improvements are yet to put the world on track to net-zero, which will require the uptake of transformative low-carbon innovations to supplement mitigation efforts. However, the role of such innovations is not yet fully understood; some of these 'miracles' are considered indispensable to Paris Agreement-compliant mitigation, but their limitations, availability, and potential remain a source of debate. We evaluate such potentially game-changing innovations from the experts' perspective, aiming to support the design of realistic decarbonisation scenarios and better-informed net-zero policy strategies. In a worldwide survey, 260 climate and energy experts assessed transformative innovations against their mitigation potential, at-scale availability and/or widescale adoption, and risk of delayed diffusion. Hierarchical clustering and multi-criteria decision-making revealed differences in perceptions of core technological innovations, with next-generation energy storage, alternative building materials, iron-ore electrolysis, and hydrogen in steelmaking emerging as top priorities. Instead, technologies highly represented in well-below-2°C scenarios seemingly feature considerable and impactful delays, hinting at the need to re-evaluate their role in future pathways. Experts' assessments appear to converge more on the potential role of other disruptive innovations, including lifestyle shifts and alternative economic models, indicating the importance of scenarios including non-technological and demand-side innovations. To provide insights for expert elicitation processes, we finally note caveats related to the level of representativeness among the 260 engaged experts, the level of their expertise that may have varied across the examined innovations, and the potential for subjective interpretation to which the employed linguistic scales may be prone to.

Abbreviations: ALBM, Alternative building materials for steel and cement; AVBI, Aviation biofuels; AVHY, Hydrogen aircraft; BECCS, Biomass Carbon Capture and Storage; BCHA, Biochar; BIOS, Advanced biofuel supply; CCS, Carbon Capture and Storage; CTIs, Core Technological Innovations; DAC, Direct Air Capture (e.g., soda/lime process); DECE, Decentralised energy supply; DIET, Alternative dietary preferences; EU, European Union; EVs, Electric Vehicles; GRID, Integrating consumers into grids; HYST, Hydrogen in steel-making; HYPER, Hyperloops; IRON, Iron ore electrolysis; MCDA, Multi Criteria Decision Analysis; MOBF, Alternative forms of auto-mobility; MOBA, Alternatives to auto-mobility; NGOs, Non-Governmental Organisations; NSER, New service providers; NETs, Negative Emission Technologies; NUCF, Nuclear fusion; OCEA, Ocean liming; ODIs, Other Disruptive Innovations; OPTB, Optimisation of buildings thermal performance; OPTU, Interconnectivity for optimised usage; PCRE, Producer-consumer relationships; PV, Photovoltaic; RFOO, Reduced demand for food; RMOB, Reduced demand for mobility; RSPA, Reduced demand for space and materials; STOR, Next-generation energy storage; TOPSIS, Technique for Order of Preference by Similarity to Ideal Solution; TRL, Technology Readiness Level; UFOO, Urban food production.

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1. Introduction

Achieving the Paris Agreement's temperature goals and reaching subsequent carbon-neutrality between 2050 and 2070 [1] require deep and rapid decarbonisation of our industrial, economic, and societal activities. While current technological advancements can offer immediate improvements in terms of energy efficiency and substitution of fossil fuels, we cannot solely rely on the falling costs of readily available or near-commercial technology to put us on track to net-zero [2,3]. The high decarbonisation rate required for this path stipulates the mobilisation of promising and potentially game-changing innovations in addition to the achievement of the overall potential of (near-) available mitigation options [4].

Game-changing low-carbon innovations usually include significant shifts in markets, systems, infrastructure, and behaviour [5]. They are broadly defined as macro-trends that can affect today's society [6,7]; yet, in the decarbonisation context, game-changers mean transformative [8] or disruptive low-carbon innovations [9]. These include both technological and non-technological innovations such as re-organisations or shifts that require managerial, institutional, social, and behavioural innovations [9,10]. Recognising ground-breaking innovations, their dynamics and their potential role in deep decarbonisation is integral for developing ambitious transition pathways [10]. Such pathways are often used to underpin the research, practice, and policy of climate change mitigation, including Nationally Determined Contributions to the Paris Agreement [11].

Principal measures that are commonly included in low-carbon pathways are energy-related technologies that are mostly already commercially available, such as solar photovoltaics (PV), wind power, and energy efficiency interventions [1]. However, in the hard-to-decarbonise sectors of energy-intensive industries, transportation, and buildings, more technological innovations are still needed to be assessed [12]. While some studies have begun assessing low-carbon innovation in a more holistic way [13], decarbonisation pathways are often modelled with insufficient spatial and sectoral granularity and without considering important non-technological drivers of emissions reductions such as international governance schemes or socio-political capabilities [14,15]. On the latter, societal innovations such as reducing mobility demand through remote working are rarely simulated [16,17], despite these innovations rising in prominence in the policy sphere [18]. In the absence of model-based analyses, the opinions of climate and energy experts can help perform a reality check of the potential role of low-carbon innovations that are rarely included in existing decarbonisation pathways [19].

Expert- and stakeholder-based methods such as interviews and surveys are often used to assess low-carbon innovations [20]. Existing studies have already assessed a large variety of low-carbon innovations, ranging from common renewable energy technologies [21,22] to floating photovoltaic systems [23], as well as from sectors beyond the energy sector, including industry [24], transportation [25,26], agriculture [27], buildings, and cities [28,29]. Additionally, innovative technologies have been assessed in terms of diverse aspects and factors, such as environmental, social, and economic impacts [30–32], drivers, risks, and barriers that may affect implementation [28,33,34], as well as perceived potentials for decarbonisation [35,36] and societal feasibility [37,38]. While expert-based methods are often criticised for eliciting uncertainties in qualitative terms and for being affected by cognitive biases such as overconfidence [39,40], formal expert elicitation methods have been developed to address some of these shortcomings [41–45].

Despite the ubiquity of expert- and stakeholder-based assessments of low-carbon innovations, some limitations still exist. First, most of the studies have focused on a limited number of innovations at a time, or on innovations coming from a specific sector, usually technologies for decarbonising the energy sector [10]. While this sectoral focus is justified for eliciting detailed assessments from field experts, it complicates the use of results coming from different studies in meta-analyses [46] and hinders the prioritisation of innovations from different sectors. Additionally, as different innovations can often overlap or interact (e.g., electric vehicles and demand response measures), there is a need to properly explore and analyse the diffusion of relevant game-changing innovations in tandem. Second, many expert-based assessments of low-carbon technologies and innovations have been performed by a small number of experts, usually ranging between 5 and 25 [47,48]. As the experts' professional background and country of residence have been shown to affect their assessments [46], a large number of experts may help reduce biases and increase the diversity of opinions.

In order to help policymakers and scientists understand and prioritise low-carbon innovations as well as to inform future decarbonisation strategies and scenarios, respectively, this paper evaluates 27 potentially game-changing low-carbon innovations based on a global, online survey with 260 climate and energy experts. Each of these experts provided a subjective assessment of identified low-carbon innovations against three evaluation criteria: mitigation potential, timing of commercial availability or widespread adoption, and risk of being delayed. The 27 low-carbon innovations included in our survey were sourced from the recent literature [9,10,49,50]; these include mainly technological solutions that may already exist at a small scale or at early stages of development (hereinafter called "core technological innovations" or CTIs), as well as societal, business, and other low-carbon innovations that are not primarily based on technology (hereinafter called "other disruptive innovations" or ODIs). Based on the evaluations of the experts on all three criteria, the selected low-carbon innovations are grouped through hierarchical clustering and then ranked based on multi-criteria decision analysis (MCDA). Through this process, the paper aims to contribute to the academic and policy discourse on the necessary innovations for effective and rapid low-carbon transitions, by suggesting priorities and risks among a large set of potentially game-changing innovations, based on the views of a global group of experts. In terms of methodological novelty, the study combines statistical methods for survey analysis with a group decision-making and consensus analysis tool in order to provide a multi-dimensional assessment of expert views. We complement this assessment with an option appraisal by each group of experts, evaluating divergences in the results among experts of different genders, professional capacities, and geographic regions to shed light on how sensitive results are to who responded to the survey. Overall, we aim to answer the following research questions:

1. How do energy and climate experts perceive pertinent game-changing, low-carbon innovations in terms of mitigation potentials, timing of adoption, and risk of being delayed?
2. How can we prioritise and select the most pertinent low-carbon innovations in light of these diverse criteria towards informing realistic transition pathways and strategies?

Section 2 introduces the low-carbon innovations that are included in the survey, elaborates the design of the expert survey, and presents the methods used to process and analyse the survey data. The results of the analysis are presented in Section 3, followed by a discussion of research findings in Section 4 and the conclusions in Section 5.

2. Methods and tools

In this section, the most relevant technological and other potentially game-changing innovations to be assessed in the survey are sourced and their status assessed from the literature. The survey design (questionnaire, expert selection and engagement, etc.) is also presented, followed by an overview of the methods used to analyse the survey results.

2.1. Identifying relevant low-carbon innovations

There are several technological innovations proposed or discussed in the recent literature for climate change mitigation. Bioenergy with

Carbon Capture Storage (BECCS), for example, is often overplayed as a mitigation technology in integrated assessments in support of climate policymaking [51–53] despite their significant transport and geological storage limitations [54]. However, other technologies that are increasingly being researched or at an earlier stage of development may also play a prominent role in decarbonisation pathways, such as hydrogen, advanced biofuels, electric furnaces for steel production, and electric trucks [4].

Whilst there is a preference towards technological innovations in decarbonisation pathways [5,55], reducing industrial emissions to Paris Agreement-compliant levels may not be possible by only focusing on technological solutions [56]. New technologies may not become technically feasible and commercially available in time for the net-zero transition [5] and there are many uncertainties surrounding these technologies, related to issues such as commercial feasibility, applicability, and operating efficiencies [56,57]. In addition to technological innovations, other solutions are crucial in enabling and supporting the rapid transition to a low-carbon economy, including societal innovations and novel business models.

Societal innovations usually imply a combination of both innovative policies and coordinated societal changes, along with fundamental changes to current lifestyles [58]. These changes typically involve low-carbon innovations that are less technology-based but cover behavioural changes or practices, innovative market designs, and new business models. Socio-technical transitions are increasingly considered critical and the promotion of behavioural innovations by individuals, policymakers, and commercial entities are deemed essential to achieve effective climate mitigation and reach net-zero targets [59]. The synergistic, cumulative effects arising from fundamental societal changes are a core part of the required dynamics to ensure that we reach the Paris Agreement goals [60,61].

Despite the wealth of innovations explored for low-carbon transitions, there is no consistent and exhaustive classification of such innovations. For the purposes of this study and particularly for the design of a meaningful survey and subsequent analysis, we discern innovations to two groups: (a) core technological innovations that have not matured enough to be used at large-scale operational level; and (b) other disruptive innovations that are primarily associated with behavioural changes or novel market settings and emerging business/economy models.

2.1.1. Core technological innovations (CTIs)

This block comprises 14 technology-based innovations for achieving a low-carbon economy, adapted from a broader list of innovations assembled by Napp et al. [49,50], who surveyed the literature on innovation priorities and mitigation pathways and created a long list of 52 low-carbon technologies. Then, using the concept of Technology Readiness Level (TRL), Napp et al. evaluated these technologies based on their level of maturity and filtered 21 technologies that are either at a basic research level (TRL 1–3) or have reached advanced development and small-scale demonstrations (TRL 4–6); technologies already at large-scale operational demonstrations or already commercialised (TRL 7–9) were excluded, even if they could benefit from further research to reduce costs or overcome non-technical barriers. To avoid overloading survey respondents by asking them to evaluate a large number of innovations, our study further condenses this list of 21 technological innovations, by grouping similar innovations together. For example, all individual carbon capture and storage (CCS) applications in the steel, cement, and chemical industry are grouped together in a single category. Based on this grouping, we eventually put together a list of 14 CTIs to include in our survey, as presented in Table 1.

Around 70% of the CO_2 emissions from energy-intensive industries come from the iron and steel, cement, and chemicals sub-sectors [62]. Iron and steel constitute the most energy-demanding industries, accounting for approximately 4% of European emissions [63] and 7% of global CO_2 emissions [64]. These industries have even been termed a 'special case' for economic activities, as both combustion and process emissions must be addressed [65,66]. Deep decarbonisation of the iron and steel sectors could be achieved via the use of carbon-free electricity sources, specifically via use of electrolysis of iron ore [57]. As electrolysis produces only oxygen and no carbon emissions, it could in theory be carbon-neutral [67]. The potential role of electrification in decarbonisation is well-established, but this needs to be accelerated via technologies that primarily extend it by means of energy storage [68]. Furthermore, despite slow progress in research and development, nuclear fusion technology can provide virtually limitless carbon-free power [69].

Table 1
List of core technological and other disruptive innovations included in this study.

CTIs
Aviation biofuel (biojet or renewable jet fuel)
Hydrogen aircraft
Hyperloops
Advanced biofuel supply (e.g., algae for bioethanol production)
Carbon Capture and Storage (CCS)
Hydrogen in steelmaking
Iron ore electrolysis (to produce iron)
Alternative building materials for steel and cement
Bioenergy with Carbon Capture and Storage (BECCS)
Biochar (soil amendment resulting from pyrolysis of biomass)
Ocean liming (addition of calcium oxide powder in oceans)
Direct Air Capture (DAC; e.g., soda/lime process)
Next generation energy storage (power-to-gas, flywheels, new batteries, etc.)
Nuclear Fusion
ODIs
Alternative forms of auto-mobility (car sharing, ride-sharing, etc.)
Alternatives to auto-mobility (e-bikes, mobility as-a-service, etc.)
Reduced demand for mobility (home-working, teleconference, etc.)
Alternative dietary preferences (flexitarian/reduced meat diet, etc.)
Urban food production (own food growing, community farming, etc.)
Producer-consumer relationships (local food distribution, food box deliveries, etc.)
Reduced demand for food (food waste, reduction, etc.)
Inter-connectivity for optimised usage (smart appliances, LED, smart homes, etc.)
Optimisation of buildings' thermal performance (e.g., smart heating controls)
Reduced demand for space and materials (sharing)
New service providers (energy service companies, energy aggregators, third-party financing)
Integrating consumers into grids (demand response, time-of-use pricing, electric vehicle-to-grid, etc.)
Decentralised energy supply (solar PV with storage, micro-wind turbines, etc.)

On the other hand, hydrogen technology can also be utilised to decarbonise steel production by directly reducing iron with hydrogen rather than natural gas [70,71]. There are two ways, in which hydrogen can be used in steel production: as an auxiliary reducing agent in the blast furnace-basic oxygen furnace route or as the sole reducing agent in a process known as direct reduction of iron or direct reduced iron. The use of hydrogen is an emerging technology that can also enable deep decarbonisation across multiple economic sectors, from light and heavy industries [72] to transportation and shipping [73]. For example, hydrogen has been recognised in aviation as a future of zero-emissions aircraft. The greatest challenge of using hydrogen, however, is the cost required in the production process [74].

Decarbonisation of transport sectors is critical, thus alternative technologies that go beyond easy fixes (e.g., Ref. [75]) should be integrated in future pathways of achieving net-zero emissions. In the aviation industry, biofuels are usually referred to as biojet or renewable jet fuel and are "drop-in" alternatives to conventional jet fuels [76]. They can be used in place of fossil fuel-derived jet fuels with no modifications to aircraft. Nonetheless, biojet fuels are uniformly more expensive than conventional jet fuel [77]. Thus, at current biojet prices, incentives are not strong enough for airlines to purchase them.

In addition, advanced production of biofuel faces some obstacles that render important innovations critical. Biofuel production needs large storage capacities, and there is little knowledge of, or experience in, the utilisation in fuel supply [78]. While the first generation of biofuel production raises an issue on food availability and price concerns, the second generation of advanced biofuels production is also challenging [79] due to costly distillation materials, uncertainty in emissions released, and overall competition with regular fuels.

Progress on biofuel innovations also affects development of other CO_2 removal technologies such as CCS [80], or negative emission technologies (NETs) such as BECCS [81] and biochar [82]. NETs, in particular, are required in the majority of decarbonisation pathways that limit warming to 1.5 °C (with limited or no overshoot) [1]. DAC of CO_2, for example, is also expected to emerge as a key technology in deep decarbonisation and climate mitigation [81,83]. Likewise, large-scale deployment of NETs also faces substantial issues due to adverse ecological and social impacts [84,85], or even unproven effectiveness as in the case of the ocean liming technology [86].

2.1.2. Other disruptive innovations (ODIs)

The survey included 13 disruptive low-carbon innovations that are not primarily technology-based (Table 1) and are adapted from Wilson et al. [10]. Following Christensen [87], Wilson [9] defines such innovations as low-end products offering novel value to users, with the potential to transform the market for energy-related goods and services. These innovations aim to transform energy supply as well as diverse energy-demanding sectors, including mobility, buildings, cities, and food. To achieve this, these disruptive low-carbon innovations employ diverse measures such as behavioural changes, market designs, and new business models [10]. While technology measures are usually included in these innovations, they are often combined with other measures. We have adopted in our survey almost all major categories used by Wilson et al. [10], with the exception of the “alternative fuel or vehicle technologies”. This category was excluded, since it refers to technologies such as electric vehicles, which are assumed to be in a much more advanced stage now than at the time of the original study.

Behavioural innovations in mobility can lead to substantial emissions reductions, for instance, by significantly increasing the number of journeys taken by foot, bicycle, and public transport and reducing journeys by private vehicles [62]. These behavioural changes are first intended to displace the incumbent internal combustion engine and limit car ownership. The latter are classified as ‘alternative forms of auto-mobility’ such as car or ride sharing. Other related examples include alternatives of auto-mobility such as e-bikes and community EVs to replace the current bikes, motorbikes, cars, or public transport. Behavioural changes also cover activities that reduce the demand for mobility, such as telecommuting and virtual meetings.

Mass changes in dietary behaviour are also expected to achieve great environmental benefits [88,89]. Innovative low-carbon practices relating to food include urban and community-based growing, reduced food waste, and modular hydroponic and aquaponic systems. These innovations perform poorly in terms of year-round availability, user involvement, and standardisation (at centralised retailers). However, they offer end-users novel attributes, including social networks, active involvement, and visibility (localisation).

The same broadly holds for low-carbon innovations identified in other domains such as innovations relating to buildings and cities. These include the optimisation of internet-based technologies, net-zero energy homes, and distributed PV-storage systems. While these innovations have disadvantages, such as high-upfront cost, low user involvement (passive consumption), and centralised networks or utility provision, they offer novel capabilities to end-users, including control, active involvement, and autonomy.

The final category is related to energy supply and distribution and includes peer-to-peer trading, vehicle-to-grid, and community or district energy networks. Despite offering active involvement of end-users, functional diversity, and network interactions, such innovations are still under-performing. Some obstacles include dependency on external provision systems, time-invariant costs, and passive consumption that creates low user involvement.

2.2. Survey questions and sampling

The survey was carried out online from January 26, 2022 to March 4, 2022, using Google Forms and, for respondents from mainland China, Mike-crm. The survey was targeted to climate and energy experts including the following individuals:

1) experts that attended the stakeholder meetings organised by the EU Horizon 2020 PARIS REINFORCE project in different regions/countries (e.g., India, Russia, the Caspian region, Switzerland, and France);
2) experts from previous partnerships and events of Bruegel, a leading thinktank on European policy and co-organiser of the survey; and
3) contacts recommended by consortium partners of the PARIS REINFORCE project as well as by scientific associations and networks, such as the International Association for Energy Economics (IAEE) and the Global Trade Analysis Project (GTAP) network.

It is important to note that our survey—and research—explicitly targeted experts, not all stakeholders in the low-carbon/net-zero transition. We perceive stakeholders as any group of individuals that can affect or are affected by the achievement of an objective (e.g., a low-carbon transition, or the Paris Agreement); in this case, that refers to people or institutions affected by, or able to affect, measures to achieve any (number of) game-changing innovations towards a carbon-free world. Instead, aiming to inform scientific and policy processes with authoritative input, we narrowed our target group down to experts—i.e., stakeholders with a professional background that is relevant to any or all of the potentially game-changing innovations examined in this research. Therefore, we sought to target people with domain expertise in low-carbon technological, market, institutional, behavioural, and/or other innovations argued, discussed, or promoted as critical for achieving climate objectives—be that researchers, academics, or representatives from industries, civil society associations, and NGOs. In this direction, our sample was built based on the available information on the working capacity of the stakeholders identified above, as an indication of their level of expertise. At the same time, the invitation sent to these contacts explicitly asked only domain experts to respond, and the survey script (see Supplementary Information) spelled out that the survey should be filled out by experts, a process intended to take a non-trivial amount of time (with an indicative duration of 15’).

To sufficiently represent non-EU regions in the survey, we extended the regional distribution of invited experts to encompass all parts of the globe, especially emerging and developing countries. Around 3000 invitations were sent worldwide: 2000 of the invited experts were from Europe, 302 from Africa and Middle East, 223 from Asia, 201 from North America, 108 from South America, 92 from Russia and former Soviet Republics, and 74 from Australia and New Zealand. The survey was conducted in English and comprised 102 questions, three of them being open-ended and the rest featuring a set of pre-defined responses from a drop-down menu. The full survey script is provided in the Supplementary Information.

The first part of the survey introduced the scope and goals of the project and the questionnaire, provided information about ethical considerations, and elicited demographic characteristics, including current working capacity, country, and gender. It should be noted that the survey was approved by the Ethics Mentor of the PARIS REINFORCE project. The subsequent page provided a piece of background information on low-carbon innovations, including a figure of the International Energy Agency (IEA) Net-Zero Emissions scenario [90] and the list of selected CTIs based on Napp et al. [49,50], and the list of ODIs based on Wilson and Tyfield [9] and Wilson et al. [10]. It is noted that the figure of the IEA scenario was only shown to illustrate that many different innovations are needed to reach net zero across multiple sectors. While the IEA figure also gave some indication about the mitigation potential of different innovations, we have not asked respondents to base their survey answers on this scenario.

The first part of the main questionnaire asked participants to first provide their perception of the level of mitigation potential of the 14 early-stage technologies by choosing among five options (very low, low, moderate, high, or very high). This was followed by a closed-ended question asking respondents about when they expect each technology to become commercially available (by 2030, between 2031 and 2040, between 2041 and 2050, post-2050, or never). We did not specify to the respondents whether this commercial availability required policy support measures such as subsidies (or essentially below which subsidy level or policy support mechanism an innovation could be considered commercially available). Instead, we relied on their expertise to envision the approximate timing of the widespread adoption of the examined innovations and to apply their criteria to define what commercially available means, also considering policy and market measures that would likely be required (e.g., some respondents may consider that to define an innovation as commercially available no carbon prices including implicit carbon prices should be maintained, while others may accept some form of such prices or incentives). Finally, participants were asked about the risk of non-availability or delay of these technologies (insignificant, low, moderate, important, or critical). As this was a follow-up of the previous question, the risk of delay here was referring to the phase of commercialisation or widespread adoption, and in the case of ODIs the risk of never materialising their potential. For all three questions (and technologies), respondents additionally had the option to indicate they are “not able to respond”.

The second part of the questionnaire was related to the other disruptive low-carbon innovations. Much like the first part about technologies, respondents were asked about the mitigation potential of 13 ODIs using the same scale. This was followed by questions on when these innovations are perceived to take off (already taken off, by 2030, between 2031 and 2040, between 2041 and 2050, post-2050, or never). Experts were then asked what the risk would be of these disruptive innovations never materialising/being adopted, with five possible answers (insignificant, low, moderate, important, or critical). Again, respondents also had the flexibility not to respond to any question about any technologies, selecting “not able to respond".

In the end, the survey included a final, open-ended question allowing respondents to indicate other prominent low-carbon innovations relevant for climate change mitigation that are not included in the survey (see Appendix A).

2.3. Methods of analysis

Prior to the analysis, survey answers had to be translated from linguistic to numerical. For instance, the five-term linguistic scale used in the mitigation potentials question (very low, low, medium, high, very high), was converted to a numerical scale that enumerated the answers (0, 1, 2, 3, 4). The “very high” term indicated a technology/innovation that should be pursued/studied as a top priority. This conversion was also performed for the other two questions. As interpretation of qualitative measures are subjective, translation to numerical gives a uniform sense of the importance of each technology to overall mitigation in respondents’ regions. The only exception was the question on the timing of expected adoption for the ODIs, where for the purposes of this analysis the responses “already taken-off and “by 2030” were treated as equal.

Then, a hierarchical cluster analysis was used to group low-carbon innovations with similar characteristics. This type of multivariate clustering classifies similar objects into clusters in a way that each cluster is as much distinct as possible from the rest [91,92]. For each low-carbon innovation, we considered survey results for all three evaluation criteria: mitigation potential, timing of commercial availability (CTIs) or widespread adoption (ODIs), and risk of being delayed. The number of respondents, who could not respond and who assessed innovations will never take place, was also included to capture uncertainty factors of these transformative innovations. The data obtained from the survey was first normalised and then used to calculate the Euclidean distance between different low-carbon innovations.

Following cluster analysis, we employed APOLLO, a group decision-making and consensus analysis tool based on the 2-tuple TOPSIS MCDA methodology [93,94]. Note that we select TOPSIS for reasons additional to its integration with consensus analysis, including its firm establishment in the energy and climate policy domain [95–97] and a solid mathematical background that is based on Euclidean distances [98], thereby retaining comparability with the hierrarchical cluster analysis. APOLLO was used to rank the CTIs and ODIs by aggregating answers for all three evaluation criteria (mitigation potential, take-off timing, and risk of delay) rather than assessing each innovation for each criterion individually, while emphasising the extent to which respondents agreed with one another (consensus). The ranking of the aggregated answers could be then viewed as a proxy of the respondents’ perceived priorities over the survey’s low-carbon innovations, factoring in the three criteria. In a sense, and following the logic of the TOPSIS method, the ideal innovation (i.e., which should receive top priority in science and policy) is assumed to have the highest mitigation potential, be available as quickly as possible, and feature the lowest risk. APOLLO comprises two steps. Initially, each respondent’s ranking of alternatives is calculated independently. Following that, the independent rankings of the individual respondents are synthesised in a new decision matrix, which is then used to calculate the final ranking (similar to Ref. [99]).

APOLLO also allowed handling “not able to respond” responses, which are typically excluded in MCDA studies. These responses were substituted with the average (mean value) vote per alternative based on the responses of the remaining stakeholders. Correcting missing values (such as “not able to respond”) based on information provided by the rest of the voters is common practice in the presence of multiple experts [100]. However, in this study we also introduced a metric to reflect how many valid responses (i.e., responses other than “not able to respond”) each respondent provided to weigh respondents upon the synthesis of individual respondent preferences in APOLLO. Respondents providing a “not able to respond” answer for more than half of the alternatives were assumed to essentially reflect the average values of the rest of the group more than their own preferences and were thus omitted from the MCDA analysis. This filtering process resulted in 12 respondents being omitted in the first questionnaire (CTIs) and 4 in the second questionnaire (ODIs), from a total of 260 respondents.

In addition to running APOLLO using all responses of the expert sample, the analysis was performed separately for different groups of respondents, based on their professional occupation/capacity, gender, and geographic region (following the countries’ classification by Income from World Bank [101]) to mitigate potential biases in the sample of the respondents. This enabled us to capture and comprehend how priorities shift depending on the different backgrounds of the respondents, as well as to what extent different (groups of) respondents agree with one another (and internally within that group). We use the following background classifications:

1. Occupation: academia/research, private sector/industry, international institutions, national governments, and NGOs
2. Geographic region: high-income, upper-middle-income, and lower-middle- income/lower-income countries (merged due to the low number of respondents from the latter category)
3. Gender: male and female

We did not consider other options, despite some few respondents providing “other” or “prefer not to say” answers for the occupation and gender questions; these respondents are included in the total and country analysis but excluded in the occupation and gender analysis (see Section 3). Geographically, clustering based on income groups was preferred to an analysis per country, as the wide range of responses would have led to many countries being represented by a small sample of respondents, rendering the calculation of robust results challenging.

3. Results

3.1. Survey respondents

The survey reached 260 responses from 56 countries, almost 10% of the experts that were initially invited. Around 70% of the respondents are male, 29% are female, and 1% preferred not to say. Despite the wide geographic coverage, European respondents comprised almost half of the total sample (Table 2). Considering the survey was targeted at climate and energy experts, half of the survey respondents expectedly reported that they work in academia and/or research, with the rest of the respondents coming from the private sector, national governments, international institutions, non-governmental organisations (NGOs), and others.

3.2. Expert evaluations of low-carbon innovations

3.2.1. Mitigation potential

For technological innovations (CTIs), most respondents assessed that next-generation energy storage, alternative building materials for cement and steel, hydrogen in steelmaking, and iron ore electrolysis had moderate-to-high potential for deep decarbonisation (see Fig. 1). These are followed by CCS, BECCS, advanced biofuel supply, and aviation biofuels. On the other hand, mitigation potentials of nuclear fusion, biochar, hydrogen aircraft, DACs, hyperloops, and ocean liming are low-to-moderate.

In the case of ODIs, most respondents believe there is a moderate-to-high potential in almost all innovations listed in the survey. Relevant innovations in mobility tend to fall in the 'high potential' range. In contrast, respondents appeared less confident about mitigation potentials for disruptive innovations in food and consumption. For example, respondents assessed that urban food production had low to moderate mitigation potentials.

Additionally, we analysed the shares of 'not able to respond' answers, considering them as a proxy of uncertainty in the respondents' perceptions of the survey's low-carbon innovations. Tables 3 and 4 present these shares according to the respondents' working backgrounds.

Technologies concentrating the highest share of no responses are ocean liming, hyperloops, iron of electrolysis, and biochar. The readiness level, complexities, and underlying uncertainties of these technologies likely prevented some respondents from providing their input. For example, the ocean liming concept of neutralising ocean acidity through alkalinisation needs considerable scientific assessment to be applied to large-scale projects. Similarly, massive transport technologies such as the hyperloop are not as established and/or still need intensive feasibility studies, while long-distance trials remain far from reaching the stage of developing models that work around the world. In contrast, most respondents seem to be very familiar with CCS and next generation types of energy storage. The number of respondents unable to identify mitigation potentials is insignificant for these technologies. Also, respondents seem to be familiar with the potential associated with biofuels (such as in aviation or advanced supply), BECCS, and hydrogen technologies (including in aviation and steelmaking).

Table 2
Survey respondents' profile.

Working background		Regional distribution	
Academia/Research	50%	EU-27	39%
Private Sector/Industry	23%	Other Europe	10%
National Government	10%	Africa	4%
International Institution	6%	Asia	25%
NGOs	9%	Russia & Caspian States[a]	3%
Others	2%	Latin America	5%
		North America	8%
		Middle East	3%
		Australia	1%

[a] Except Iran, which is included in Middle East.

Responses for ODIs, on the other hand, show a different picture. Only a small percentage of respondents were unable to respond, and overall experts appear more familiar with these not-so-technological innovations. The highest share of "not able to respond" input is for reduced demand for space and materials, followed by urban food production. The distribution among all respondents also shows higher percentage of responses for ODIs: around 84% of participating experts were able to answer all questions in this section of the questionnaire, whereas only 48% in the technological section.

3.2.2. Expected time of adoption

Fig. 2 shows the modal value for the time that the listed technological innovations are expected to be commercially available alongside the percentage of respondents, who project these innovations will never really materialise. The survey results show that nuclear fusion, ocean liming, and hyperloops will be commercially available post-2050, with a relatively higher percentage of respondents perceiving that these technologies may even fail to launch to begin with. Among these technologies, nuclear fusion faces the highest uncertainty in terms of commercial availability. Respondents also include DAC in this category while projecting that this technology will be available around the middle of the century. Other technologies are expected to be commercially available by the 2040s.

For ODIs, again, the survey reveals a different picture. Respondents project that all behavioural changes can be adopted within the next two decades (Fig. 3). Disruptive measures related to food and consumption seem, however, to be more challenging than others. The percentage of respondents finding these innovations likely never to be implemented is almost double the same share on other ODIs. It is also worth noting that respondents overall project that it will take a little longer before these innovations to take off. The survey also reveals a similar case for reducing space and materials and consumers to be integrated into grids.

3.2.3. Risk of delay

In terms of the respondents' perception of the risk of non-availability or delay, most technologies fall within the moderate-to-high range. Almost all ODIs, in contrast, fall within the low-to-moderate range, which indicates higher feasibility for non-technological/behavioural/societal innovations. The distribution of the risk of non-availability or delay is detailed in Fig. 3.

Mapping the mean value of mitigation potentials and the risk of delay for each low-carbon innovation results in four groups (Fig. 4). Most CTIs lie in the first quadrant (higher mitigation potentials, higher risk). In comparison, non-technological innovations lie in the fourth quadrant (higher potentials with a lower risk of never being adopted). Three technologies fall in the second quadrant (lower potentials with high risk), i.e., nuclear fusion, hydrogen aircraft, and DAC. Another three technologies and two ODIs belong to the third quadrant (lower potentials and lower risk), i.e., ocean liming, hyperloops, and biochar along with two non-technological innovations for food consumption (urban food and producer-consumer relationship). Interestingly, next-generation energy storage is found to have the highest potential for mitigation, yet its risk of delay is also high. A similar pattern is found for iron ore electrolysis, hydrogen in steelmaking, and alternative building materials for cement and steel.

3.3. Grouping evaluations of low-carbon innovations through hierarchical clustering

Hierarchical Clustering resulted in a cluster dendrogram with a highest possible classification of five clusters. Fig. 5 maps the cluster

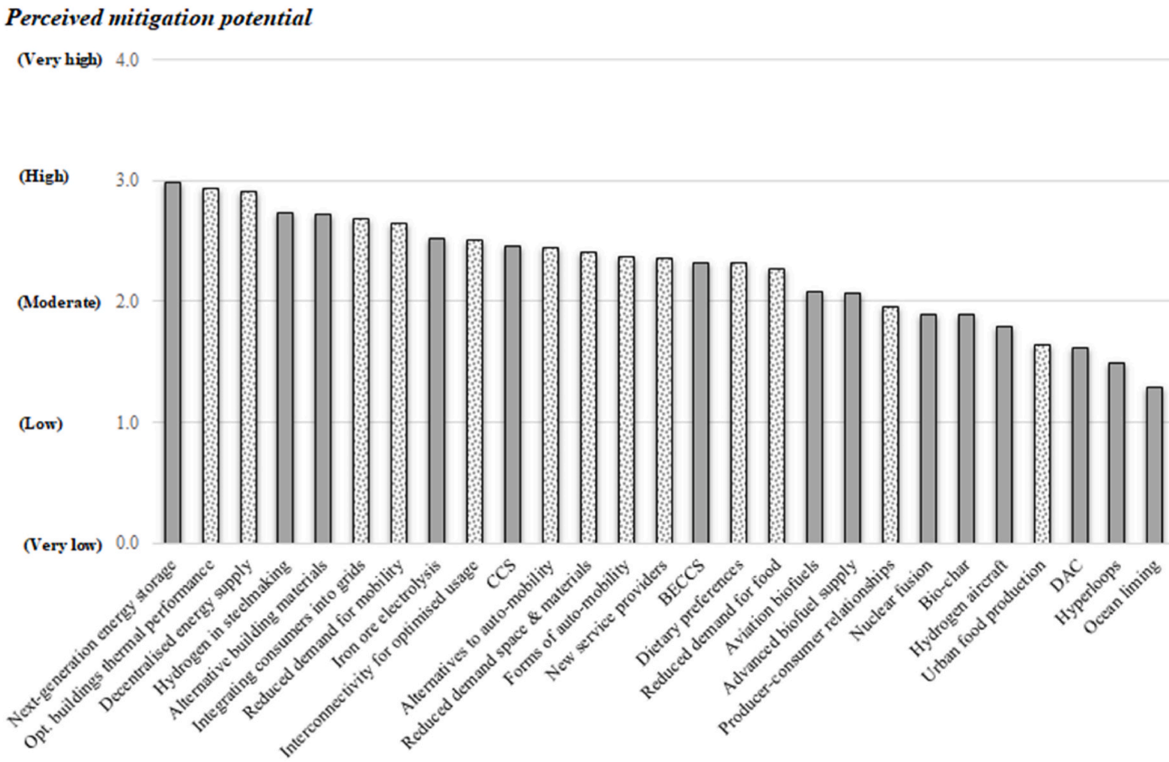

Fig. 1. Ranking of mitigation potentials of low-carbon innovations based on the perceptions of the expert respondents. Filled bars show CTIs while dotted bars show ODIs.

Table 3
Respondents' share of "not able to respond" answers in % for CTIs.

	Academia/Research	Private Sector/Industry	National Government	International Institution	Other	Total
AVBI	3%	3%	4%	0%	7%	3%
AVHY	5%	3%	8%	6%	17%	6%
HYPER	18%	36%	27%	25%	41%	26%
BIOS	2%	5%	15%	0%	10%	5%
CCS	1%	3%	4%	0%	3%	2%
HYST	5%	5%	19%	6%	10%	7%
IRON	17%	34%	38%	13%	41%	25%
ALBM	3%	7%	12%	6%	10%	6%
BECCS	2%	14%	12%	0%	10%	7%
BCHA	15%	31%	35%	13%	31%	22%
OCEA	21%	39%	46%	19%	31%	29%
DAC	7%	17%	23%	25%	14%	13%
STOR	3%	5%	8%	0%	7%	4%
NUCF	6%	12%	23%	19%	7%	10%
Mean	8%	15%	20%	9%	17%	12%

Table 4
Respondents' share of "not able to respond" answers in % for ODIs.

	Academia/Research	Private Sector/Industry	National Government	International Institution	Other	Total
MOBF	1%	2%	0%	0%	3%	1%
MOBA	1%	3%	0%	0%	7%	2%
RMOB	0%	0%	0%	0%	3%	0%
DIET	2%	2%	4%	0%	10%	3%
UFOO	4%	3%	0%	0%	17%	5%
PCRE	0%	2%	0%	0%	7%	1%
RFOO	1%	0%	0%	0%	3%	1%
OPTU	2%	2%	0%	13%	3%	2%
OPTB	2%	2%	0%	6%	10%	3%
RSPA	6%	7%	12%	6%	14%	8%
NSER	3%	2%	8%	0%	7%	3%
GRID	2%	2%	4%	0%	7%	2%
DECE	4%	2%	12%	6%	7%	5%
Mean	2%	2%	3%	2%	8%	3%

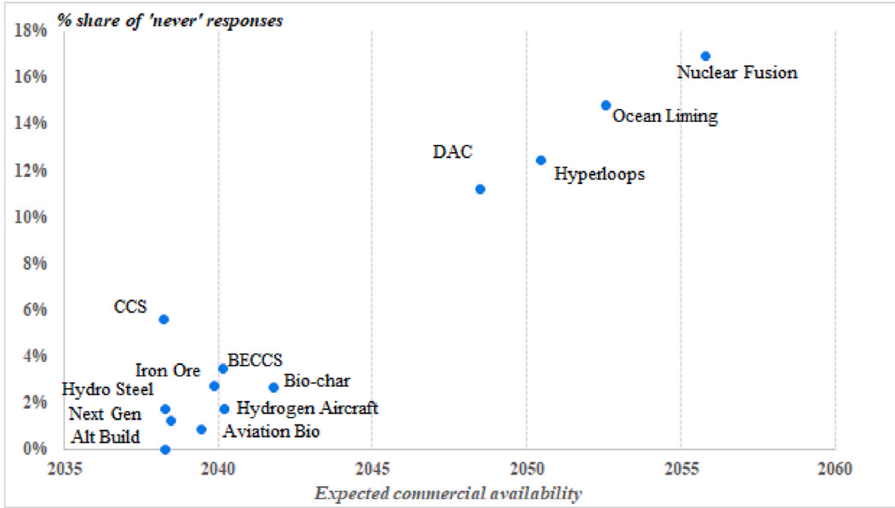

Fig. 2. Timing of expected commercial availability for CTIs according to the respondents.

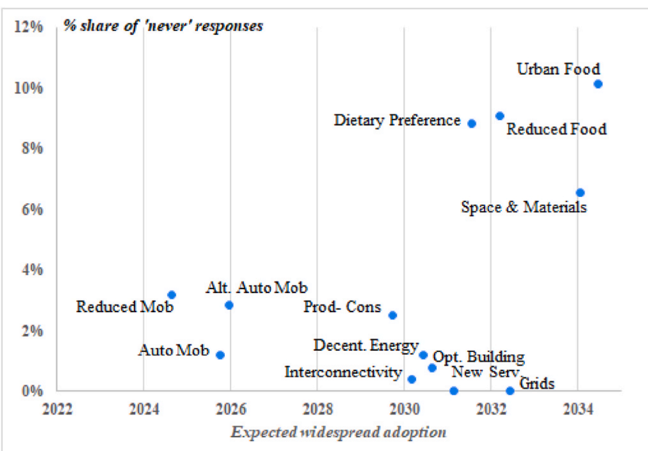

Fig. 3. Timing of expected widespread adoption of ODIs according to the respondents.

classification, and Table 5 lists the low-carbon innovations that belong to each cluster. Cluster I includes the technologies of nuclear fusion, hyperloops, hydrogen aircraft, ocean liming, and DAC. Survey respondents assessed these technologies as more likely to be adopted in the long run (post-2050) with relatively low mitigation potentials and high risks of delayed/non-availability.

Cluster II consists of innovations with less uncertainty relative to Cluster I. All biofuel-related technologies belong to this group. Their adoption is expected earlier, in the 2030s–2040s, with biochar technology becoming available at the end of this interval for large-scale implementation (see also Fig. 2). Mitigation potentials are varied, reflecting a high degree of uncertainty still (Fig. 1). The two non-technological innovations belonging to this cluster are related to food consumption. These justify our previous finding that urban food production and producer-consumer relationship (i.e., improving food distribution) are more challenging to adopt than other ODIs. In contrast, respondents suggested that next generation energy storage, hydrogen in steelmaking, and alternative building materials have high mitigation potentials. They are expected to achieve large-scale implementation shortly before 2040 but they feature high risks of being delayed. Respondents also indicate the same affirmative positions to all CCS-related CTIs of Cluster IV, which also includes ODIs of reducing space, reducing food, and alternative diets. The rest of the ODIs are grouped in Cluster V: these demand-side changes in mobility and energy potentially affect deep decarbonisation pathways, with their adoption/availability mostly expected before 2030 with no substantial risk of delays.

3.4. Multi-criteria assessment of low-carbon innovations

3.4.1. Core technological innovations – rankings for the whole expert sample

We then perform an MCDA analysis (Fig. 6) to assess each of the innovations against all three criteria. On the purely technological front, we identify three groups of distinct priority levels among the 14 game-changing CTIs considering their mitigation potentials, expected at-scale commercial availability, and risk of delay (cf. Fig. 4).

The top priority group includes three technologies for industrial decarbonisation—including alternative building materials for steel and cement (TOP- SIS score = 2.78), hydrogen in steelmaking (2.72), and iron ore electrolysis (2.58)—as well as next-generation energy storage (2.70). Technologies of relatively moderate-to-high priority include those for carbon sequestration—i.e., BECCS (2.34), CCS (2.24), and biochar (2.24)—and technologies for aviation biofuels (2.36) and securing an advanced biofuel supply (2.24).

Lowest priority technologies include hydrogen aircraft (1.47) and hyper-loops (1.40), DAC (1.30) and ocean liming (1.19), as well as nuclear fusion (1.05). Although the 2-tuple TOPSIS and group-decision making in general are primarily ranking and not clustering methods, the intuitive trends observed from the 'global solution' are close to the ones observed in the clustering analysis discussed in the previous section. We also find high consensus among all stakeholders (84.8%), hinting at small deviations between the 'global solution' (i.e., the results of the group as a whole) and individual stakeholder views.

3.4.2. Core technological innovations – ranking differences among expert groups

Among different stakeholder groups, rankings do not differ markedly, with technologies for decarbonising industry and next-generation energy storage remaining of the highest priority (Fig. 6). When looking at working capacity, the ranking among academics (the largest group) was expectedly similar to the global solution, despite slightly undermining top-priority technologies and boosting the moderate-priority technology group (slightly reducing the distance between the two groups). In contrast, the gap between the top-priority group and the moderate-priority group was more accentuated for private-sector stakeholders, who furthermore prioritised aviation biofuels while showing relatively limited faith in iron ore electrolysis (essentially

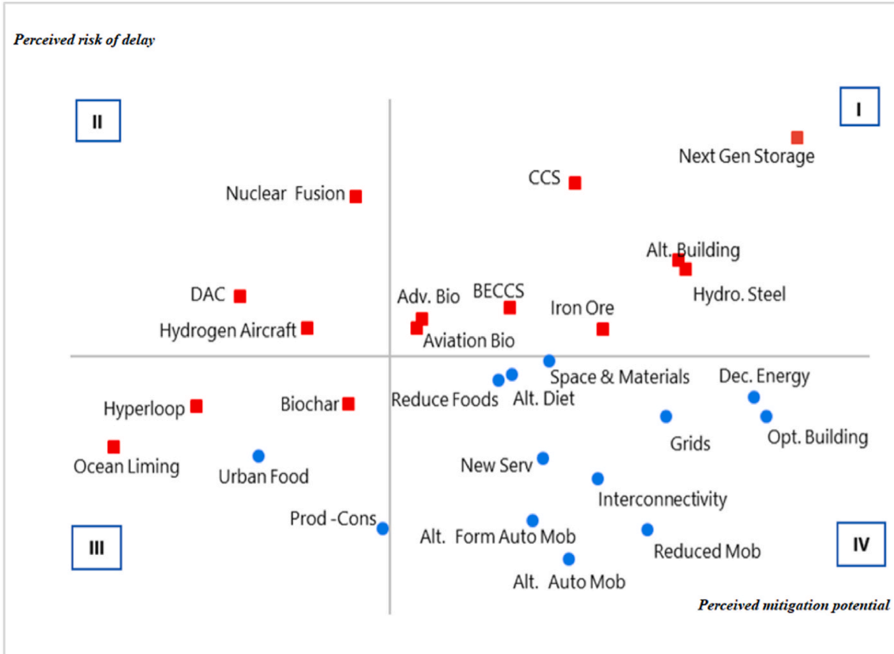

Fig. 4. Risk of delay along with mitigation potentials of low-carbon innovations as perceived by the survey respondents. Red squares show CTIs while blue circles show ODIs.

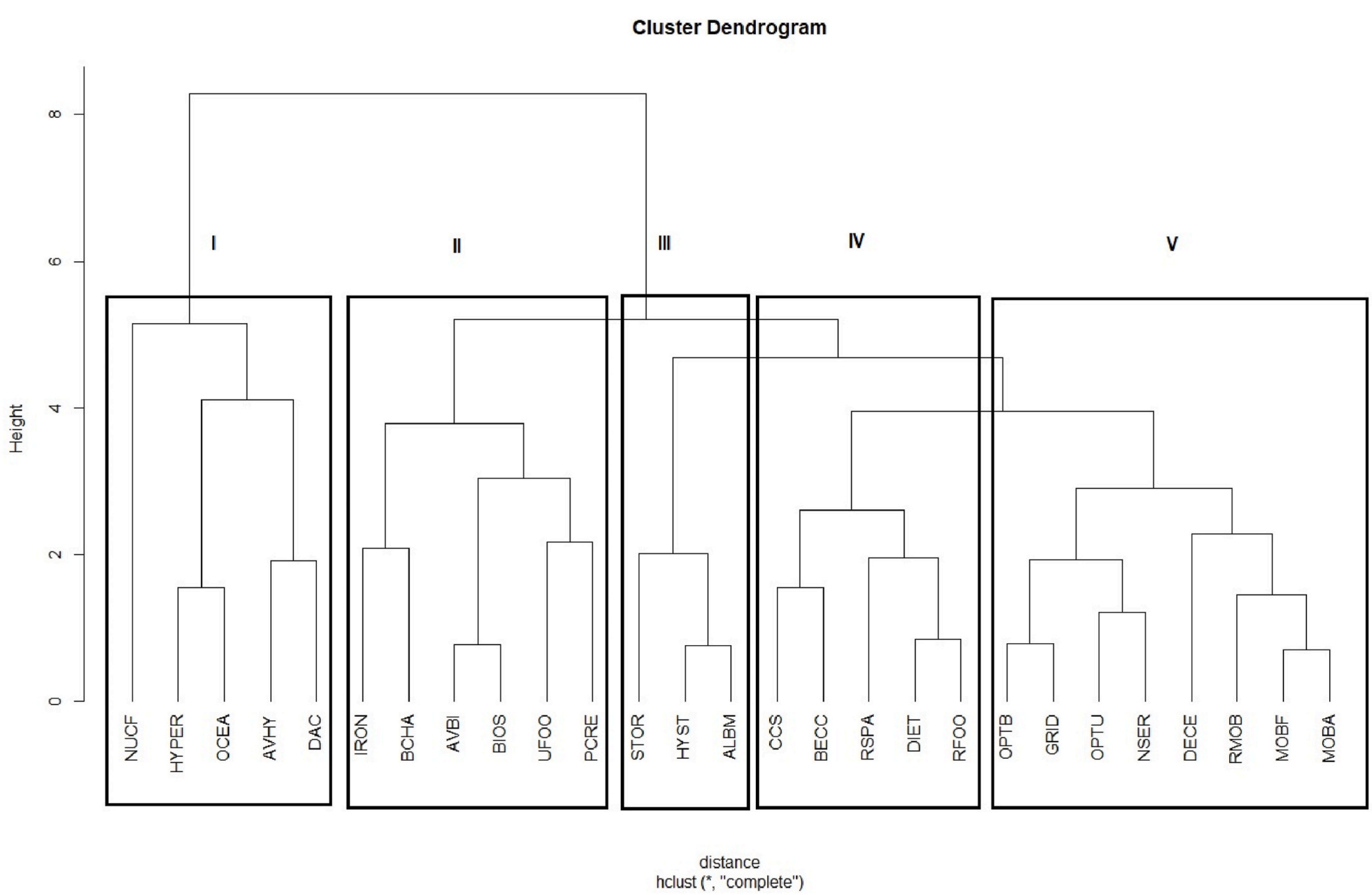

Fig. 5. Cluster dendrogram of low-carbon innovations based on respondent perceptions.

swapping aviation biofuels and iron ore electrolysis in the top priority group). National policymakers also prioritised aviation biofuels but also singled out alternative building materials as the most prominent technology.

Stakeholders from international institutions, however, gave the highest priority to next-generation energy storage and steel-sector

Table 5
Hierarchical cluster classifications of low-carbon innovations based on perceived mitigation potential, widespread availability/adoption, and risk of delay.

Cluster I (low mitigation potentials, mostly available post-2050, high-to-moderate risk of delay)
NUCF Nuclear fusion
HYPER Hyperloops
OCEA Ocean liming
AVHY Hydrogen aircraft
DAC Direct Air Capture
Cluster II (varied mitigation potentials, adoption 2030–2040)
IRON Iron ore electrolysis
BCHA Biochar
AVBI Aviation biofuels
BIOS Advanced biofuel supply
UFOO Urban food production
PCRE Producer-consumer relationships
Cluster III (high mitigation potentials, adoption before 2040, high risk of delay)
STOR Next-generation energy storage
HYST Hydrogen in steelmaking
ALBM Alternative building materials for steel and cement
Cluster IV (moderate-to-high mitigation potentials, adoption 2030–2040)
CCS Carbon Capture and Storage
BECCS Biomass Carbon Capture and Storage
RSPA Reduced demand for space and materials
DIET Alternative dietary preferences
RFOO Reduced demand for food
Cluster V (moderate-to-high mitigation potentials, adoption before or closely after 2030, almost no risk of delay)
OPTB Optimisation of buildings thermal performance
GRID Integrating consumers into grids
OPTU Interconnectivity for optimised usage
NSER New service providers
DECE Decentralised energy supply
RMOB Reduced demand for mobility
MOBF Alternative forms of auto-mobility
MOBA Alternatives to auto-mobility

hydrogen; compared to all other groups, they also largely boosted CCS, bringing this technology closer to the top-priority CTIs, while emphatically undermining nuclear fusion. NGO representatives featured the largest divergence from the global solution, clearly prioritising steel-sector hydrogen, increasing the importance of transport technologies (hyperloops, hydrogen aircrafts), and showing less faith in CCS (with or without bioenergy), advanced biofuel supply, and biochar. In further analysing these expert assessments from a regional perspective, we find that stakeholders from high-income countries closely followed the global solution but overemphasised the top-priority technology group (and aviation biofuels), contrary to nuclear fusion. Respondents from upper-medium-income countries (most Chinese) also emphasised the importance of industry measures (including iron ore electrolysis, which was placed first in that group). Still, they appeared more favourable towards globally lower-priority technologies, such as nuclear fusion, hyperloops, and hydrogen aircraft (not for DAC, though, which received the lowest priority). This pattern is even more evident among stakeholders from low-medium- and low-income countries, who also favour BECCS (perhaps considering high biomass potential in their countries and the role of agriculture in their economies).

From a gender perspective, although female respondents emphasised hydrogen in steelmaking more, negligible deviations were found overall. A notable exception can be found in CCS and aviation biofuels, with female respondents favouring the former and male respondents highlighting the latter as part of their top priorities, respectively.

Agreement of each stakeholder group on the global solution was around global consensus, ranging from 82.2% (lower-middle- and low-income countries) to 85.9% for stakeholders from high-income countries (Fig. 6), which explains the small differences among groups. Likewise, a high consensus within stakeholder groups hinted at similar expectations among people from the same profession or same-income regions.

3.4.3. Other disruptive technologies – rankings for the whole expert sample

In contrast to technologies, groups were less distinct for ODIs (Fig. 7), which showcased relatively even differences. The top-priority disruptive innovations are oriented towards mobility, including reduced demand for (2.95) and alternatives to (2.80) auto-mobility, although alternative mobility models (e.g., car-sharing) received a lower priority score (2.56).

ODIs of relatively high priority are also directed to innovations in buildings and energy supply that have been already pursued by policy yet not fully achieved to the desired extent. These include optimising buildings' thermal performance (2.72), consolidating a decentralised energy supply (2.60), and ensuring interconnectivity for usage optimisation (2.57); reduced demand for space and materials was an outlier of the buildings-related innovations, placing in the bottom (1.84). Other measures for energy supply received rather average priorities, including consumer integration into grids (2.42), e.g., through demand response measures, and new (energy) service providers (2.37). Food-related innovations were perceived as low priority; these included improved producer-consumer ties (2.16), reduced food demand (1.85), alternative dietary habits (1.79), and urban food production (1.30). Consensus among participants on these innovations (80.2%) was lower than in the CTI survey, reflecting higher competition among individual alternatives.

3.4.4. Other disruptive technologies – ranking differences among expert groups

By working capacity, and as in the case of the technologies, academics showed small divergences from the global analysis, slightly reducing the priority of the highest-ranked innovations (alternatives to and reduced demand for auto-mobility, and optimisation of thermal performance), without considerable changes in the ranking. Again, this is an expected outcome, considering this stakeholder group made up half of the entire expert sample. Industry representatives indicated measures to reduce demand for mobility as top priority; they also emphasised decentralised energy supply but slightly undermined the importance of thermal performance in the built environment. National policymakers further boosted mobility measures as a top priority while also favouring energy-supply related measures, such as integrating consumers into grids and decentralised energy supply. International organisations gave the highest priority to optimising thermal performance in buildings, with mobility measures following. Overall, NGOs appeared to deem most ODIs almost of equally as high priority, in contrast to the other stakeholder groups, who instead displayed a clearer ranking of their preferences. NGO representatives notably prioritised alternatives to auto-mobility but, contrary to all other stakeholder groups, also boosted food-related game-changers, such as urban food production and alternative diets.

From a regional point of view, like in the technological component of the survey and considering their high share among respondents, there was a large agreement between stakeholders from high-income countries and the global solution, with both (global and high-income) preference models favouring consumer integration into the power grid and provision of new services (aggregators, third-party financing, etc.). Stakeholders from upper-middle- income countries gave the highest priority to smart inter-connectivity and all mobility measures, notably including alternative forms of auto-mobility as well; they instead showed relative disbelief to energy-supply measures (decentralised energy supply, integrating consumers into grids, and new service providers). Stakeholders from lower-medium- and low-income countries were more pessimistic overall, except for a slight preference of reduced demand for mobility.

Finally, gender-wise, female stakeholders had higher evaluations for most ODIs, although trends in their ranking remained close to the global solution; a notable difference was higher preference for decentralised energy supply.

Consensus on the ODIs among stakeholder groups differed slightly more than that on CTIs (Fig. 7), ranging from 76.7% (lower-middle-

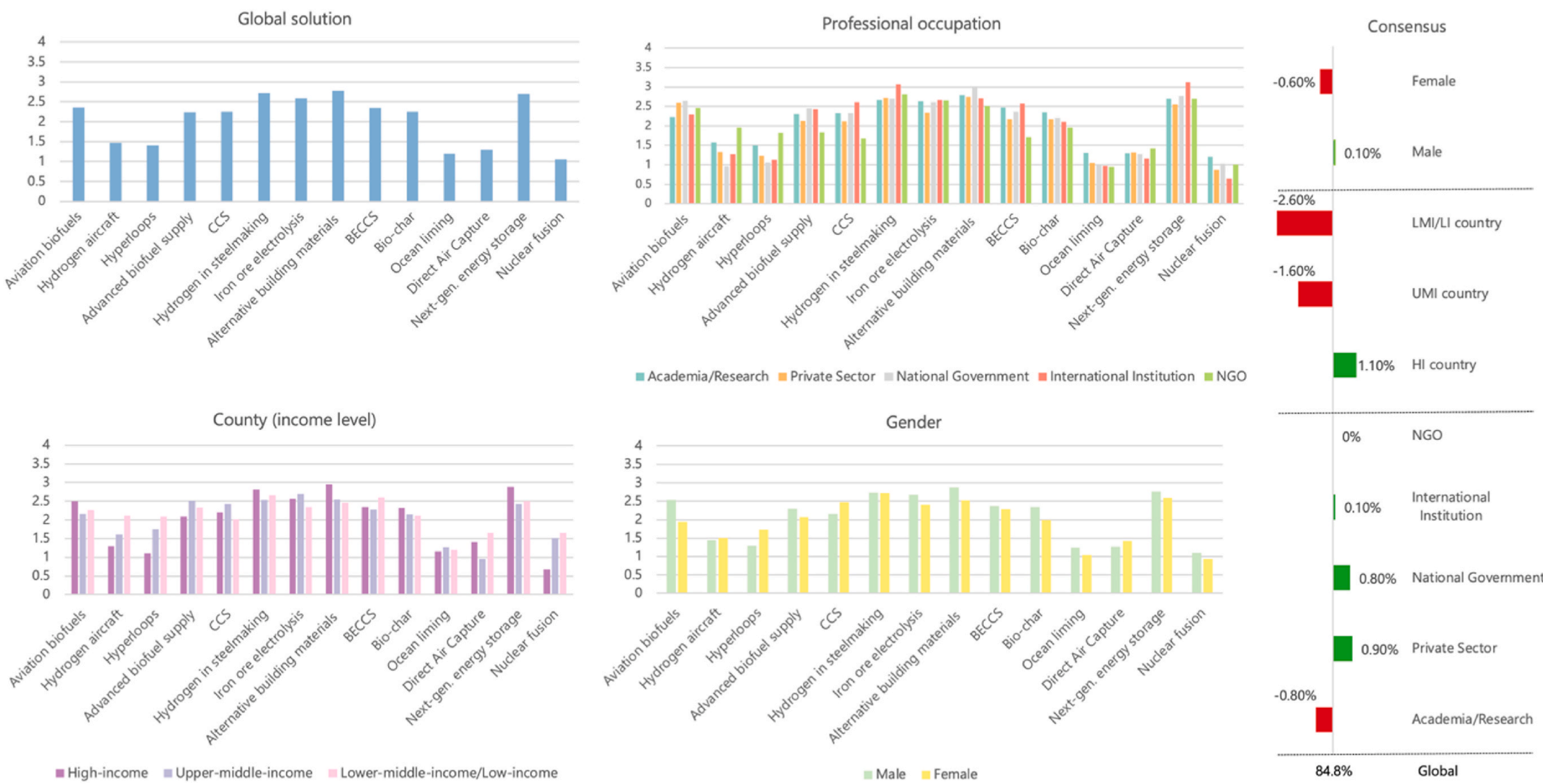

Fig. 6. TOPSIS scores and consensus among respondents in terms of perceived mitigation potential, commercial availability, and risk of delay for CTIs.

Fig. 7. TOPSIS scores and consensus among respondents in terms of perceived mitigation potential, widespread adoption, and risk of delay for ODIs.

income and low-income countries) to 83.7% (international organisations). The reason behind this lower consensus, vis-a-vis the consensus on technologies, may lie in the much clearer conflicts among ODIs (e.g., building-related measures vs. energy supply-related measures, the role of alternative forms of auto-mobility, etc.). Much like (albeit lower than) that of the technological survey, the consensus among stakeholders of the same groups was at similar levels. Detailed numerical evaluation of TOPSIS scores (and, consequently, of the ranking) of technological and other disruptive innovations according to each stakeholder group is given in Figure B1 and Figure B2 in Appendix B.

4. Discussion

Respondents' opinions on potential technological innovations could be classified into three groups. Next-generation energy storage, alternative building materials, iron ore electrolysis, and hydrogen in steelmaking are technologies with high mitigation potentials and likely available before 2040, yet with moderate-to-critical risk of being delayed. Experts' assessment classifies these as the top priorities of technologies for decarbonisation. Following this, most respondents evaluate CCS, BECCS and other biofuel-related technologies to have moderate-to-high priority. However, CCS and BECCS also have a high risk of being delayed. Such risk is a critical consideration, as it may invalidate widespread scenario frameworks [102–104], which are compliant with the Paris Agreement temperature goals by assuming/relying on early and considerable contributions from these technologies. Recent literature also emphasises that massive reliance on yet unavailable such technologies may even rely on modelling preferences rather than scenario assumptions [105]. On the other hand, both hyperloops and ocean liming face higher uncertainty compared to others, and respondents assess their mitigation potentials as relatively low, with a high potential of being delivered post-2030 or further delayed. Perceptions of hydrogen aircraft, DAC, and nuclear fusion tend to be even less optimistic, with low mitigation potentials and high risks of never materialising.

For almost all non-technological innovations, most experts believe in moderate-to-high mitigation potentials. Most assessments converge that these innovations can be implemented shortly after 2030. This finding renders further support to calls in the literature that urge researchers and modellers to include behavioural and societal aspects in decarbonisation pathways in order to increase their realism, relevance, and societal feasibility [16,17,106–108]. Some are expected to be implemented even sooner (before 2030) and are less likely to be delayed. These include alternative forms of auto-mobility (car-sharing, ride sharing), alternatives to auto-mobility (e.g., e-bikes), and reduced demand for mobility (e.g., homeworking, teleconferences, etc.). Innovations related to food and space reductions are expected to be more challenging than others. Reduced demand for food, space and materials, alternative dietary preferences, and urban food production are characterised by the lowest priority and considered to be less feasible than the rest, while their mitigation potentials varied.

While the focus of this study was to collect numerous expert-based evaluations on different innovations, there is a number of caveats in our data collection. Most importantly, we acknowledge that our sample was not representative of the global population of climate and energy experts. Instead, we aimed to gather a large enough sample of experts from different fields and countries in order to maximise the diversity of the collected perspectives. This is illustrated by the fact that our final sample of 260 experts from 56 counties is larger and more diverse regionally than many similar expert evaluations related to low-carbon innovations [109–111]. However, our sample still included groups of different sizes (e.g., males constituting a markedly higher share; this could however also be a reflection of the existence of broader gender and other inequalities in the expert population) and aggregated results can be influenced by these large groups. To mitigate this risk, an independent group analysis based on occupation/capacity, gender, and region, was performed to understand the preferences of smaller groups of experts and the overall sensitivity of our aggregated findings. As shown in Sections 3.4.2 and 3.4.4, results for non-technological innovations are mostly similar among respondents with different working backgrounds, genders, or regions of origin. Nevertheless, some conflicts are still identified among groups on the prioritisation of building and energy-supply measures: for example, both academics and international institutions greatly prioritise optimal thermal performance in buildings, which is not the case with private-sector and national government respondents. In terms of technological innovations, rankings are slightly more similar among different groups of respondents, with technologies for decarbonising industry and next-generation energy storage remaining at the top of the priority list among all groups. These results suggest that, while some differences exist between groups, ranking patterns among examined innovations are not significantly biased by imbalances in our sampling.

In addition to sampling issues, our methodological choices may have also led to a number of cognitive biases during the elicitation of expert views, such as framing effects. First, while we have used the IEA net-zero scenario to showcase the need for innovations in multiple sectors, this scenario may have inadvertently downplayed the need for Carbon Dioxide Removal (CDR) compared to other such pathways (e.g., from the IPCC [112]). Nevertheless, we assume that this framing effect would be small, as most respondents seemed to be aware of the significance of BECSS—the most widely used CDR measure in decarbonisation pathways [113]—as shown by the moderate-to-high mitigation potentials assigned for this technology (Fig. 1) and the relatively small number of respondents that could not decide on a potential (Table 3). Second, in order to reduce the number of questions in our survey, we had to group together innovations that may differ in terms of potentials and risks, such as in the case of next-generation energy storage including power-to-gas, flywheels, and new batteries. While we acknowledge that respondents may have contextually evaluated innovations by judging the entire group based on their perceptions for one or few of the listed innovations within that group, we believe that our findings still have value as they can help policymakers understand the relative significance among major innovation categories, e.g., energy storage versus DAC technologies. Future studies can shed more light on differences between innovations that had to be grouped together in our work.

Other potential biases that may affect the quality of the results relate to the way the respondents answered our survey. Notably, survey respondents were not necessarily experts in all 27 innovations included in the survey. We addressed this issue by offering a "not able to respond" option and by adjusting the contribution of each expert in the MCDA exercise based on how many times this respondent chose this option. Experts that selected "not able to respond" for more than half of innovations were removed from the MCDA analysis. Still, some experts may have responded on innovations that they do not have expertise into. Additionally, all survey questions used linguistic scales for simplifying the assessments. However, linguistic scales are often prone to subjective interpretations. For instance, a high mitigation potential may be interpreted differently for different innovations, especially among ODIs, the potentials of which are rarely quantified in analytical/modelling studies. Nevertheless, since the same questions and scales were used for all innovations, it is assumed that the survey captured the relative differences among innovations, allowing us to perform the prioritisation shown in Section 3.4. Finally, even though the aforementioned effects were indeed minimal, the responses of the experts may have been affected by other cognitive biases such as overconfidence [39,40]. Due to the size of the sample and the survey, it was not possible to use formal expert elicitation methods for reducing these biases. While the diversity of our expert sample can already help mitigate some of the biases [114], future studies need to explore more ways to reduce biases in large-scale, expert-based surveys.

5. Conclusions

Deep and rapid decarbonisation is critical for achieving the temperature goals of the Paris Agreement. This paper evaluates 27 potentially game-changing technological and non-technological innovations for deep decarbonisation through a worldwide online survey with 260 climate and energy experts. The survey elicited the views of the experts on the mitigation potentials of the selected low-carbon innovations, along with the timing of their commercial availability or widespread adoption, and their risk of being delayed for the broader transition they are hoped to promote (i.e., not materialising their mitigation potential). Based on the results of the survey, hierarchical clustering as well as multi-criteria decision and consensus analysis are performed to group and rank the experts' assessments of all selected low-carbon innovations.

Overall, results show large differences among technological innovations in terms of perceived mitigation potential and feasibility, in contrast with the non-technological (behavioural/societal/business) innovations, for which evaluations were much more uniform. Most respondents were optimistic about almost all non-technological innovations and perceived them as having moderate-to-high mitigation potentials, with mobility measures receiving the most positive evaluations. On technological innovations, the most positive evaluations have been found on measures for diverse sectors, i.e., next-generation energy storage, advanced building materials, and iron ore electrolysis for steel production.

Although based on the subjective views of the participating experts (see caveats at the end of Chapter 4), these results provide indications on the relative strengths and weaknesses of a wide range of low-carbon innovations, which can be valuable to policymakers and researchers, especially in lack of robust modelling results. We outline four critical recommendations stemming from our findings, which can be used to develop more realistic net-zero strategies as well as new decarbonisation scenarios and associated pathways in support of such transformational strategies.

First, scenarios that consider non-technological innovations, including but not limited to behavioural changes, must be explored. This especially concerns disruptive mobility innovations, which in our study received the highest priority among expert participants.

Second, demand-related innovations, such as demand-side management and smart grids, also need to be considered. These are aspects that have been looked at in the broader energy literature (e.g., Refs. [115–119]), but they remain detached from the principal modelling studies driving the large scientific assessments and policy strategies. The same can be said about the role of hydrogen-based technologies in industrial sectors, next-generation energy storage, and decentralised energy supply, which expert stakeholders seemingly expect to play a vital role in deep decarbonisation pathways.

Third, energy and climate experts appear to deem CCS and BECCS as valid mitigation options, but their significant potential is associated with considerable risk of delay in their widespread adoption. Scenarios featuring large shares from these technologies need to be re-evaluated and potentially incorporate contributions from other transformative innovations that experts deem more plausible to land or take off at scale, to mitigate this risk.

Finally, technologies like DAC, hyperloops, ocean liming, and nuclear fusion are almost unlikely to be available before the middle of the century, and thus should be considered less relevant in mitigation scenarios aiming for net neutrality close to or around 2050. This is especially relevant for DAC technologies and advances in nuclear fusion, which are increasingly gaining ground in the public debate on promising low-carbon technologies.

Future research can draw from the expert preferences and views discussed in this study to inform modelling exercises about the true potential and expected time of readiness of the game-changing innovations to build realistic scenarios that avoid exaggerating the role of technologies not yet available or underrepresent the role of demand-side related innovations. Further analysis on the survey results could be performed through clustering of respondents to accompany the clustering of innovations and shed light on common patterns in the votes of participants. Finally, future studies could attempt to replicate the analysis performed here based on national surveys, to shed light on additional regional differences that our high-level analysis here was not designed to highlight.

Authorship contribution statement

Sigit Perdana: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Vizualisation. Geogios Xexakis: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Vizualisation, Validation. Konstantinos Koasidis: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Vizualisation. Validation. Marc Vielle: Conceptualization, Methodology, Writing – original draft, Vizualisation, Supervision. Alexandros Nikas: Methodology, Formal analysis, Investigation, Data curation, Resources, Writing – original draft, Writing – review & editing, Vizualisation, Supervision, Project administration. Haris Doukas: Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. Ajay Gambhir: Methodology, Investigation, Writing – review & editing, Supervision. Annela Anger-Kraavi: Methodology, Formal analysis, Writing – original draft, Supervision. Elin May: Formal analysis, Writing – original draft, Writing – review & editing. Ben McWilliams: Conceptualization, Investigation, Data curation, Writing – review & editing. Baptiste Boitier: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Vizualisation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Additional technologies & non-technological innovations

The survey also asked respondents about specific technologies and non-technologies innovation with potential mitigation of deep decarbonisation, outside those listed in the questionnaire. Table A.1 below summarises those notable mentions.

Table A1
Low-carbon innovations suggested by the respondents

#	Technologies	Non-Technologies
1	Digital technologies	Circular/repair economy
2	Related hydrogen technology - Hydrogen infrastructure (energy intermediation)	Clothing materials changing
3	Ecosystem restoration on land-forestry or ocean Ocean pasture	Sustainable farming
4	Energy conversion from waste	Reduced demands of new products
5	Photocatalysis	Reduced space of commercial buildings
6	Deep geothermal	
7	Fourth generation of nuclear power	
8	Electric aircraft	
9	Ocean energy	

Appendix B. TOPSIS scores and consensus of evaluated low-carbon innovations

Technologies	Full sample	Grouping by professional capacity/occupation					Grouping by country			Grouping by gender	
		Academia/ Research	Private Sector	National Government	International Institution	NGO	HI	UMI	LMI+LI	Male	Female
Aviation biofuels	2.36	2.22	2.60	2.64	2.30	2.46	2.50	2.16	2.26	2.54	1.94
Hydrogen aircraft	1.47	1.58	1.33	0.96	1.28	1.95	1.29	1.61	2.12	1.44	1.50
Hyperloops	1.40	1.49	1.23	1.06	1.12	1.82	1.10	1.75	2.09	1.29	1.73
Advanced biofuel supply	2.24	2.30	2.12	2.45	2.42	1.84	2.09	2.51	2.33	2.30	2.07
CCS	2.24	2.33	2.11	2.33	2.61	1.67	2.20	2.42	2.01	2.15	2.47
Hydrogen in steelmaking	2.72	2.66	2.73	2.69	3.06	2.80	2.82	2.53	2.67	2.74	2.72
Iron ore electrolysis	2.58	2.63	2.34	2.61	2.67	2.66	2.57	2.69	2.35	2.67	2.40
Alternative building materials	2.78	2.79	2.75	2.98	2.71	2.51	2.96	2.55	2.46	2.87	2.52
BECCS	2.34	2.47	2.18	2.36	2.58	1.71	2.34	2.28	2.60	2.37	2.28
Bio-char	2.24	2.35	2.17	2.21	2.11	1.96	2.33	2.15	2.12	2.34	1.98
Ocean liming	1.19	1.31	1.05	1.01	0.98	0.95	1.15	1.27	1.20	1.25	1.04
Direct Air Capture	1.30	1.29	1.32	1.28	1.16	1.42	1.41	0.96	1.65	1.26	1.42
Next-gen. energy storage	2.70	2.70	2.55	2.76	3.12	2.69	2.88	2.43	2.49	2.76	2.59
Nuclear fusion	1.05	1.20	0.87	1.03	0.64	1.01	0.68	1.51	1.66	1.10	0.93
Consensus (%)	84.8	84	85.7	85.6	84.9	84.8	85.9	83.2	82.2	84.9	84.2
Number of stakeholders	*248*	*126*	*55*	*24*	*16*	*22*	*154*	*69*	*25*	*173*	*71*

Note: Scores range from 4 = high priority to 0 = low priority. HI = high-income county; UMI = upper-middle-income country; LMI + LI = low-middle- and low-income countries.

Fig. B1. TOPSIS scores and consensus for CTIs among respondents of different professional capacities, countries, and gender

DLCI	Full sample	Grouping by professional capacity/occupation					Grouping by country			Grouping by gender	
		Academia/ Research	Private Sector	National Government	International Institution	NGO	HI	UMI	LMI+LI	Male	Female
Alternative forms of auto-mobility	2.56	2.43	2.55	2.53	2.59	3.26	2.53	2.71	2.32	2.57	2.49
Alternatives to auto-mobility	2.80	2.69	2.66	3.05	2.78	3.36	2.86	2.74	2.57	2.85	2.64
Reduced demand for mobility	2.95	2.83	3.12	3.04	2.73	3.08	3.04	2.73	3.02	2.94	2.96
Alternative dietary preferences	1.79	1.66	1.91	1.73	1.88	2.21	1.90	1.40	2.23	1.81	1.74
Urban food production	1.30	1.32	1.23	1.05	0.96	1.87	1.22	1.25	1.89	1.16	1.57
Producer-consumer relationships	2.16	2.19	2.03	1.98	2.26	2.46	2.12	2.23	2.21	2.07	2.40
Reduced demand for food	1.85	1.98	1.54	2.26	1.63	1.51	1.83	1.91	1.79	1.73	2.17
Interconnectivity for optimised usage	2.57	2.63	2.59	2.55	2.53	2.37	2.53	2.74	2.37	2.48	2.80
Optimisation of buildings' thermal performance	2.72	2.75	2.58	2.52	3.16	3.02	2.85	2.60	2.28	2.67	2.80
Reduced demand for space and materials	1.84	1.94	1.52	2.21	1.51	1.85	1.76	2.00	1.92	1.81	1.97
New service providers	2.37	2.40	2.31	2.30	2.15	2.66	2.51	2.22	1.87	2.32	2.46
Integrating consumers into grids	2.42	2.27	2.42	2.75	2.56	2.86	2.63	2.16	1.81	2.30	2.65
Decentralised energy supply	2.60	2.45	2.75	2.81	2.46	3.06	2.78	2.29	2.39	2.47	2.90
Consensus (%)	80.2	79.8	81.3	77	83.7	79.1	81.1	79.5	76.7	80.6	79.1
Number of stakeholders	*256*	*128*	*59*	*26*	*15*	*22*	*160*	*70*	*26*	*179*	*73*

Note: Scores range from 4 = high priority to 0 = low priority. HI = high-income county; UMI = upper-middle-income country; LMI + LI = low-middle- and low-income countries.

Fig. B2. TOPSIS scores and consensus for ODIs among respondents of different professional capacities, countries, and gender

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