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REINFORCE

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D6.5 GAME-CHANGING INNOVATION ACROSS THE GLOBE

WP6 – Promoting Sustainable Transitions Across the Globe

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA. The deliverable was submitted in November 2021, in line with the DoA deadlines. However, an updated version was submitted upon completion of the survey and analysis of the results (see Sections 3.4-3.5), in March 2022.

2. Dissemination and uptake

This deliverable will remain confidential, available only to members of the consortium and the Commission Services, until its content is published in (a series of) academic journals.

3. Short summary of results (<250 words)

This deliverable identifies potential transformative innovations that can help deliver a deep decarbonisation pathway in line with the Paris Agreement and overall climate goals. Selected low-carbon innovations, both technological and non-technological, are chosen based on recent scientific literature. An evaluation of these innovations is then conducted by means of a worldwide online survey targeting climate and energy experts. The survey results reveal considerable differences of perception among 260 different experts regarding technological innovations, although their assessments appear to converge on non-technological innovations. Next-generation energy storage, alternative building materials, iron ore electrolysis, and hydrogen in steelmaking are technologies with high mitigation potentials and likely available (i.e., expected) before 2040, yet with moderate to critical risk of being delayed/unavailable. Hyperloops and ocean liming face higher uncertainty relative to other technologies, with respondents assessing their mitigations potential as relatively low and with a higher possibility of delayed at-scale diffusion. Similar results are found for DAC, hydrogen aircraft, and nuclear fusion. In comparison, expert assessments converge towards expected adoption of several non-technological innovations shortly after 2030. Some of these innovations are even expected before 2030 and less prone to delays. Innovations related to food (demand, production, dietary preferences, etc.) as well as space and materials are expected more challenging. The deliverable further assesses the extent to which the considered innovations are represented in (the project's) IAMs.

4. Evidence of accomplishment

This report.

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Preface

PARIS REINFORCE will develop a novel, demand-driven, IAM-oriented assessment framework for effectively supporting the design and assessment of climate policies in the European Union as well as in other major emitters and selected less emitting countries, in respect to the Paris Agreement. By engaging policymakers and scientists/modellers, PARIS REINFORCE will create the open-access and transparent data exchange platform I²AM PARIS, in order to support the effective implementation of Nationally Determined Contributions, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake. Finally, PARIS REINFORCE will introduce innovative integrative processes, in which IAMs are further coupled with well-established methodological frameworks, in order to improve the robustness of modelling outcomes against different types of uncertainties.

NTUA - National Technical University of Athens	GR	EPU N·T·U·A
BC3 - Basque Centre for Climate Change	ES	bc3
Bruegel - Bruegel AISBL	BE	bruegel
Cambridge - University of Cambridge	UK	UNIVERSITY OF CAMBRIDGE
CICERO - Cicero Senter Klimaforskning Stiftelse	NO	°CICERO
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT	cmcc
E4SMA - Energy Engineering Economic Environment Systems Modeling and Analysis	IT	E4SMA
EPFL - École polytechnique fédérale de Lausanne	CH	EPFL
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE	Fraunhofer ISI
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK	Grantham Institute Climate Change and the Environment
HOLISTIC - Holistic P.C.	GR	HOLISTIC
IEECP - Institute for European Energy and Climate Policy Stichting	NL	IEECP
SEURECO - Société Européenne d'Economie SARL	FR	SEURECO ERAΣME
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR	Centro de Desenvolvimento Sustentável UnB
CUP - China University of Petroleum-Beijing	CN	
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU	IEF RAS
IGES - Institute for Global Environmental Strategies	JP	IGES
TERI - The Energy and Resources Institute	IN	teri

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Executive Summary

Rapid decarbonisation is critical to achieving the Paris Agreement temperature goals. The analysis of deep decarbonisation pathways, in turn, requires the identification of transformative innovations, framed as low-carbon innovations, to investigate their potential for substantial emissions reduction and readiness of widespread adoption. This deliverable identifies and evaluates potential transformative innovations for a deep decarbonisation pathway to achieve climate goals in line with the Paris Agreement.

Identification of technological innovations is based on Technology Readiness Level (TRL) and covers the transportation, industry, building, and construction sectors, and technologies related to negative emissions. Likewise, non-technological innovations include any disruptive and sustainable actions that trigger fundamental shifts in society and societal behaviour, which may affect decarbonisation/climate goals. These include innovations with regard to mobility, building and interconnectivity, food consumption, and energy distribution.

The evaluation is conducted by means of a worldwide online survey on these selected technological and non-technological low-carbon innovations. The survey is targeted at climate and energy expert stakeholders, aiming to elicit the respondents' specific knowledge about the mitigation potential and availability of, and risk associated with, those innovations. Statistical analysis is finally used to synthesise the experts' assessments of these selected low-carbon innovations, to understand the extent to which they should play a role and thus be represented in scientific research in Paris-complaint pathways.

Survey results indicate the likelihood of positive mitigation potentials of non-technological innovations. The experts' assessment of non-technological innovations appears to be more homogeneous across all criteria. On the other hand, stakeholders' perceptions appear to diverge considerably more for technological innovations. Next-Generation energy storage, alternative building material, and hydrogen in steelmaking are expected to be instrumental in deep decarbonisation pathways. Following those, carbon captured storage (CCS), with bioenergy (BECCS) or otherwise—which are widely used in net-zero emissions pathways (IPCC 1.5°C report, 2020)—are highly recognisable to have significant mitigation potential in the near-term (up to 2040).

In contrast, respondents tend to be sceptical of mitigation potentials for technologies like ocean liming or hyperloops. These insights also correlated with experts' expectations on the commercial availability of these technologies. Along with hydrogen aircraft, nuclear fusion, and direct air capture (DAC), these technologies are expected not to be available before the second part of the century.

Interesting insights are gained on the perception of the possible role of the considered technological and other disruptive game-changers, which appear to depend on the working capacity, region, and to a lesser extent gender of the respondents.

The survey results draw five critical recommendations for further modelling development. First, scenarios that consider non-technological innovations (such as behavioural changes) must be explored in detail, especially when it comes to mobility. Second, options related to demand (demand-side management, smart grids, etc.) must also be considered. Third, the role of hydrogen-based technologies in industrial sectors, next-generation energy storage, and decentralised energy supply must be further investigated as stakeholders expect them to play a central role in the road to well-below-2^{o}C. Fourth, scenarios considering considerable contributions of BE/-CCS as valid mitigation options must be realistically constrained/adapted to provide for greater shares of other transformative innovations. Finally, technologies like DAC, hyperloops, ocean liming, hydrogen aircraft, and nuclear fusion are unlikely to be at-scale available before the middle of the century, and thus should be deemed as insignificant when designing mitigation pathways for 2050 (and beyond).

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Contents

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Table of Figures

Table of Tables

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

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1 Introduction: Low-Carbon Innovation in Net-zero Emissions Pathway

Since pre-industrial levels, the global mean surface temperature has increased by approximately 1.1°C. Without substantial intervention, it is predicted to reach a 1.5°C rise between 2030-2052 (IPCC, 2018). Consequently, limiting the global temperature from rising less than 2°C at the end of the century requires a global effort of deep and rapid decarbonisation pathway. Global CO_2 emissions need to decrease by approximately 45% from 2010 levels by 2030 and net-zero emissions by 2050. In line with the Paris Agreement's goals, achieving this target requires decarbonising our industrial, economic, and societal activities. Decarbonisation requires transformative innovation, which is defined as significant shifts in markets, systems, infrastructure, and behaviour (Nelson and Allwood, 2021). Task 6.2.5 sets out to identify transformative innovations, or "game changers", and their effects on global decarbonisation pathways and overall climate goals in light of the need to increase ambition (Box 1).

Box 1 Protocol for studying innovation dynamics in Europe and non-EU countries (MS7)

Consortium partners are invited to pay attention to the following while preparing respective deliverables (D5.3 and D6.5):

(1) The deliverables should have a section on innovation, which is normally technological and/or institutional (i.e. changing the rules of the game) in its nature.
(2) It is also possible to envision innovative deployment or implementation of technologies that may already exist and be also in use at a small scale. However, upscaling an already commonly used technology and reaching economies of scale is generally NOT innovation, nor does the implementation of least-cost policies or existing legislation qualify as innovation.
(3) This work should not repeat what has already been done in the published papers and other deliverables of Paris Reinforce. It should obtain value-added beyond these.
(4) The expected climate mitigation impacts of the observed or desired innovations should be significant, either in quantitative terms or because they create a new pathway that is arguably low carbon or low emissions in the longer term.
(5) The innovations considered have to bear some broader appeal. Otherwise, these are certainly not game-changing in any way.
(6) The game-changing innovations should be discussed with stakeholders and additional options will be identified/co-created during these engagements.

The sections on innovations dynamics in D5.3 and D6.5 should:

1. Provide the background and rationale as to why the issue is important
2. Identify and explain what and in which ways the identified or desired innovation is innovative and/or game-changing
3. Explain the appropriate geography and why it is significant in climate terms.
4. Demonstrate clearly value-added to other work done in Paris Reinforce.
5. Explain the modelling or analytical approach taken and how this goes beyond previous approaches (i.e. adds value) even if using the same tool(s) or methods.
6. Describe any key linkages with other WPs, tasks, sub-tasks, deliverables and milestones.
7. Provide results, discussion, and conclusions and scope for further research.

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Conceptually game-changers are broadly defined as macro-trends that are perceived to change the game's rules and how society is organised based on today's understandings, values, institutions, and social relationships (Haxeltine et al., 2013; Avelino et al., 2017). In a narrower sense, game-changers mean transformative innovations, which for global climate change is framed as low-carbon innovation in the context of policy discourse (Diercks et al., 2019). Further, Wilson et al. (2019) define this as disruptive low-carbon innovation (DLCI), which is integral to energy transformation research, policy, and practice for climate change mitigation. This definition acquires characteristics to have the potential to reduce greenhouse gas emissions substantially if adopted at scale, requires a supportive policy or regulatory environment, and disrupts high-carbon practices and associated infrastructure and firms. Following these definitions, low carbon innovation is not mainly technological in this premise. It can also involve other disruptive non-technological innovations such as re-organisations or shifts that require managerial, institutional, social, and behavioural innovations, including at national or global levels. Yet to set the role of technologies apart, the DLCI focuses on and is used interchangeably with non-technological innovation in this deliverable.

Understanding the concept and the role of low carbon innovation is important for two reasons. First, principal technologies commonly included in low-carbon pathways analysis are mostly already commercially available, while additional technologies that are increasingly being investigated as part of low-carbon pathways or are at an earlier stage of development are often under-represented. And second, in addition to technological innovation, social innovation is crucial in enabling and supporting the rapid transition to a low-carbon economy. Key technologies and behavioural shifts can potentially change the nature of deep decarbonisation pathways. Recognising these ground-breaking innovations and their dynamics is crucial to exploring and understanding climate scenarios.

The role of technologies in low-carbon innovations is elemental. In its recent net-zero pathways analysis, the IEA (2021) found that over one-third of cumulative emissions in the net-zero carbon scenario stems from technologies that are not commercially available today. Achieving net-zero requires technologies to be deployed on a far greater scale, particularly in the power sector which needs more rapid development of low-carbon generation and hard-to-decarbonise industries such as transportation and building. Transforming the power sector alone will only reach one-third of the net-zero target. At the same time, transport, industry, and building, which account for 55% of energy emissions today, are the most challenging emissions to reduce. Technologies development in low-carbon innovation needs to be extended to cover these sectors.

In addition, the complexity of net-zero emissions in 2050 goes well beyond technology innovation alone and is likely to require fundamental changes to current lifestyles (IEA, 2019c). Nelson and Allwood (2021) warn that one should not assume new technologies will become technically feasible and commercially available in time for the net-zero transition. A successful transition to a decarbonised society will require a combination of both innovative policies and coordinated intentional changes. These changes belong to other disruptive low-carbon innovations, which are generally less technology-based but cover behavioural changes, market design, and new business models. Despite half of the cumulative reduction in IEA's net-zero emissions scenario being contributed by technology at the demonstration or early development (prototype) stage today, behavioural changes (such as reducing transport demand) are equally essential. They are covering another half of contributed reduction.

Exploring the applicability of disruptive innovation is timely, relevant, and important yet still poorly understood. For example, carbon Capture Storage (CCS) is often overused in modelling mitigation technologies for reaching net-zero emissions. Without considering the capacity from a regional perspective or other CO_2 removal and biofuel technologies, over-dependency on this technology makes projections in modelling results less realistic. Though uncertainty factors play a significant part in the current exclusion of some technologies in IAM, the feasibility analysis is critical in developing a more realistic decarbonisation pathway.

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Likewise, low carbon innovation through intensification of electricity, hydrogen, synthetic fuel, and bioenergy needs to secure a sustainable energy system. Today, coal, oil, and gas account for 70% of total final energy demand, and achieving net-zero emissions requires these low-carbon fuels to attain the same level as today's fossil fuels. Reaching sustainability means upscaling these technologies to a larger scale of implementation, accelerating the energy transition, and incorporating new practices (De Geus and Wittmayer, 2019). This is a simultaneous process that entails technological, economic, and policy innovations, while different types of innovation can overlap and are not clearly delineated.

These complexities substantiate the need to properly explore and analyse the diffusion of game-changing innovations. The role of stakeholders is elemental. Their preferences are crucial to performing a reality check on the potential role of mitigation and the expected time of the readiness of these technologies and non-technological innovations in modelling exercises. This deliverable aims to identify these potential innovative solutions to deep decarbonisation globally and elaborate on low-carbon innovations and their significance in reaching the net-zero emissions pathway. First, we review the innovative deployment of specific technologies that may already exist at a small scale or in the early stages of development, and non-technological low carbon innovations for rapid decarbonisation. This review becomes the basis of an evaluation through a global survey, targeting climate and energy experts to identify the innovation dynamics in/of non-EU countries. Statistical analysis is then performed to group/rank those innovation-based mitigation potentials and feasible scale of taking part in the deep decarbonisation pathway. It is then followed by a review of how the survey’s findings and insights could have been integrated into current modelling development/ scenario design.

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2 Game-Changing Innovation: Review

Innovation refers to technology or technological transformation and includes fundamental shifts in society and societal behaviour that could affect decarbonisation pathways and climate goals. It should be disruptive, which accounts for widespread adoption, leading to substantial emission reductions and sustainability (Wilson et al., 2018). In scrutinizing this concept, a comprehensive search was conducted in JSTOR and Google Scholar from 01/10/21 to 20/10/2021 to identify potentially transformative innovations and their effects on decarbonisation pathways, following the protocol outlined in the Paris Reinforce Milestone 7 ("Protocol for studying innovation dynamics in Europe and non-EU countries").

In identifying relevant studies that reported technological or behavioural innovation or innovative solutions to deep decarbonisation, the following key terms were queried: "innovation for deep decarbonisation"; "innovation for net-zero"; "technological innovation decarbonisation"; "technological innovation net-zero"; "behavioural innovation decarbonisation"; "behavioural innovation net-zero"; "deep decarbonisation pathways"; "disruptive low carbon technology". In addition, both the listed references of applicable studies and studies they were cited in were manually evaluated to ensure a comprehensive search. To create a comparison between Europe and other large emitters across the globe, "deep decarbonisation" and "decarbonisation innovation" were searched for alongside the country in question. For example, to investigate the decarbonisation pathways in China, "deep decarbonisation China" was searched for.

2.1 Technological Innovation

There is some debate regarding the future of technological innovation. Otto et al. (2020) have suggested that technological development is likely to play a role in achieving net-zero through adapting existing technologies (primarily in the power sector and the smart utilisation of energy) rather than novel, innovative technological solutions. However, whilst it is agreed that current technological advancements can offer immediate improvements in terms of energy efficiency, we cannot solely rely on the falling costs of current or near-commercial technology to put us on the path to net-zero (Goldthau et al., 2019). A significant portion of carbon mitigation arises from highly disruptive technological options (Nelson and Allwood, 2021), as innovative and transformative technologies are required to achieve deep decarbonisation. Su et al. (2020) found that, on average, a 1% increase in technological innovation causes a -0.006% and -0.050% decline in the short- and long-run, respectively, for consumption-based carbon emissions.

After the power sector, particular interests are placed on the Energy-Intensive Industries (EII). Along with the transportation and building sectors, high process heat requirements or chemical process emissions in EII have been particularly difficult for decarbonisation (Davis et al., 2018). EII represents unique hurdles on the path to net-zero, and there are a number of challenges surrounding the decarbonisation of industrial sectors. For example, the longevity of many industrial facilities and their associated equipment is over 20 years, and the replacement and updating of existing infrastructure are dependent upon the remaining lifespan of installed equipment, operation costs, and the expected costs of novel technologies (Bataille et al., 2018; Gerres et al., 2019; IEA, 2019a). Moreover, there is extraordinary demand for high-temperature heat and the unavailability of alternatives to specific chemical reactions (IEA, 2019a). Even if applied on a large scale, the best available technologies for EII can currently only reduce emissions by up to 30% (Fischedick et al., 2014). However, these industries and the materials they produce are vital, essentially forming the building blocks of society (Allwood et al., 2012).

Around 70% of EII's CO_2 emissions come from the iron and steel, cement, and chemicals subsectors (IEA, 2020). The iron and steel industry is the most energy-demanding subsector of the industrial sector, accounting for

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approximately 4% of European emissions (Berger, 2020) and 7% of global CO_2 emissions (Philibert, 2017). Iron and steel production is particularly difficult to decarbonise (Åhman et al., 2017; Koasidis et al., 2020). It has even been termed a 'special case' of economic activities as both combustion and process emissions require decarbonisation. Yet, the industry is essential for other climate mitigation options, such as the construction of wind and hydro power (Mayer et al., 2019). A detailed analysis of the bottlenecks and challenges to decarbonise such industries from a socio-technical perspective can be found in D4.1. Although the scientific literature surrounding deep decarbonisation appears to focus on these industrial processes and EII, the technological innovation analysis elaborated in the next subsections concentrates on the development of these technologies in holistic applications.

2.1.1 Negative Emission Technologies (NETs)

Net-negative emissions are required in the majority of decarbonisation pathways that keep us within 1.5 °C or 2°C warming, and all pathways that limit warming to 1.5°C (with limited or no overshoot) require net negative emissions through the use of Carbon Dioxide Removal (CDR) (IPCC, 2018). In addition to the NET-based-CCS, the CDR technology of Direct Air Capture (DAC) of CO_2 is expected to emerge as a key technology in deep decarbonisation and climate mitigation (Breyer et al., 2019).

However, there are concerns surrounding the large-scale deployment of NETs. Smith et al. (2016) and Dooley and Kartha (2018) highlight several substantial issues such as: the technologies NETs rely on are as yet unproven; NETs may prove less effective than initially expected; and there may be adverse ecological and social impacts in terms of biodiversity, carbon leakage, food security, water use, and land footprints.

NETs appear to be the most difficult to develop and implement in a risk-averse way. Suboptimal solutions could create even greater issues through collateral impacts, but suitable NET portfolios could complement other mitigation strategies (Rueda et al., 2021). The development of combined DACCS and DACCU (Direct Air Carbon Capture Storage/ Usage) technology depends on CCS deployment. An optimised NET portfolio, consisting of NETs (primarily DACCS) and soil carbon sequestration, could potentially be a superior option for NET deployment (Rueda et al., 2021).

2.1.1.1 Carbon Capture Usage and Storage (CCUS) Technologies

CCS technologies are expected to become a leading solution to the deep decarbonisation of EII (Bui et al., 2018), energy systems (Audoly et al., 2018), and the maritime shipping industry (Mallouppas and Yfantis, 2021). It is one of the key technologies focused on in the literature due to its disruptive potential, practicality, and versatility for decarbonisation (e.g., Åhman et al., 2016; Bataille et al., 2018; Bui et al., 2018).

In the steel and iron industry, CCS utilisation primarily includes smelting reduction, top gas recycling blast furnaces, and near net shape casting, with CO_2 emissions being directly captured to be stored underground or utilised in alternative industries (Gerres et al., 2019; Griffin and Hammond, 2021). By combining conventional blast furnace techniques, it could achieve an estimated CO_2 reduction of 60%-80% (Material Economics, 2019; Bataille et al., 2020)

CCS technologies are also expected to provide the highest potential to decarbonise the cement industry due to a lack of alternatives, and the high purity of exhaust steams (Bataille et al., 2018; Gerres et al., 2019). Further, the cement sector is able to capture the highest proportion of emissions through CCS than other EII (Leeson et al., 2017). A key technology to facilitate cost-effective CCS is calcium looping, using calcium carbonate as a CO_2 absorbent (Gerres et al., 2019).

Compared to CCS, a key circulatory benefit of CCUS is that the captured carbon can be used in other sectors. For example, this captured carbon can be used as feedstock for the production of basic chemicals and synthetic

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hydrocarbons (e.g., renewable methanol, ethanol) or fine chemicals and polymers (Bataille et al., 2018; Wyns et al., 2018; Bataille, 2019; Draxler et al., 2020). Further, renewable hydrogen could be added to the captured carbon to create higher-value chemicals, such as ethylene (Wyns et al., 2018). However, there are limitations to the amount of carbon that can be accommodated through utilisation, and increased storage will be required, which can pose issues depending upon the geographic location of the industry (Bataille et al., 2018).

2.1.1.2 DAC

DAC removes CO_2 from ambient air and, when driven from renewable energy sources, could become a valuable NET (Bajamundi et al., 2019). DAC is an enabling technology, meaning it allows for direct air capture and storage (DACCS) and utilisation (DACCU). DACCU, in particular, can be used for fuels in the transport sector where low-carbon alternatives are limited (Fuss et al., 2018; Haegel et al., 2019)

However, a key challenge of both DACCS and DACCU is the amount of energy required to power the process (Breyer et al., 2019). To provide affordable yet effective synthetic hydrocarbons and carbon sequestration, the role of renewable energy will be essential to avoiding emissions from fossil fuels (Haegel et al., 2019). This expected transition to a renewable, decarbonised energy system could enable a widely sustainable and available power source for DACCS (Breyer et al., 2019).

2.1.1.3 Bioenergy Carbon Capture and Storage (BECCS)

Due to the associated energy costs of DACCS and DACCU, a preferred route to CCS and CCU is bioenergy-fuelled CCS and CCU known as BECCS and BECCU, respectively (Breyer et al., 2019). Biomass-based residues and waste, such as waste incinerators with CCU, are best suited for BECCU technology due to the subsequent CO_2 utilisation for the production of synthetic hydrocarbons (Breyer et al., 2019). BECCS technology is able to produce power, hydrogen, aviation fuel, or in industrial applications it could deliver more carbon abatement than its use in other energy systems, including road transportation (CCC, 2018). A key benefit of BECCS is that it allows for global net-negative emissions.

Application of bioenergy such as biofuels with CCUS is significant for transport, power, and heat generation to achieve net-zero emissions. Combining bioenergy with CO_2 capture and storage removes CO_2 from the natural carbon cycle, creating negative emissions, enabling the goal of net-zero emissions to be reached. Even if the cost developments of technology are known, there are still uncertainties about their feasibility. For example, the large-scale use of CCS with or without bioenergy in the electricity and industrial sector is highly uncertain. CCS largely depends on regional characteristics of natural resources and storage availability. Public acceptance of this technology is limited (Fuss et al., 2014), and the risks of using large-scale CCS to biodiversity, food security, and water availability are highlighted (IPCC, 2019). Countries with strategies to use CCS in the power sector might also use CCS in geographically advantageously located industrial plans, allowing the use of existing infrastructure and storage facilities.

Also, the contribution of bioenergy to reducing CO_2 emissions is significant where direct electrification is difficult. An essential advantage of bioenergy is that it can be converted into energy forms that are compatible with existing energy technologies that rely on the combustion of fossil fuels: it can be used as feedstock in the chemicals industry, and it can be used in existing vehicle fueling networks and gas pipelines, for example in the form of biomass-to-liquid (BTL) thermochemically produced fuels, hydrotreated vegetable oil, or biomethane.

Around 60% of final bioenergy use (and 40% of primary bioenergy use) is today in the form of the traditional use of solid biomass for cooking in emerging economies, which negatively impacts human health through indoor air pollution with harmful social, economic, and environmental consequences. Meeting Sustainable Development

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Goals entails a reduction in the traditional use of solid biomass by almost 90% over the next ten years. This requires a steady increase in the efficient use of biomass in solid, liquid, or gaseous forms (e.g., modern cooking stoves, space heating boilers) and behavioural changes as one determinant factor.

2.1.1.4 Biochar

Combustion of carbon-rich biomass is called pyrolysis. It generates a carbon-rich solid, *i.e.,* bio-char, a gas (syngas), and a liquid (bio-fuel) as by-products. Bio-char can then be either sent to land or used to enrich agricultural lands and fix carbon by keeping carbon in the soil for years. Its utilisation as a soil nutrient is also seen as a negative-emission process, preventing the return of biotic carbon to the atmosphere via decomposition (McLaren, 2012) and, therefore, serving as a carbon sink (Dang et al., 2015). The sequestration of CO_2 in bio-char can also help to inhibit the release of N_2O and CH_4 from the soil.

Although there have been many studies on the production and application of bio-char in a range of areas, bio-char as a soil nutrient is still under research, investigation, and trials. “Bio-char for soil impact” and “bio-char pyrolysis” technologies currently hold technology readiness level (TRL) values of 1-2 and 3-4, respectively (Lomax et al. 2015). Several field trials of bio-char were conducted in the US, Kenya, Zambia, China, Paraguay, Brazil, and Cambodia. Still, the interaction of bio-char with various soils across the world needs more extensive research.

2.1.1.5 Ocean-Liming

Ocean-Liming is when CO_2 is naturally captured from the atmosphere and stored in the oceans as bicarbonate ions. In this process, limestone is first extracted and calcined, during which the generated CO_2 is captured using the available methods, e.g., post-combustion capture scrubbers. The produced calcium oxide is then shipped to the ocean and is directly dispersed on a large scale. The resulting increase in the pH of the surface water then leads to the rapid absorption of atmospheric CO_2. This technology has a TRL value of 2-4 (McLaren, 2012).

The process consists of two steps: calcination of crushed limestone in high-temperature kilns and its post grinding and the transportation of the primary limestone and the lime product. When deployed at a scale to reduce atmospheric levels of CO_2 in the order of ppm levels, the entire process comprising the transport, slaking, and dispersion will need a fleet of vessels similar in size to the world’s aggregate transportation fleet. Based on the predominantly fossil fuels energy required for this process, the cost of ocean-liming is intrinsically linked to global energy prices, which are likely to increase in the coming century. In addition to the uncertainty in this type of geoengineering technology, this remains the main challenge in innovating this technology.

2.1.2 Electrification

The potential uses for electricity in decarbonisation and net-zero are well established, from carbon-free electricity to electric vehicles (EVs). However, electricity has the potential to be used in a number of innovative ways to assist in the decarbonisation of EII. For example, Fortes et al. (2019) found that the electrification of Portugal’s energy system has a decarbonisation potential of nearly 80% compared to 1990’s levels. Electrochemical separation techniques, such as electrolysis, use minimal thermal energy and are utilised in the iron and steel sectors to reduce emissions and produce hydrogen (Gerres et al., 2019).

2.1.2.1 Carbon Direct Avoidance (CDA)

Steel can be produced via two main processes: either using an integrated blast furnace (BF)/basic oxygen furnace (BOF) or an electric arc furnace (EAF). While integrated players produce steel from iron ore and need coal as a reductant, EAF producers use steel scrap or direct reduced iron (DRI) as their main raw material. Although EAF is

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more energy-efficient than Bf-BOF, the decarbonisation potential from EAF is still associated with electricity supply (Gerres et al., 2019). CDA is primarily dedicated to developing new technologies and processes to allow steel production from virgin ores without the direct release of carbon, such as through the use of renewable electricity or hydrogen derived from renewable sources (Draxler et al., 2020). The usage of both electricity (primarily as electrolysis) and hydrogen in the iron and steel industries are explained further below.

2.1.2.2 Electrolysis of Iron Ore

Deep decarbonisation of the iron and steel industry could also be achieved via the use of carbon-free electricity sources, specifically via the use of electrolysis of iron ore (Gerres et al. 2019). As the only gas produced via electrolysis is oxygen, with no carbon emissions, it could theoretically be carbon-neutral (Cavaliere, 2019). In Europe, if electrolysis is used to produce virgin steel, and the use of EAF is continued for secondary steel, the carbon footprint of the entire industry would decrease by 84% (Gerres et al., 2019). There are numerous projects currently developing this concept, such as Siderwin, ULOLYSIS, and LUCWIN (Gerres et al., 2019; Draxler et al., 2020; Zhang et al., 2021). Assuming that carbon-neutral electricity from renewable sources is used in the electrolysis process, steel production can be near-carbon-neutral with a decarbonisation potential of up to 98%-99% (Gerres et al., 2019; Bataille, 2019).

2.1.2.3 Next-Generation Energy Storage

This type encompasses several technologies that primarily extend electrification through energy storage. For example, Power-to-Gas (PtG) plants convert electricity into hydrogen (H_2) or synthetic methane (CH_4, natural gas). This gas is then stored in tanks, caverns, or the gas grid and can be re-electrified, used in transport, heat generation, or in industrial applications as feedstock. Conversion with electricity is through electrolysis, in which renewable power is used. The plants can make renewable power available for other energy sectors (transport, heat) and the chemical industry. Large amounts of energy can be stored while utilising existing gas network infrastructure, which could make this technology particularly attractive for seasonal storage. High electrolyser cost and relatively low efficiency in response remain the most important barriers to PtG deployment today (Hassan et al., 2019).

Another example is Flywheel Energy Storage (FES) which works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. Flywheels could play an important role in frequency response, rapidly providing and absorbing electrical energy when output from renewables fluctuates (Greenwood et al., 2017). Around 1 GW of stationary flywheels are installed worldwide, but the flywheel technology is relatively expensive. The current implementation still needs to translate into higher power densities for long-term operation.

2.1.2.4 Nuclear Fusion

Fusion is a nuclear reaction that occurs when two light nuclei smash together and fuse to create a heavier nucleus and release energy. Fusion is the energy source of the sun and stars, which can provide virtually limitless carbon-free electricity power. In a fusion power plant, the plasma thermal energy would heat water, create steam, and spin a turbine to generate electricity. Compared to the current developed technology of Nuclear Fision, Nuclear fusion could be a limitless source of carbon-free electricity and a game-changer as it results in a limited amount of radiation. Present challenges of this technology are in the provision of sustaining plasma, the development of materials to handle extreme temperatures, and accelerating the pace of commercial power (Linke et al., 2019)

Nuclear fusion and plasma physics research are carried out in more than 50 countries. Fusion reactions have been successfully achieved in many experiments, albeit without demonstrating a net fusion power gain. How long it will

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take to recreate the process of the stars will depend on mobilising resources through global partnerships and collaboration.

2.1.3 Hydrogen

The use of hydrogen is an emerging technology that could enable deep decarbonisation across multiple industries, including light and heavy industries (Rissman et al., 2020). Hydrogen holds a particular advantage for decarbonising industry as carbon emissions are not produced during combustion (Andrews and Shabani, 2012). The greatest challenge of using hydrogen, particularly green hydrogen, is the cost required in the production process (Mallouppas and Yfantis, 2021). Nevertheless, it has been argued that nuclear power or renewables electricity generation can drive the development of the hydrogen production industry (Zhang et al., 2021).

Hydrogen technologies have received considerable attention in recent years. Like biofuels, hydrogen technologies are not new, as they were used to fuel early internal combustion engines over 200 years ago. Hydrogen today is mainly used for oil refining and as feedstock in the chemical industry. Almost all of it still comes from fossil fuels, emitting more than 800 million tonnes of carbon dioxide ($MtCO_2$). Hydrogen can be burned or converted in such a way as to produce no harmful emissions, and if produced without emitting any GHG, it has the potential to make a massive contribution to a sustainable energy system.

Hydrogen, as an energy carrier, is critical to extending electricity reach. The case for hydrogen to play a significant role in a future cleaner energy system is becoming increasingly clear, especially in sectors where CO_2 emissions are hard to reduce, such as transportation. The role of hydrogen is instrumental in the decarbonisation of heavy trucks, aviation and shipping, and the production of chemicals and steel. The principal barrier to the uptake of low-carbon hydrogen is its high cost, which partly results from the lack of economies of scale in production, supply, and use (IEA, 2019d). Another main challenge is the long-standing problem of developing supply infrastructures in tandem with end-use equipment: why develop hydrogen cars if there is no distribution network, and why develop a distribution network if there are no hydrogen cars? Technical and trade regulations also have hindered the development of the hydrogen industry in some cases.

Several countries, such as the US (Majumdar et al., 2021) and Japan (Chaube et al., 2020), have designed a roadmap to realise a hydrogen economy in the near future (Kasai, 2020). The grand idea of hydrogen economy development in the US is called sector coupling, where the energy-consuming sectors are integrated with power-producing sectors in 2050. Hydrogen is now used only in FCEV forklift material handling and distributed power; market and sectoral expansion are aimed to be achieved in 2050 with a large scale of hydrogen production (Singh et al., 2021). On the other hand, Japan’s target in 2030 is still focused on developing high combustion efficiency (Ozawa et al., 2018). Although Japan is currently developing a hydrogen-powered town, the target for 2050 is still undefined. Other countries, such as China and Korea, also aim to vitalise the hydrogen economy, despite still being widely debated (Ren et al., 2020).

2.1.3.1 Hydrogen Direct reduction (H-DR): Hydrogen in Steelmaking

Hydrogen technology can be utilised to decarbonise the iron and steel industry by directly reducing iron with hydrogen (H-DR) rather than natural gas (Nilsson et al., 2017; Wyns et al., 2018; Draxler et al., 2020). If iron is produced via hydrogen (H_2) as the main reductant, hydrogen then reacts with the iron oxides to form water rather than CO_2, the produced iron is then heated and melted in an EAF (HYBRIT, 2017; Rissman et al., 2020). This H_2 can be produced via water electrolysis, using a decarbonised energy supply, resulting in H_2 being a low (or zero) energy carbon carrier (Griffin and Hammond, 2021).

H-DR can emit as little as 2.8% of the CO_2 produced in current blast furnaces (Vogl et al., 2018). If renewable

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energy sources are used in H_2 production with processing being conducted in an EAF, the entire process will produce near zero carbon emissions (Vogl et al., 2018). Estimates for the carbon reduction potential from using H-DR compared to conventional BF/BOF routes are approximately 35% (Scheck and Lüngen, 2016) but increase to 98-99% when combined with EAFs (Otto et al., 2017; Bataille, 2019). It has been suggested that H-DR followed by EAF, could compete with conventional blast furnaces in northern Europe with relatively low carbon prices (Vogl et al., 2018). However, the production cost using H-DR is approximately 20-30% higher than under current production methods (HYBRIT, 2017; Åhman et al., 2018).

Bataille et al. (2018) note two key advantages of H-DR. One, the reduction process is 10 times faster than conventional methods. Two, electrolysed hydrogen can be made during down cycles in electricity demand. Therefore, H-DR could be used to maximise the value of off-peak renewable electricity, stabilise electricity prices, and assist in smoothening the electricity load curve. A prime example of an H-DR pilot project is HYBRIT (Hydrogen DRI-EAF) in Sweden, which estimates the H-DR process will be ready for commercial implementation by 2035 at the earliest (Pei et al., 2020).

2.1.3.2 Hydrogen as Energy Carrier

Hydrogen as an energy carrier is one of the key methods expected to provide a pathway to a decarbonised transportation and shipping industry. Hydrogen batteries are powered via fuel cells converting hydrogen into electrical energy, emitting water vapour as a by-product (Charters, 2016). Hydrogen can be produced via two primary routes: water electrolysis, where electricity is used to split water into oxygen and H_2; alternatively, steam methane reforming, where H_2 is produced by chemically reforming methane into H_2 with carbon monoxide as a by-product (Bicer and Dincer, 2018; Logan et al., 2020).

There are numerous categories, or 'colours', of hydrogen, with the key types expected to be used for decarbonisation being green and blue. Blue hydrogen is a low-carbon gas produced via the thermochemical conversion of fossil fuels with CCS, and green hydrogen is a renewable gas produced via renewable electricity sources (Peters et al., 2020; Mallauppas and Yfantis, 2021).

For heavy road transport, hydrogen will become an important energy carrier (Peters et al., 2020). Whilst the use of EVs for decarbonising road transport is currently being implemented, and expanded upon for passenger vehicles. It is unsuitable for heavy freight vehicles or heavy road transport. However, by exploiting the current natural gas transport infrastructure, hydrogen could become a carbon-neutral alternative to fossil fuels (Gerres et al., 2019) and may prove important for decarbonising shipping and aviation, where EVs are unfeasible (Peters et al., 2020).

2.1.4 Alternative fuels

Alternative fuels, such as hydrogen, ammonia, and liquefied natural gas (LNG), are among concepts that could decarbonise transport and shipping industries, presuming that LNG makes the transition to carbon-recycled methane (Jaques, 2020). However, there are issues surrounding the efficiency of storage possibilities for hydrogen, as it requires a variety of conditions: high pressure, low temperatures, and suitable materials (Moradi and Growth, 2019).

There are a number of additional fuels being considered for decarbonising transport, such as (green) ammonia and methanol. Green ammonia, produced using renewable energy sources, is generally cheaper to produce and store than hydrogen fuels, and methanol, produced via methane or renewable energy sources such as carbon capture, industrial waste, or biomass, is a potential future maritime fuel for decarbonisation (ITF, 2018).

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2.1.4.1 Biofuels

Biofuels, produced from organic waste materials, are potential fuel solutions for the maritime industry (ITF, 2018). They are currently one of the most viable low-carbon alternatives to current fuel methods; however, there is little knowledge or experience of biofuel utilisation, and they require large storage capacities (Hsieh and Felby, 2017). While the first generation of biofuel production raises an issue of food availability and price concerns, the second generation of Advanced Biofuels production is also challenging for costly distillation materials, uncertainty in emissions released, and overall competition with regular fuel.

In the aviation industry, biofuels (usually referred to as biojet or renewable jet fuel (RJF)) are "drop-in" alternatives to conventional jet fuels, i.e. they can be used in place of fossil fuel-derived jet fuels with no modification to aircraft. To ensure the required properties are achieved, biojet is currently blended with fossil fuel-derived jet fuel. However, 100% of unblended drop-in biojet fuels are in the early stages of development (Fuel Readiness Level1 1-3) (E4tech, 2009). These high feedstock costs will prevent some biojet products from becoming price-competitive because the feedstock cost may already exceed the current petroleum-derived jet fuel price.

Biojet fuels are uniformly more expensive than conventional jet fuel (De Jong et al., 2015). Thus, at current biojet prices, incentives are not strong enough for airlines to make purchases that are not wholly voluntary. However, airlines may still view investments as an opportunity to decouple their fuel supply from crude oil markets since volatility can significantly affect medium-term business projections.

2.1.4.2 Fuel Cells

Fuels cells are a key technology to fully unlock the potential of alternative fuel sources (Balcombe et al., 2019). Fuel cells containing hydrogen or ammonia are promising technologies for the decarbonisation of maritime shipping. Mallouppas and Yfantis (2021) noted that both green hydrogen and green ammonia are particularly favourable as not only can they eliminate GHG emissions, but they can also eliminate other pollutants such as NOx and SOx.

2.2 Decarbonisation Projects: Regional Update

2.2.1 Projects within the EU

The EU and its member states have several research programs focusing on decarbonisation, some of which are listed here. The UCLOS project aims to reduce CO_2 emissions by 50% or more for the iron and steel industry, while HYBRIT aims to produce zero-carbon steel using H-DR. The H2Future project intends to develop carbon-free hydrogen. Carbon2Chem and SALCOS aim to recycle discharged CO_2 in the exhaust gas of iron and steel production and use it as raw materials for chemical production. And HYBRIT develops H-DR in the iron and steel industry. ULCOWIN and ULCOLYSIS investigate electrowinning and electrolysis for low-carbon steel making (Quader et al., 2015; Åhman et al., 2017; Thomas et al., 2020; Zhang et al., 2021).

2.2.2 Non-EU large emitting economies

The European Union has thus far been a global leader in decoupling carbon emissions from economic growth (Nurdiawati and Urban, 2021). Across Europe, the primary potential for innovative decarbonisation technologies focuses on EEIs, such as the steel and iron industry, through technologies such as hydrogen and CCS. This trend is replicated in many other countries across the globe. However, whilst the key technologies required for decarbonisation tend to be replicated worldwide, there are differences in the weight of each technology, with different countries placing greater focus on certain technologies due to their respective geosocial or geopolitical

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contexts. Further, there is a discrepancy between the presence of developed and developing countries in the literature, with developed countries (with the notable exclusion of China) investing substantially more into the research and development of innovative technologies for deep decarbonisation. This discrepancy and lack of representation may partly arise from the fact that developed countries still own most of the patents for low-carbon technology in industries like the iron and steel sector (Zhu, 2020).

2.2.2.1 China

China is mainly investing in the best available technologies to reduce carbon emissions. However, it is starting to increase investment in the R&D of technologies such as CCS (Åhman et al., 2017) and hydrogen fuel cells (Thomas et al., 2020). China has the decarbonisation programs COREX and HIsmelt, and has begun investing in hydrogen metallurgy to create a carbon-neutral country by 2060 (Zhang et al., 2021).

2.2.2.2 USA

The USA is primarily investigating hydrogen technologies, such as fuel cell development for heavy haulage and aircraft (Thomas et al., 2021). Under the AISI program, the USA is also researching hydrogen flash smelting and molten oxide electrolysis for the iron and steel industry, intending to combine CCS technologies (Quader et al., 2015; Zhang et al., 2021).

2.2.2.3 Japan

Japan also has ambitions to become a hydrogen economy, utilising hydrogen fuel cells for transportation in both private vehicles and maritime transport (Thomas et al., 2020). Japan is also looking to develop low-carbon steel making through its CO_2 Ultimate Reduction in Steelmaking Process by COURSE50, aiming to reduce carbon by 10% through H-DR and an additional 20% through CCUS (Quader et al., 2015; Åhman et al., 2017; Zhang et al., 2021)

2.2.2.4 South Korea

Like many countries, South Korea has ambitions to become a hydrogen society (Thomas et al., 2020). South Korea's primary emission reduction program, POSCO, aims to reduce GHG emissions in the workplace, reduce social GHG emissions, and promote policy cooperation on climate change (Zhang et al., 2021). As noted in Zhang et al., POSCO has resulted in the development of a novel technique of carbon capturing and more efficient steel making. South Korea also has the FINEX project with the aim of reducing CO_2 emissions from iron and steel using CCS by 45% (Zhang et al., 2021)

2.2.2.5 Australia

Australia has two major emission reduction projects for the iron and steel industries, using biomass as a BF fuel and a heat recovery process (Quader et al., 2015).

2.2.2.6 Russia

Under the protocol used in this literature review, no innovative decarbonisation strategies or projects were found. However, it has been noted that there are large opportunities for CCS technologies in Russia (Safonov et al., 2020).

2.2.2.7 India

Like Russia, no innovative decarbonisation strategies or projects were found in India under the search protocol. A

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recent case study by Sharma et al. (2021) has suggested that India's lack of decarbonisation initiatives is likely tied to the country's social reliance and culture surrounding coal.

2.2.2.8 Latin America

Latin American countries focus on electrification and more efficient management of AFOLU sectors (Bataille et al., 2020). For example, under modelling scenarios, the following are seen as key priorities for Latin American countries: Colombia's primary pathway to decarbonisation is largely achieved via renewable energy and sustainable bioenergy (Delgado et al., 2020). However, Colombia can also utilise CCUS to continue using fossil fuels in electricity generation or support bioenergy with CCS (Delgado et al., 2020). Similarly, Ecuador focuses on CCS technologies, specifically BECCS and biofuels (Villamar et al., 2021).

Countries like Costa Rica focus on energy efficiency, a shift towards public transport, digitalisation, and renewable energy as key drivers of deep decarbonisation (Godínez-Zamora et al., 2020). In Mexico, decarbonisation revolves around renewable electricity, bioenergy, EVs, the efficient management of AFOLU, nuclear, and CCS (Elizondo et al., 2017; Buira et al., 2021). Finally, the role of AFOLU and biofuels has also been stressed in Brazil and Argentina, two major biofuel producers, with many programs and legislation (Köberle et al., 2020; Nikas et al., 2022). Argentina's deep decarbonisation priorities include drastic changes to energy systems, particularly hydroelectric and nuclear, and AFOLU, as the potential use of CCS should the technology become cost-effective (Lallana et al., 2021).

2.3 Non-technological Innovations (Disruptive Low Carbon Innovation)

Deep decarbonisation cannot happen through technological innovation alone. Whilst there is a start preference towards technological innovation in the literature (Cajaiba-Santana, 2014; Nelson and Allwood, 2021), there are many uncertainties surrounding decarbonising technologies, related to issues such as commercial feasibility, applicability, and operating efficiencies (Bataille et al., 2018; Gerres et al., 2019). Thus, reducing industrial emissions to the Paris Agreement-compliant levels may not be technically possible by only focusing on technological solutions (Bataille et al., 2018). Therefore, sociotechnical transitions are a necessity; and behavioural innovations by individuals, policymakers, and commercial entities are essential to achieve climate mitigation and reach net-zero targets (Skoczkowski et al., 2020; Marteau et al., 2021). The concept of social innovation has risen in prominence in the policy sphere (Baer et al., 2021). However, modelling literature tends to only reflect this importance rather than expressing the specific innovations required to achieve the deep decarbonisation of society.

One way in which societal dynamics can be influenced is through social "tipping points" - if the majority of individuals in a society support an ambitious action, and this majority pass what is known as the critical threshold, then a minor intervention can achieve an exaggerated and irreversible effect (Farmer et al., 2019). Such contagious social dynamics could assist in large-scale decarbonisation. However, changing behaviour at scale requires creating an environment that drives said behaviour (Marteau et al., 2021).

Otto et al. (2020) emphasize six potential social tipping interventions. These interventions could incite contagious processes of rapidly spreading technologies, behaviours, and the infrastructural reorganisation required to put us on the path to net-zero. Those interventions are:

1. Incentivising a decentralised energy generation system.
2. Creating carbon-neutral cities.
3. Disinvesting from assets that are linked to fossil fuels and fossil fuel production.

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4. Strengthening climate education engagement
5. Disclosing information on GHG emissions
6. Removing fossil fuel subsidies

These interventions then have the potential to produce unexpected, cascading effects. In their review paper, Goldthau et al. (2019) use the transition of our energy systems to renewable sources as an example. While not radical or innovative, this transition will hold the potential to be highly disruptive. Further, this study highlights those potential cascading effects from this relatively "trivial" intervention, which could be, for example:

1. Economies that produce oil and gas stand to lose US$ 6 trillion by 2040.
2. Industry leaders in the oil and gas industry, such as China and the US, may create new relationships or allegiances, such as the Global Energy Interconnection Development and Cooperation Organisation.
3. Competition for land use for renewable energy production will likely have repercussions for food and water security and migration in developing countries.

As changing behaviour at scale poses difficulties, multiple interventions will be necessary across numerous contexts to achieve sufficient changes to put us on the path to net-zero. There are a few key mechanisms present in the literature by which we can invoke significant behavioural change. Carmichael (2019) suggests interventions should focus on areas with the larger contribution of GHG to incite behavioural innovations. For high-income European countries, the largest contribution to GHG emissions on the household level comes from travel (car and aviation), animal-based food, and heating.

2.3.1 Potential Practices of Disruptive Low Carbon Innovation (DLCI)

2.3.1.1 Mobility

Mobility-related examples of DLCI linked to behavioural changes are first intended to displace the incumbent Internal Combustion Engine (ICE) and limit car ownership. These are classified as 'the alternative form of automobility. In this category, potential DLCI could be car-sharing and 'mobility as a service' that refers to integrated scheduling, booking, and payment system for multiple transport modes such as ride-sharing, bus, or train via a single mobile application account. These include 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 currently in trends, such as telecommuting with video conferences and virtual meetings.

Behavioural innovations in how we travel on land can lead to substantial emission reductions. Behavioural changes in land travel constitute activities such as a greater number of journeys taken by foot, bicycle, and public transport, accompanied by fewer journeys by private vehicles (IEA, 2020a). There are several interventions recommended in the literature to stimulate consumers against carbon-intensive travel, for example, by increasing the air miles levy, introducing a ban on air miles and loyalty schemes, or increasing the availability of safe and attractive active travel routes (Carmichael, 2019; Arcanjo, 2020; Frank et al., 2021; Marteau et al., 2021). Some tactics have already been implemented in stimulating these potential practices throughout Europe. For example, the Norwegian government has removed the sales tax on EVs to increase their uptake among consumers (Arcanjo, 2020). Public acceptability of EVs is also high in Norway; in fact, the public has recently insisted on the high subsidies against progressive subsidy reductions on EVs from 2017 (Koasidis et al., 2020).

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2.3.1.2 Dietary Shifting / Changes in Consumption Pattern

Practices of DLCIs relating to food include urban and community-based growing, reduced food waste schemes, and modular hydroponic and aquaponic systems. These innovations perform poorly on valued mainstream attributes such as year-round availability, low user involvement, and standardisation (at centralised retailers). However, they offer end-users novel attributes, including social networks, active involvement, and visibility (localisation).

Mass changes in dietary behaviour are expected to achieve great environmental benefits (Poore and Nemecek, 2019). In Europe, meat consumption would need to decrease by an average of 68% to achieve the planetary health diet recommendations (Springmann et al., 2020). There are a number of potential pathways to increase the uptake of low-carbon dietary lifestyles, primarily driven through governance changes and an increase in the amount of information provided to consumers. For example, governments could fund food technology research to accelerate the development and commercialisation of low-carbon and plant-based "meat" or blended products; or introduce a traffic light system for the climate impacts of consumable items to allow informed decision-making (Carmichael, 2019)

2.3.1.3 Buildings and Cities

Although not analysed here in detail, the same broadly holds for DLCIs identified in other domains. DLCIs relating to buildings and cities include the internet of things, net-zero energy homes, and distributed PV-storage systems. These innovations perform poorly on valued mainstream attributes such as low-upfront cost, low user involvement (passive consumption), and centralised networks or utility provision. However, they offer novel attributes to end-users, including control, active involvement, and autonomy

2.3.1.4 Energy Supply and Distribution

Examples of DLCIs relating to energy supply and distribution include peer-to-peer trading, vehicle-to-grid, and community or district energy networks. Despite orienting towards end-user novel attributes by active involvement, functional diversity, and network interactions, these innovations are still under-performed. Some obstacles include valued dependency on external provision systems, time-invariant costs, and passive consumption create low user involvement.

2.3.2 Factors Invoking Social Innovations

2.3.2.1 Financial accounting for GHG

As many companies do not disclose information surrounding their GHG emissions or account for the risks that the climate crisis will bring, the transparent financial accounting and disclosure of GHG emissions from large companies could have outsized, cascading effects (Farmer et al., 2019). A change in the accounting standards or disclosure guidelines could therefore result in the substantial repricing of fossil fuel assets and thus reduce the capacity of the oil and gas sector to develop new fields, reducing committed emissions. Preventing these investments can lower the economic, social, and political costs of transforming the energy system.

2.3.2.2 Transparency and information

The provision of accurate information and education is an important mechanism by which we can invoke societal innovation. People's knowledge of the behaviours that generate the most emissions is poor (Marteau et al., 2021). Only 20% of individuals identified 'not owning a car' and a plant-based diet as among the most effective individual

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actions to reduce GHG emissions (Bruce-Lockhart, 2021). Comprehensive changes in climate education could strengthen changes in social norms, rapidly inspiring individual changes and thus leading to societal transformation (Carmichael, 2019; Otto et al., 2020).

The clear transparency of individual consumer and lifestyle choices' impact on GHG emissions could result in a positive informational feedback loop, stimulating lifestyle changes that support rapid decarbonisation (Otto et al., 2020). For example, Carmichael (2019) suggests the development of a digital comparison tool to provide clear information on the running costs, savings, and payback periods for EVs. It can also include smart hybrid heat pumps or allow consumers to share consumption data with third parties to facilitate informed consumer decisions.

2.3.2.3 Governance

The deep decarbonisation of many industries, such as EII, cannot be driven by improved economic performance alone but require long-term climate policies (Åhman et al., 2017). A radical shift in the climate crisis's narratives is needed, leading to low-carbon choices being viewed as important, normal, and (arguably most importantly) easily achievable in line with other everyday concerns (Carmichael, 2019). A valuable method to change these narratives is through informative governance and policy. Two interdependent strategies can inform policy for societal change: the one enabling consumers to take specific and concrete actions that deliver large emissions reductions and the other creating a wider context that nurtures public engagement with action on climate change. Using the diffusion of smart hybrid heat pumps as an example, the mainstream adoption of such pumps could deliver stark reductions in emissions. However, they require policy introductions to reduce running costs. Therefore, if governments were to redistribute tax and regulatory costs to increase the proportion that fell on the electricity and gas sector (rather than consumers), they could deliver low-cost electricity and increase the diffusion of such technologies (Carmichael, 2019).

There is long-standing evidence indicating the importance of policies in stimulating technological innovation. Noailly (2012) found that an increase in the stringency of European building standards led to the rise in energy efficiency innovation which was higher than investing in R&D. Yet it has been argued that the Paris Agreement's reliance on the nationally driven green industrial policy only suits innovation in particular kinds of technologies and therefore needs to be supplemented by measures to coordinate R&D, demonstration, deployment, and regulations across countries (Molhotra and Schmit, 2020).

Many studies have mirrored this message, emphasising the importance of informed and coordinated policy implementation. Peters et al. (2020) highlight the importance of strengthening EU policy to facilitate a fully integrated energy system, and Rissman et al. (2020) highlight the importance of smart policy to accelerate the uptake of emerging technologies, such as renewable hydrogen in industry.

Eikeland and Skjærseth (2020) have recommended the EU must improve its coordination of low-carbon technology 'push' policies and better align them with the market 'pull' policies. Interestingly, when investigating innovation-inducing policies in the U.S.A., Bloom et al. (2019) found that R&D tax credits and direct public funding are the most effective at stimulating innovation over the short term. However, over the long term, increasing the supply of human capital (for example, via expanding STEM university admissions or relaxing immigration) is most effective at encouraging innovation.

Linkages between different systems may also drive deep decarbonisation. As highlighted by Geels et al. (2017), political attention must be broadened toward interactions between various innovations and sociotechnical systems. Thomas et al. (2020) highlight an interesting case of how changes in societal behaviour can lead to the diffusion of technology for both technical and commercial applications in unexpected ways. Using Amazon as an example – as Amazon Prime Air is expected to commence drone delivery services, multiple suppliers now have

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proposals for hydrogen fuel cell-powered drones for this purpose.

2.4 Interaction Between Technologies and Behavioural Changes

Some promising technologies on the horizon could assist in deep decarbonisation. However, it has become increasingly clear that we cannot rely on technological advancements alone. Both technological and behavioural innovations are needed to achieve climate targets. Investment in R&D and coordination of strategic public policies to stimulate innovation, are instrumental. Whilst the required sociotechnical transition may be challenging to achieve, it is essential if we are to reach net-zero by 2050. Therefore, governments must rebalance policy efforts and spendings across technology with behavioural options for climate mitigation and decarbonisation (Nelson and Allwood, 2021).

Favourably, technological and behavioural innovations can interact with one another, creating a complex dynamic, including additional concerns that need to be overcome. Goldthau et al. (2019) foresee how a technological breakthrough in renewable energy could lead to instability in fossil-fuel-producing. This is potentially due to insufficient time and no capacity to adapt. The internal conflicts could spill over into neighbouring regions.

To deliberately achieve positive outcomes and put us on the path to net-zero, there must be a combination of different types of transformative innovations – both technological and societal – which must be included in future modelling scenarios and emission pathways. The synergistic, cumulative effects arising from fundamental societal changes will be a core part of the required dynamics to ensure we reach the Paris goals. Deep decarbonisation requires an internationally coordinated response to assemble necessary resources and avoid adverse impacts, such as unfair competition or carbon leakage (Åhman et al., 2017). This standing point justifies the need to evaluate transformative innovation through a global survey to understand stakeholders' preferences for such types of innovation and inform modelling scenarios.

It is clear that we cannot wait for technology to be ready for implementation or commercialisation but require more action from governments, policymakers, businesses, and individuals if we are going to reach global net-zero goals. Despite this, most of the literature surrounding the topic presents behaviour changes as nudges or simple encouragement in the right direction rather than ground-breaking innovation that changes the playing field. For example, they speak about the need to encourage individuals to take up a plant-based diet, lower EVs' lifetime costs, or implement harsher levies on aviation. Whilst the importance of these activities should not be undermined, they are not radical, revolutionary suggestions but a method to coax individual consumers in the right (and low-carbon) direction.

As highlighted in Marteau et al. (2021), the measures and interventions would create an environment that would allow innovation, vital to systemic behaviour changes at scale. These suggestions would make it easier for individuals to live sustainable and low-carbon lifestyles and transition to decarbonisation. Finally, the behavioural innovations presented in the literature tend to focus on the short term. They reflect immediate interventions to stimulate the diffusion of new, low-carbon technologies or alterative, low-carbon lifestyles. Perhaps due to the stochastic nature of society, there appears to be a lack of far-reaching potential innovations in societal behaviour.

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3 A Co-Creation Survey on Game-Changing Innovation

3.1 Identification of Transformative Innovation in the Survey

Identifying transformative innovation to achieve a low-carbon economy in the future is crucial. Following Napp et al. (2017) and the innovation protocol established in Section 1, in this survey, technologies that are currently commercially deployed, even if they could benefit from further research to reduce costs or overcome non-technical barriers, are not included in game-changing innovation identification. The concept of TRL is used as a way of ranking technologies based on their level of maturity. Three different technology levels are defined, basic research at the lab scale (TRL 1-3), technology development and small-scale demonstration (TRL 4-6), and large-scale operational demonstration and commercialisation of the full system (TRL 7-9). For a technology to be included in the survey, it should not be at a commercial scale and still require significant R&D (Research and Development). Under this definition, those technologies under TRL 1-3 and 4-6 are included in the survey.

Transformative innovation in several important sectors does not require extensive technical R&D as the technologies and processes are already available. That does not mean that other types of innovations could not accelerate the uptake of technologies in these sectors. These sectors include buildings and electricity generation. In transportation, extensive technical R&D focuses on the aviation industry. Land transport innovation is relatively more advanced, while maritime transport depends mostly on electrification with hybrid and renewable technologies (Bugge et al., 2021). Napp et al. (2019) identified 21 technologies (including artificial photosynthesis for biofuels and thermal cycle for energy storage) critical for achieving a low-carbon economy and still require substantial R&D investment before they will be commercially viable.

The survey follows Wilson (2018), drawing sets of potential innovations relating to mobility, buildings & cities, food, and energy supply. Wilson (2018) uses Christensen's canonical definition of disruptive innovation as low-end products offering novel sources of value to users with the potential to transform the market for energy-related goods and services (Christensen, 2013). His identification is justified by scientific discussions involving innovators, market intermediaries, policymakers, and researchers (Wilson et al., 2019). The sets include behavioural changes that are of limited technological nature, market design, and new business models. These classifications align with the definition elaborated in subsection 2.3; for simplicity, we acknowledge it as non-technological innovation. The list of technology and non-technological innovations is elaborated in the subsequent sub-section.

3.2 Survey Design

The survey was done online, run from 26 January 2022 to 4 March 2022 using *Google Forms* and *mikecrm* (targeted for respondents to access from mainland China). Envisioning innovative deployment of low-carbon innovations requires the involvement of climate and energy experts; thus, respondents are targeted and identified as experts in the field based on the PARIS REINFORCE contact database (Section 3.3). The survey was conducted in English and comprised 102 questions, of which three open-ended and three sociodemographic. The questionnaire is provided in Appendix 1. The survey was intended to take no more than 15 minutes and divided into four parts, each in a separate webpage. Respondents were asked to evaluate the identified (selected) technologies and non-technological innovations against their mitigation potentials, risk, and timing in deep decarbonisation.

The first page introduced the PARIS REINFORCE project as well as the survey and provided some considerations on ethics, especially regarding the use of demographic characteristics (elicited in the second page, including e-mail address, current working capacity, country, and gender). It should be noted that the survey was approved by the Ethics Mentor of the project and conducted following the ethical regulations set out in WP9 deliverables. The

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ethics disclaimer read:

"The information provided in this form (email address, working capacity, country, gender) is collected by the PARIS REINFORCE Project Consortium partners responsible for the organisation of this survey. These partners are the Energy Policy Unit of the National Technical University of Athens (EPU NTUA, https://www.epu.ntua.gr/), École Polytechnique Fédérale de Lausanne (https://www.epfl.ch/labs/leure/), Grantham Institute of Imperial College London (https://www.imperial.ac.uk/grantham/), SEURECO (http://www.erasme-team.eu/), and Bruegel (https://www.bruegel.org/). This information will be used only in relation to this specific survey and as follows. The email address will be used to communicate information related to the outcomes of the survey (if the participants select to), as well as to ensure the survey has been filled in once per participant. Working capacity, country, and gender will be used for aggregated statistics on the participants and for differentiated the analysis of the results.

The anonymised survey results will be used in the scientific process of the PARIS REINFORCE research project, for the purposes of designing scenarios on game-changing technological, economic, and societal/behavioural innovations that respond to the needs identified by stakeholders, and therefore serve to enhance the societal/policy relevance and co-ownership of the produced outputs. The anonymised survey results may also be published as part of the peer-reviewed paper(s) documenting the scientific process and results.

The personal information included in the primary source of data (the survey's results) will be held for up to four years after the end of the PARIS REINFORCE Project based on its contractual obligation with the EC (30/11/2022), after which, they will be removed from the data set. In accordance with articles 14-17 of the EU-GDPR, we inform you that you have the right to access, rectify, delete or restrict the processing of your data at any time. You may withdraw this consent at any time. You may place any such request or ask for more information by emailing contact@paris-reinforce.eu, paris@epu.ntua.gr, or the Data Protection Officer of EPU NTUA, Christos Ntanos (dpo@epu.ntua.gr)."

The third page provided a piece of background information, including a figure of the International Energy Agency (IEA) Net-Zero Emissions scenario (IEA 2021) and a list of early-stage technologies based on Napp et al. (2017) and Napp et al. (2019), and other (non-technological) innovations based on Wilson (2018) and Wilson et al. (2019). The fourth page listed 14 early-stage technologies and asked the participants to answer three closed-ended questions about each technology: (i) "What is the mitigation potential of these technologies up to 2050", (ii) "When do you think the technologies will be available commercially?", and (iii) "What is the risk of non-availability or delay of these technologies?". The stakeholders provided their perception of the potential importance of these technologies by choosing between 5 options ("Very low", "Low", "Moderate", "High", "Very high"), while an alternative option provided the participant with the option to indicate they are "Not able to respond". These mitigation technologies are listed in **Table 1**.

Table 1: Survey Questions on the Mitigation Technologies

Technology	Very low	Low	Moderate	High	Very high	Not able to respond
What is the mitigation potential of these technologies up to 2050						
Aviation biofuel (biojet or renewable jet fuel)						
Hydrogen aircraft						
Hyperloops						
Advanced biofuel supply (e.g. algae for bioethanol production)						

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Technology	Very low	Low	Moderate	High	Very high	Not able to respond
Carbon Capture and Storage (CCS)						
Hydrogen in steelmaking						
Iron ore electrolysis (to produce iron)						
Alternative building materials for steel and cement						
Biomass Carbon Capture and Storage (BECCS)						
Bio-char (soil amendment resulting from the pyrolysis of biomass)						
Ocean liming (addition of calcium oxide powder in oceans)						
Direct Air Capture (e.g. soda/lime process)						
Next-generation energy storage (Power-to-Gas, Flywheels, new batteries, etc…)						
Nuclear fusion						

In the second question, experts were asked when each technology is expected to become commercially available with the following sentence:

"When do you think the technologies will be available commercially?"

The participant could use one of the following options:

- "By 2030"
- "Between 2031 and 2040"
- "Between 2041 and 2050"
- "Post-2050"
- "Never"
- "Not able to respond"

Finally, the third question of the technological survey asked:

"What is the risk of non-availability or delay of these technologies?"

The participants were able to use one of the following options:

- "Insignificant"

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- "Low"
- "Moderate"
- "Important"
- "Critical"
- "Not able to respond"

The second part of the survey is related to other disruptive low-carbon innovations. The list of these innovations is based on Wilson et al. (2018). We identify 12 disruptive low-carbon innovations listed in **Table 2**, while the questions posed to the stakeholders follow the same format as those in the "technology" part of the survey. In particular, we surveyed their mitigation potential for each one, and the participant could choose among the six options presented in the same Table.

Table 2: Survey Questions on Other Disruptive Low-Carbon Innovation

Disruptive low-carbon innovations	Very low	Low	Moderate	High	Very high	Not able to respond
What is the mitigation potential of these disruptive low-carbon innovation up to 2050						
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 (Reduced meat diet, etc...)						
Urban food production (own food growing, community farming, etc...)						
Producer-consumer relationships (local food distribution, food bow deliveries, etc...)						
Interconnectivity for optimised usage (smart appliance, LED, smart homes, etc...)						
Optimisation of buildings' thermal performance (Home energy management systems, smart heating controls, etc...)						

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Disruptive low-carbon innovations	Very low	Low	Moderate	High	Very high	Not able to respond
Reduced demand for space and material (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 + storage, Micro-wind turbines, etc...)						

Similarly to the technologies survey part, we also asked when these innovations are perceived to take off by using the following sentence:

"When do you think these disruptive low-carbon innovations will take off?"

The participants could respond by selecting one of the following options:

- "Already taken off"
- "By 2030"
- "Between 2031 and 2040"
- "Between 2041 and 2050"
- "Post-2050"
- "Never"
- "Not able to respond"

The survey complemented this part by asking:

"What is the risk of these disruptive innovations never materializing/being adopted?"

With the following options for the respondent:

- "Insignificant"
- "Low"
- "Moderate"
- "Important"
- "Critical"
- "Not able to respond"

An open-ended question was added at the end of pages 4 and 5 to allow respondents to indicate other

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technologies and non-technological innovations not included in the survey. The sixth page thanked the participants and asked them if they wished to stay informed about the results.

3.3 Sampling & Survey Analysis Methods

We invited 3,000 individuals to participate in our survey on game-changing innovation mainly based on contacts from the PARIS REINFORCE database. The sample selection process was the following:

1. First, we separated the invited participants into two groups: those living in Europe and those coming from non-European countries. The objective was to have a representative sample for the two regions and to be able to design lessons that can be implemented in the scenario definition for WP5 and WP6, respectively.
2. For both groups, the recruitment of the invited participants was based on:
    a. The list of individuals that participated in the stakeholder meetings organised by the project consortium in different regions/countries (e.g., India, Russia, the Caspian region, Switzerland, France, etc.).
    b. Stakeholders from Bruegel's stakeholder database. This list was based on several partnerships and events that it has organised in the past.
    c. Recommendations from consortium partners.
    d. Selected contacts from scientific associations and networks, such as the International Association for Energy Economics and the Global Trade Analysis Project network, with relevant interest areas (energy and climate change, energy economics, mitigation, etc.).

To sufficiently represent non-EU regions in the survey, we extended the regional distribution of invited participants encompassing all parts of the globe, especially emerging and developing countries. The sample of non-European countries included 1,000 contacts. These include the project's existing stakeholders and additionally invited respondents that were obtained through methods 2.c and 2.d. **Table 3** lists the geographical distribution of invited participants for this survey. **Figure 1** shows the geographical distribution of non-EU invited participants.

Table 3: Geographical Distribution of Invited Participants by Region

Region	Number of invited participants
Europe	2,000
Africa	190
Asia	223
Australia and New-Zealand	74
Middle East	112
North America	201
Russia and former Soviet Union countries	92
South America	108
Total (non-European countries)	**3,000**

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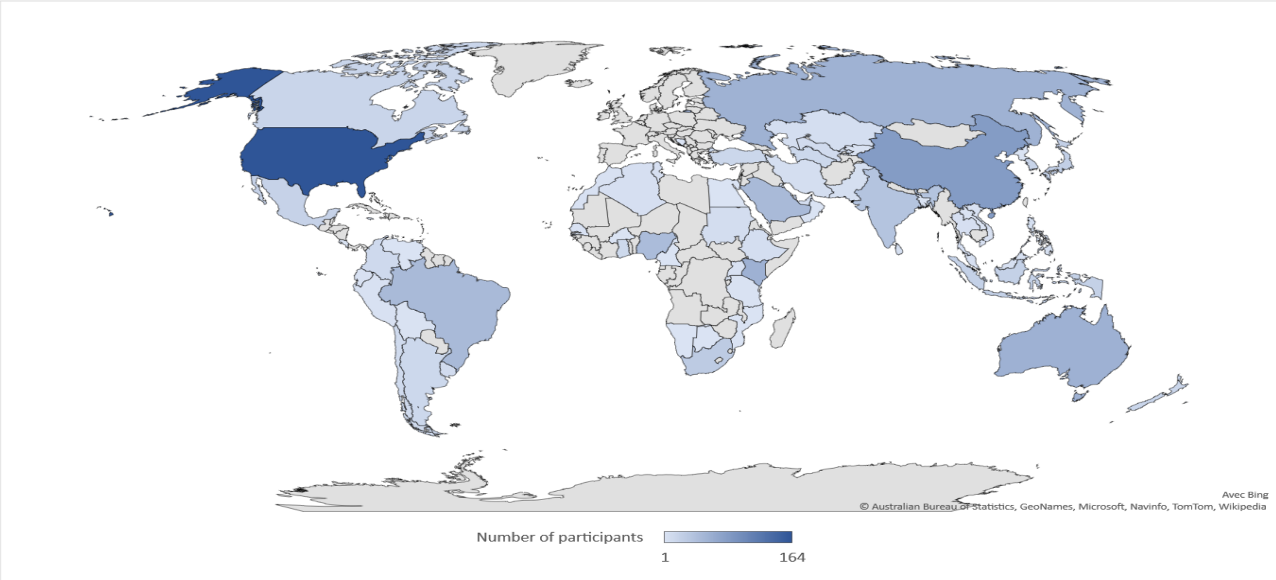

Figure 1: Geographical distribution of non-European invited participants

Statistical analysis was performed in two stages. The first stage covers statistical analysis based on the distribution of obtained data responses to investigate trends and patterns from the survey results. The second stage involved advanced statistical analysis using Hierarchical Clustering and Multiple Criteria Decision Analysis (MCDA). The hierarchical clustering or hierarchical cluster analysis builds a hierarchy of clusters based on some similarity measures among listed transformative innovations. At the same time, the distanced-based MCDA method (TOPSIS) synthesises the obtained information by combining weight and scores to derive and rank those innovations based on respondents' responses. Statistical analysis is part of the integrated process in this deliverable, as detailed in **Figure 2.**

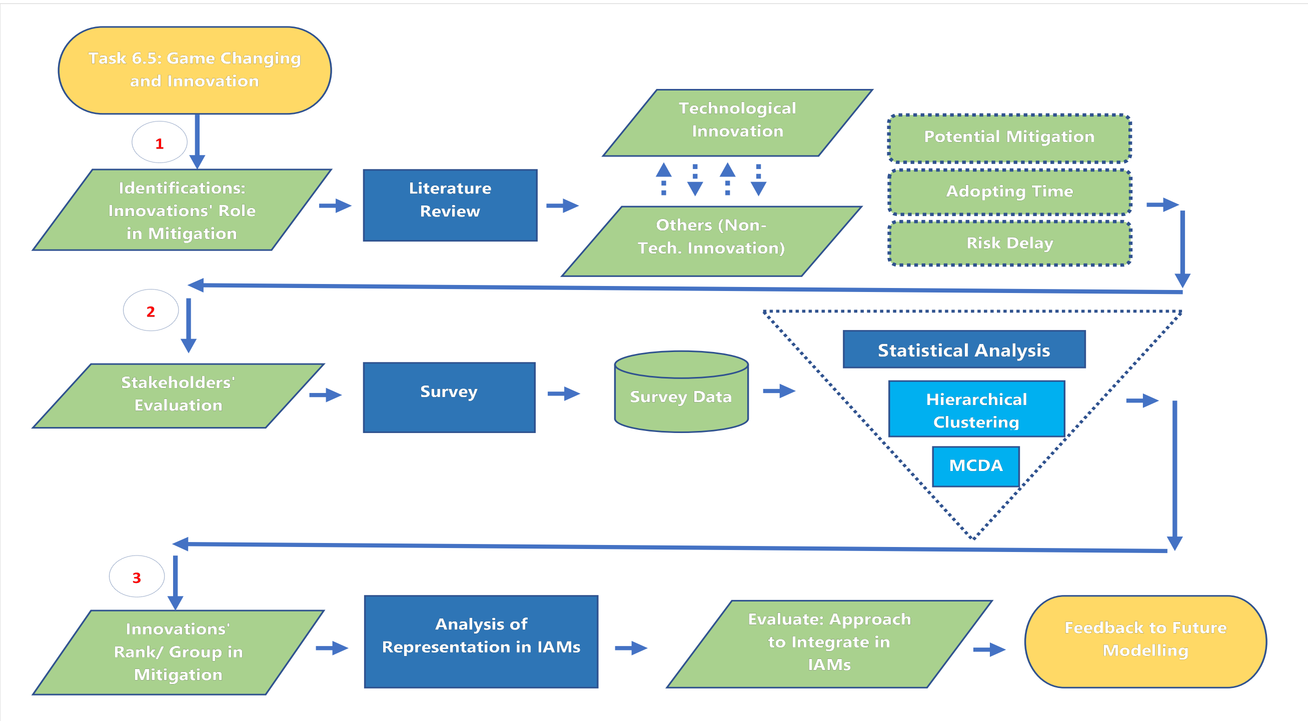

Figure 2: Flowchart Task 6.5 – Game-Changing Innovations: Identification, Evaluation and Analysis

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3.4 Survey Results: Analysis

The survey received 260 responses from 56 countries, almost 9% of the targeted participants. Around 70% of the respondents are male, 29% are female, and 1% prefer not to say. Despite the EU respondents constituting almost half the votes, the sample is relatively dispersed, with all other countries or regions being well represented (**Figure 3**). The survey respondents are also well dispersed in terms of their professional working background, being classified as Academia, Private sector, National Government, International Institutions, NGOs, and others (**Figure 4**). Respondents' responses to each survey question are summarised in Appendix 2.

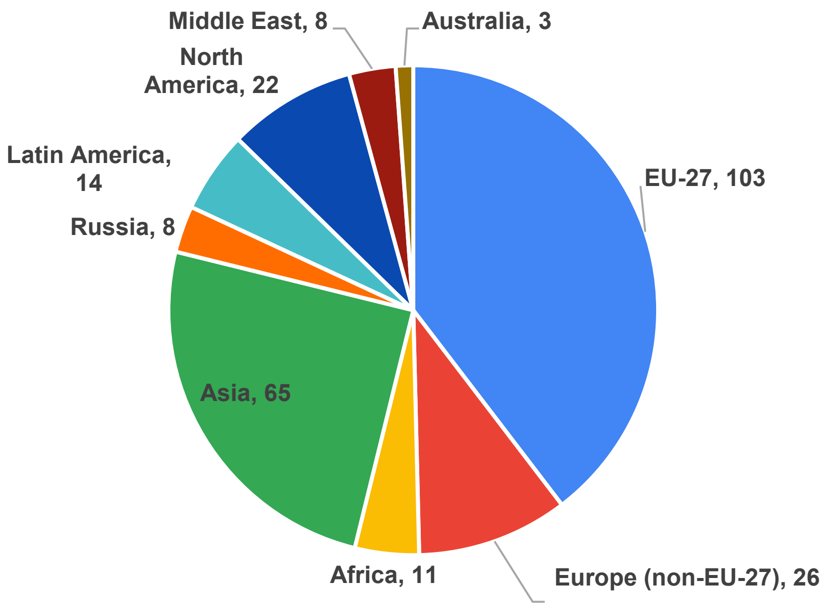

Figure 3: Survey Respondents' Regional Distribution

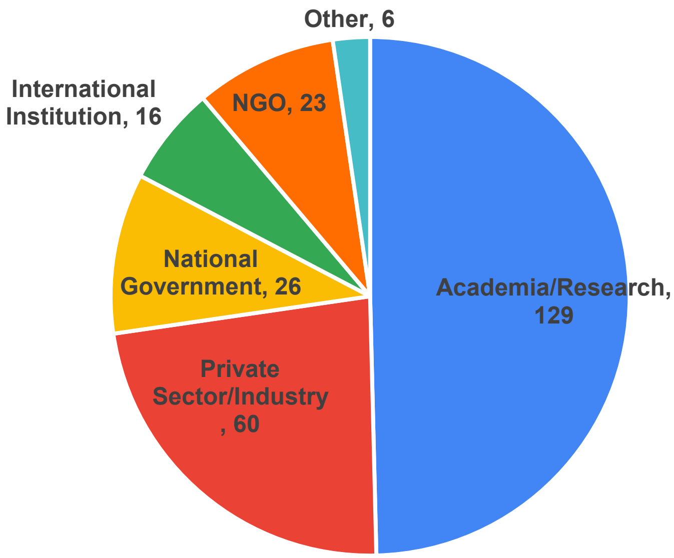

Figure 4: Survey Respondents' Working Background

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3.4.1 Not Able to Response: Statistical Review

We refer to the statistical results on respondents who choose the option of 'Not Able to Response,' particularly in responding to the first surveyed question of mitigation potentials of specific technologies (**Table 4**) and non-technological innovation (**Table 5**). The results reflect uncertainty in the respondents' knowledge about specific technological and non-technological low-carbon innovations. The statistical tables present the differences in this response according to the respondents' working backgrounds.

Table 4: Respondents' Share for Not Able to Response: Technological Innovation

Technologies	Academia /Research	Private Sector/Industry	National Government	International Institution	Other	**Total**
Aviation biofuels	3%	3%	4%	0%	7%	**3%**
Hydrogen aircraft	5%	3%	8%	6%	17%	**6%**
Hyperloops	18%	36%	27%	25%	41%	**26%**
Advanced biofuel supply	2%	5%	15%	0%	10%	**5%**
CCS	1%	3%	4%	0%	3%	**2%**
Hydrogen in steelmaking	5%	5%	19%	6%	10%	**7%**
Iron ore electrolysis	17%	34%	38%	13%	41%	**25%**
Alternative building materials for steel a	3%	7%	12%	6%	10%	**6%**
BECCS	2%	14%	12%	0%	10%	**7%**
Bio-char	15%	31%	35%	13%	31%	**22%**
Ocean liming	21%	39%	46%	19%	31%	**29%**
DAC	7%	17%	23%	25%	14%	**13%**
Next-generation energy storage	3%	5%	8%	0%	7%	**4%**
Nuclear fusion	6%	12%	23%	19%	7%	**10%**
Mean	**8%**	**15%**	**20%**	**9%**	**17%**	**12%**

Table 5: Respondents' Share for Not Able to Response: Non-Technological Innovation

	Academia /Research	Private Sector/Industry	National Government	International Institution	Other	**Total**
Alternative forms of auto-mobility	1%	2%	0%	0%	3%	**1%**
Alternatives to auto-mobility	1%	3%	0%	0%	7%	**2%**
Reduced demand for mobility	0%	0%	0%	0%	3%	**0%**
Alternative dietary preferences	2%	2%	4%	0%	10%	**3%**
Urban food production	4%	3%	0%	0%	17%	**5%**
Producer-consumer relationships	0%	2%	0%	0%	7%	**1%**
Reduced demand for food	1%	0%	0%	0%	3%	**1%**
Interconnectivity for optimised usage	2%	2%	0%	13%	3%	**2%**
Optimisation of buildings thermal perfo	2%	2%	0%	6%	10%	**3%**
Reduced demand for space and materi	6%	7%	12%	6%	14%	**8%**
New service providers	3%	2%	8%	0%	7%	**3%**
Integrating consumers into grids	2%	2%	4%	0%	7%	**2%**
Decentralised energy supply	4%	2%	12%	6%	7%	**5%**
Mean	**2%**	**2%**	**3%**	**2%**	**8%**	**3%**

The technologies that concentrate the highest share of no responses are technological innovations of Ocean Liming, Hyperloops, Iron Ore Electrolysis, and Bio-Chars. The readiness level and the complexities of these technologies likely caused the absents of respondents to answer. For example, the ocean liming concept of

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neutralizing ocean acidity through alkalinisation needs enormous scientific assessment to be applied to large-scale projects. It is the same as low carbon massive transport technologies of hyperloop that still need intensive feasibility studies with long-distance trials and are still 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 who cannot identify mitigation potentials is insignificant for these technologies. Also, respondents know about the energy associated with Biofuels (such as Aviation Biofuels, advanced biofuels supply, and CCS) and Hydrogen technology (Hydrogen Aircraft, Hydrogen in Steel Making).

Nevertheless, a different picture is shown in non-technological innovations. Only a small percentage of respondents were not able to give a response. Somehow respondents are more familiar with these disruptive innovations. The highest share is for Reduced Demand for Space and Materials, followed by Urban Food Production. There is still ground for increasing awareness over their decarbonisation potential, even for such less complicated innovations.

Statistical distribution among all respondents also shows a higher percentage of responses for non-technological innovations (**Figure 5**). Around 84% of respondents are able to answer all questions related to nontechnological innovations, and 49% for technology-related innovations. Only 5% of the respondents cannot answer more than five questions related to technologies and none to non-technological innovations.

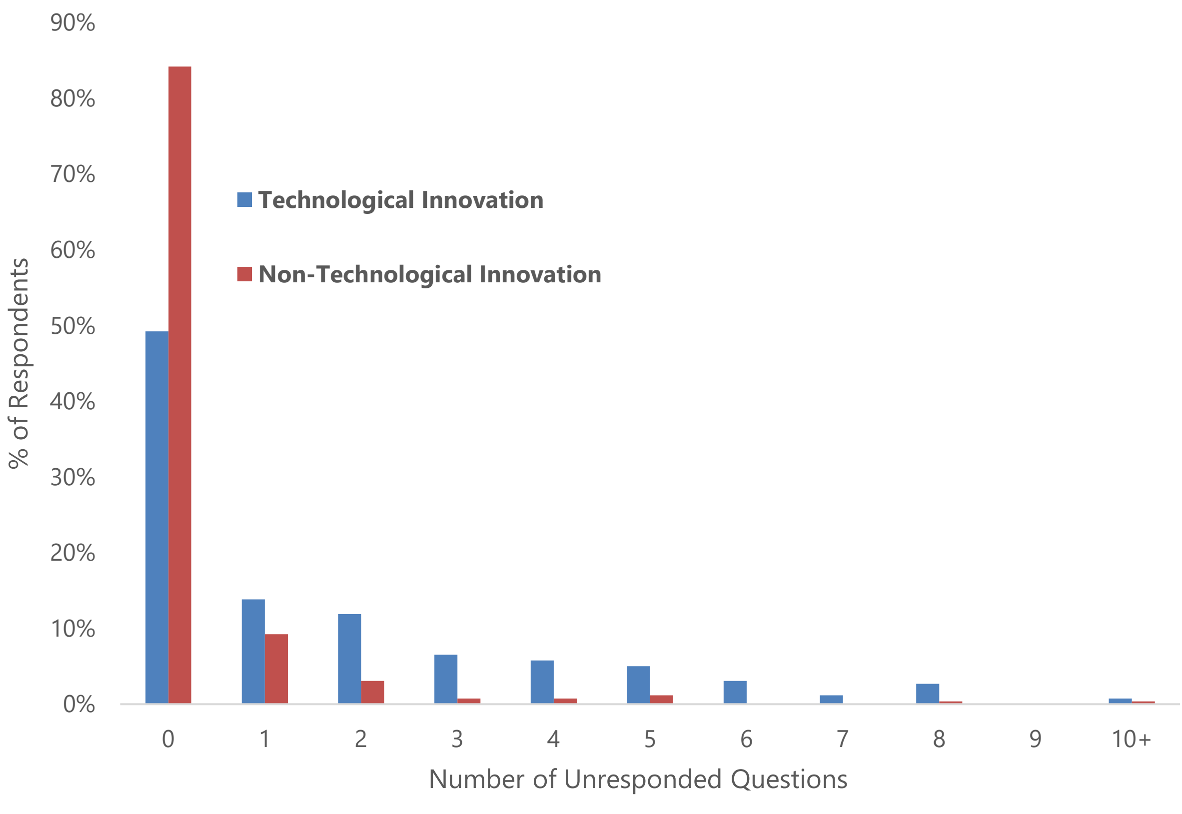

Figure 5: Statistics of Unresponded Questions.

For the first stage of statistical analysis, we omit the number of "Not Able to Respond" while keeping the optimal number of observations. Despite this approach slightly tending to undermine the inferences of the statistical results, we assess this as a better approach in data analysis for such a large expert survey rather than an analysis-specific assumption. Yet, given the number of "Not Able to Respond" was not a very large share of the total responses, these are included for the second stage of statistical analysis as additional information to perform Hierarchical Clustering and MCDA.

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3.4.2 Mitigation Potentials of Technologies and Non-Technological Innovations

In determining the mitigation potentials, the survey responses of mitigation options are ordinarily scaled from -2 to represent very low mitigations potentials to +2 for very high mitigation potentials. The mean values for each technology and non-technological innovation are summarized in **Figure 6**.

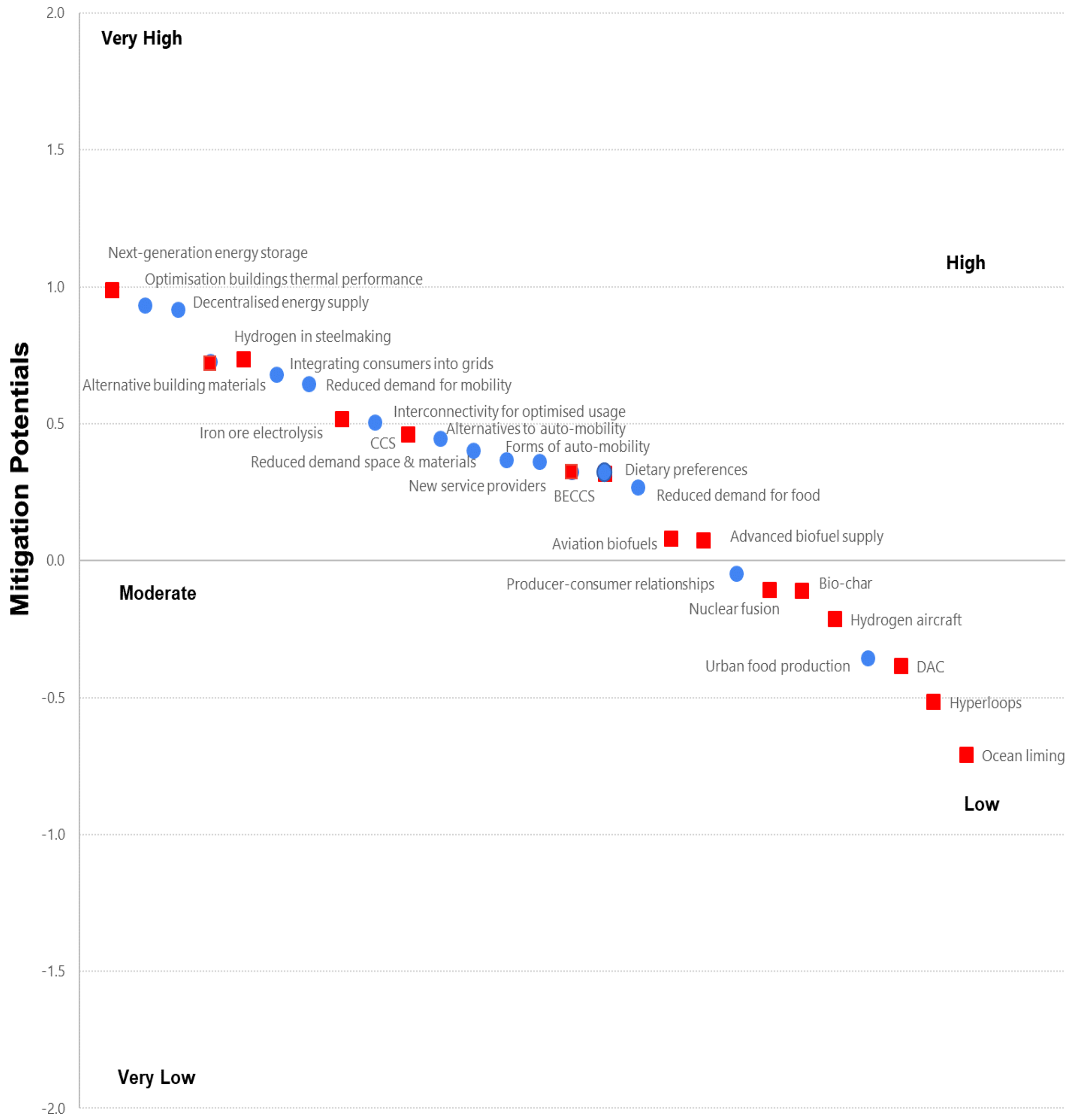

Figure 6: Ranking of technologies per Mitigation Potential

For technological innovations, most of the respondents assess that Next-Generation Energy Storage, Alternative Building Materials for Cement and Steel, Hydrogen in Steel Making, and Iron Ore Electrolysis tend to be moderate to high potential for deep decarbonisation. These are followed by CCS, BECCS, Advanced Biofuels Supply, and Aviation Biofuels technologies. On the other hand, mitigation potentials of Nuclear Fusion, Bio-Char, Hydrogen Aircraft, DAC, Hyperloops, and Ocean Liming are low to moderate.

In the case of non-technological innovations, most respondents believe there is moderate to high potential in almost all innovations listed in the survey. Disruptive Low carbon innovations in mobility tend to fall in the high

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potential range. In contrast, respondents are less confident about mitigation potentials for disruptive innovations in food and consumption. For example, respondents assess that it has low to moderate mitigation potentials in urban food production.

3.4.3 Expected Time of Adoption and Risk of Failure

Following the quantifying method of numerical scale for mitigation potentials, the expected adopting time uses a median between the range of years as scale (the same also applies to the risk of failure). The numerical scale of these factors is detailed in Appendix 3. **Figure 7** exhibits the mean value of the expected time of the listed technological innovations to be commercially available alongside the percentage of respondents who project these innovations have never been applied. The survey results show that Nuclear Fusion, Ocean Liming, and Hyperloops will be commercially available post-2050, with a relatively higher percentage of respondents who think these technologies can even fail to launch altogether. Respondents also include DAC in this category while projecting that this technology will be available by 2050. Other technologies are expected to be commercially available by the 2040s.

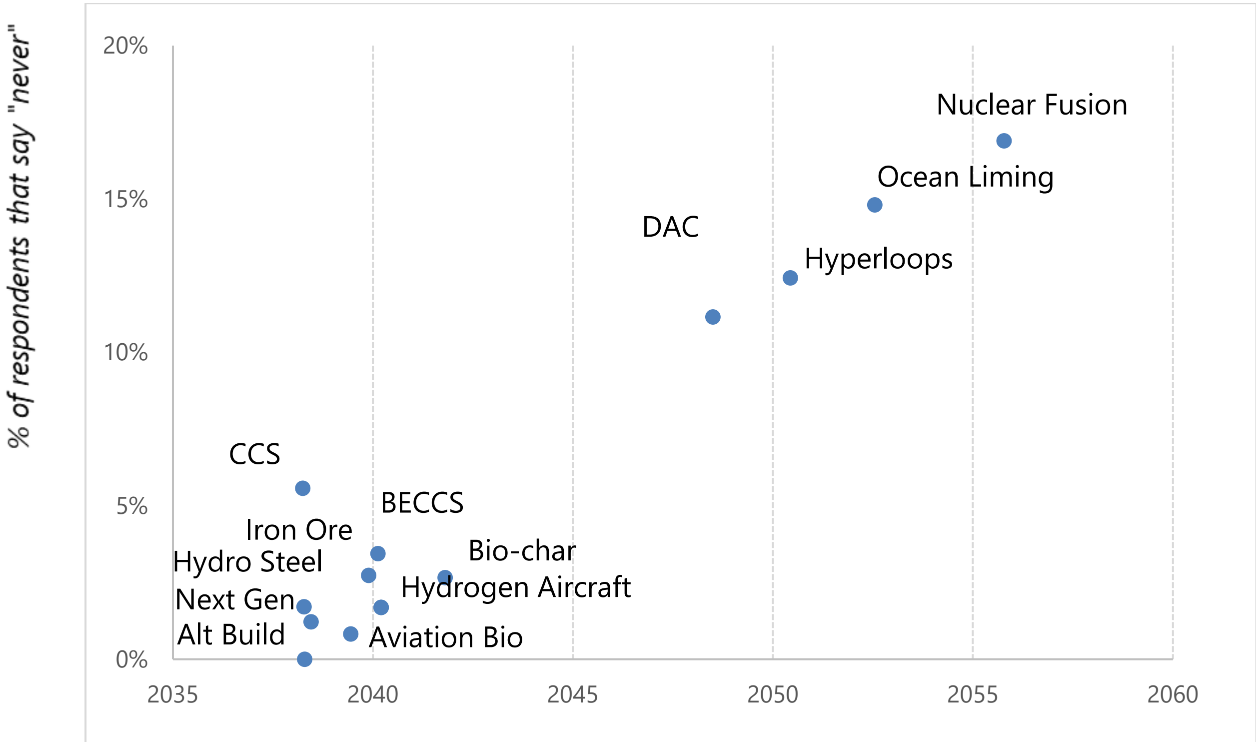

Figure 7: Potential Timing: Technological Innovation

For non-technological disruptive behaviour, again, the survey reveals a different picture. Respondents project that all behavioural changes can be adopted in a shorter period by 2040 (**Figure 8**). Disruptive behaviour related to food and consumption seems to be more challenging than others. The percentage of respondents who said these innovations might never be implemented is almost double compared of others. It is worth noting that respondents also project that it will take a little longer for these disruptive innovations to be adopted. The survey also reveals a similar case for Reducing Space and Materials and Consumer Integration into Grids.

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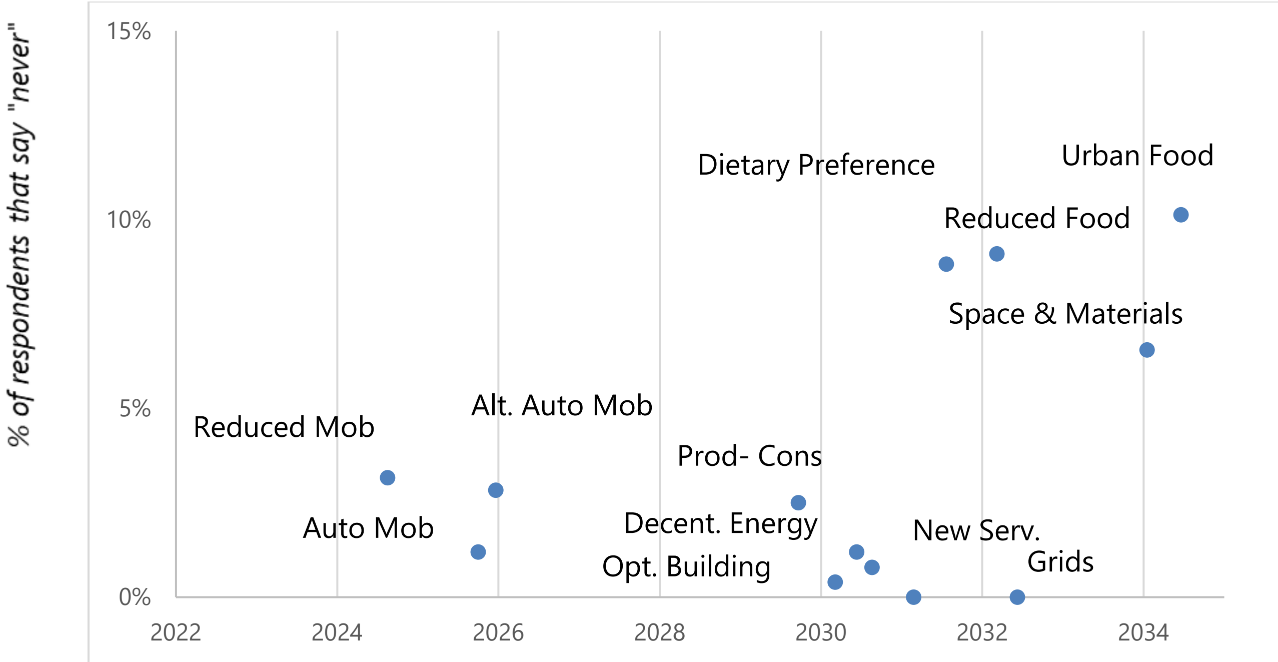

Figure 8: Potential Timing: Non-Technological Innovation

For respondents' perception of the risk of non-availability or delay, most technologies fall in the moderate to high range. Almost all non-technological innovation, in contrast, falls in low to moderate ranges, which indicates the feasibility of non-technological innovations. Statistical distribution of the risk of non-availability or delayed and never been implemented are detailed in Appendix 2.

Mapping the mean value of mitigation potentials and the risk of being delayed for each disruptive innovation results in four groups (**Figure 9)**. In brief, most technologies 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 non-technological innovations belong to the third quadrant (lower potentials and lower risk), i.e., Ocean Liming, Hyperloops, Biochar, and two non-technological innovation for food consumption (Urban Food and Producers-Consumer Relationship).

The average mitigation potentials and risk for Next-Generation Energy Storage is peculiar. This technology is found to be the most potential for mitigation, yet the risk of being delayed is also high. A similar pattern is found for Iron Ore Electrolysis, Hydrogen in Steelmaking, and Alternative Building Materials for cement and steel. We found the overall correlation of innovations listed in the survey is positive.

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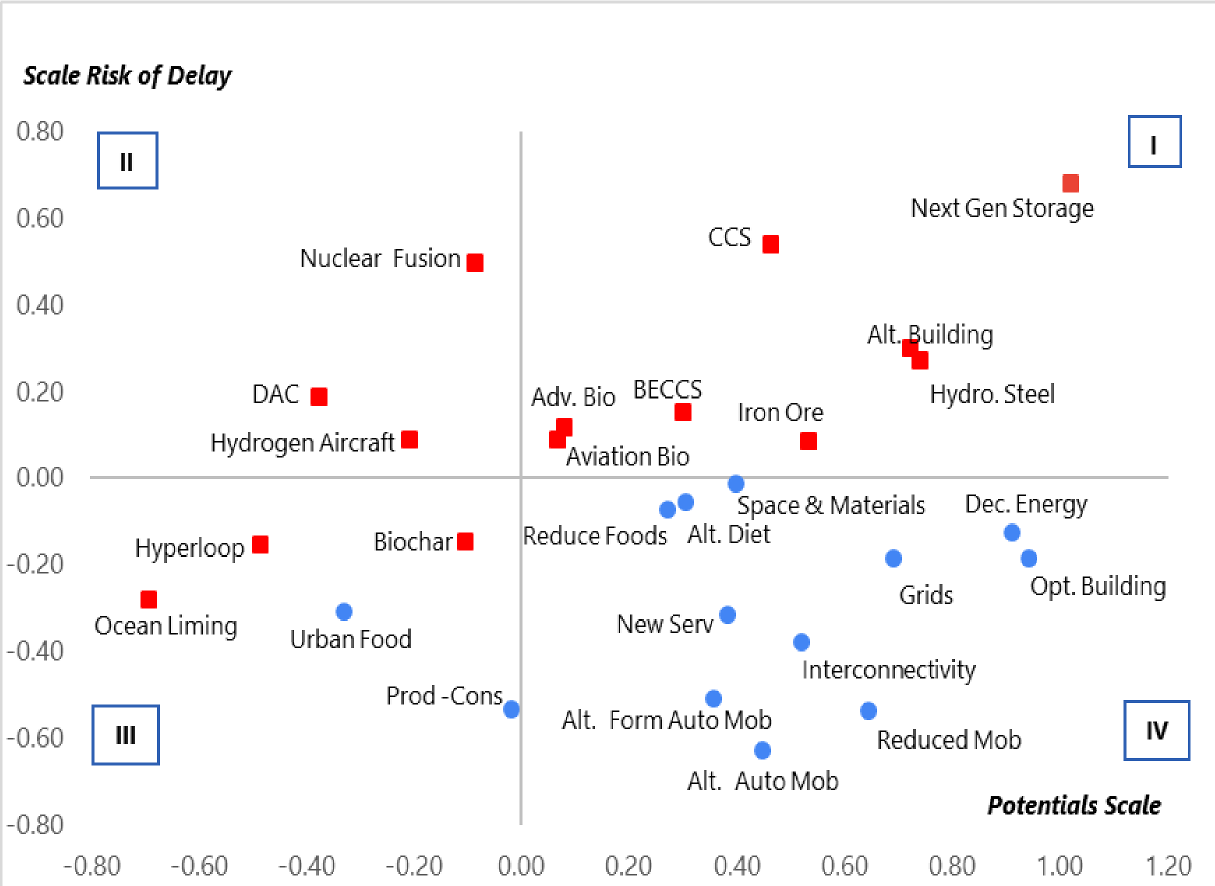

Figure 9: Mitigation Potentials and Risk of Delay/ Never Adopted

3.4.4 Hierarchical Clustering Analysis

Further statistical analysis is conducted with multivariate clustering, an algorithm that groups similar objects into clusters. The endpoint is a set of clusters, where each cluster is distinct from the other cluster, and the objects. This clustering uses all statistical information for all the factors. For these 27 low carbon innovations being surveyed, we use the mean value and standard deviations for three surveyed indicators (variables) as information to perform a hierarchical cluster analysis. The number of respondents who cannot respond and who assess innovations will never take place is also included in the database to capture uncertainty factors of these transformative innovations. Before the analysis, the database obtained from the survey is normalised, followed by calculating the Euclidean distance between samples. Hierarchical Analysis results in a Cluster Dendrogram (**Figure 10**) showing commonality among innovations based on their mitigation potentials, expected implemented time, and risk scale. The highest possible classification is 5 clusters.

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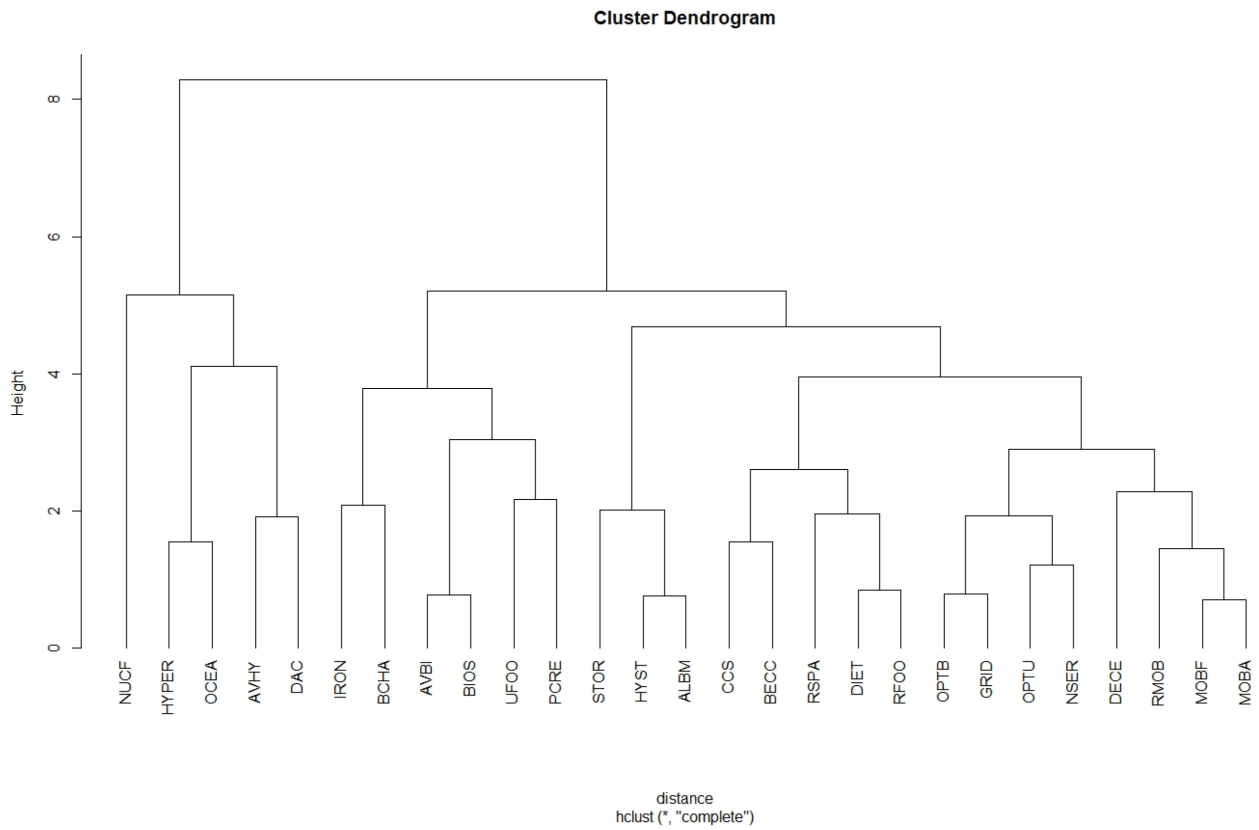

Figure 10: Cluster Dendrogram of Low Carbon Innovations

A similar pattern is found for the technologies of Nuclear Fusion, Hyperloops, Hydrogen Aircraft, Ocean Liming, and DAC. There is a clear hierarchical difference that sets this group apart. The experts assess that these technologies are more likely to be adopted in the long run (post-2050) with a relatively high degree of uncertainty for mitigation potentials and risk of being delayed. This type of technological innovation will be unlikely to be implemented shortly. Nuclear Fusion seems to have a more robust separate line within this group, as it faces higher uncertainty than other technologies in the same group. **Figure 11** maps this cluster classification, and **Table 6** lists these five hierarchical cluster classifications for each low carbon innovation.

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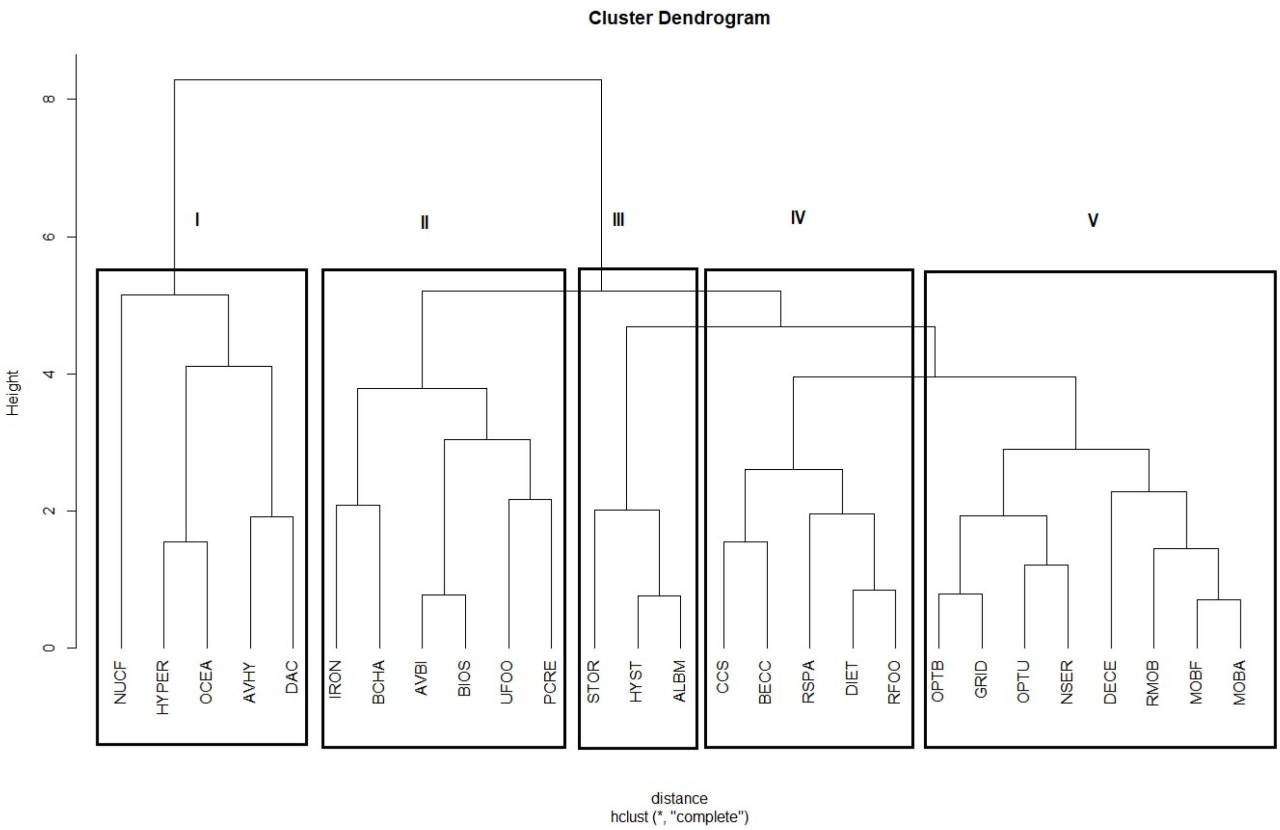

Figure 11: Cluster Dendrogram of Low Carbon Innovations: Classifications

Table 6: Hierarchical Cluster Classifications – Low Carbon Innovations

Cluster No	Cluster Explanation	Sub Cluster	Cluster Code	Disruptive Innovations
I	• High Degree of Uncertainty in Mitigation Potentials and Risk of Delay; • Likely to be Adopted Post 2050	1.a	NUCF	Nuclear Fusion
		1.b	HYPER	Hyperloops
		1.b	OCEA	Ocean Liming
		1.c	AVHY	Hydrogen Aircraft
		1.c	DAC	Direct Air Capture
II	• Mitigation Potentials vary • Adoption Timespan 2030-2040	2.a	IRON	Iron Ore Electrolysis
		2.a	BCHA	Bio-Chars
		2.b	AVBI	Aviation Biofuel
		2.b	BIOS	Advance Biofuel Supply
		2.c	UFOO	Urban Food Production

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		2.c	PCRE	Producer-Consumer Relationship
III	• High Mitigation Potentials • Adopted shortly before 2040 with low risk of delay	3.a	STOR	Next-Generation Energy Storage
		3.b	HYST	Hydrogen in Steel Making
		3.b	ALBM	Alternative Building Materials
IV	• Positive Mitigation Potentials • Adoption Timespan 2032-2040	4.a	CCS	Carbon Captured Storage
		4.a	BECC	Bio-CCS
		4.b	RSPA	Reduced Demand for Space & Materials
		4.c	DIET	Alternative Dietary Preferences
		4.c	RFOO	Reduced Demand for Food
V	• Positive Mitigation Potentials • All Non -Technological Low Carbon Innovations • Likely to be Adopted before 2030 • No Risk for Delay	5.a	OPTB	Optimisation of Building Thermal
		5.a	GRID	Integrating Consumer into Grids
		5.b	OPTU	Interconnectivity for Optimised Usage
		5.b	NSER	New Service Providers
		5.c	DECE	Decentralised Energy Supply
		5.d	RMOB	Reduced Demand for Mobility
		5.e	MOBF	Alternative Form of Auto-Mobility
		5.e	MOBA	Alternative to Automobility

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, between 2030 and 2040, with Bio-Chars technology becoming available at the end of this interval for large-scale implementation. Mitigation potentials vary, reflecting a high degree of uncertainty still. 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 (cut the food distribution line) are more challenging to adapt to other non-technological disruptive innovations.

In contrast, respondents show no strong opposition to the technologies of Cluster III. The Next-Generation Energy Storage, Hydrogen in Steel Making, and Alternative Building Materials have high mitigation potentials. They will likely achieve their large-scale implementations almost simultaneously, shortly before 2040, with no risk of delayed. Respondents also indicate the same affirmative positions to CSS and BECCS technologies in Cluster IV. This cluster also includes non-technological innovations of Reducing Space, Reducing Food, and Alternative Diets. The rest of the non-technological innovations are grouped in Cluster V. These demand-side changes in mobility

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to energy potentially affect deep decarbonisation pathways. Adoption is expected before 2030 with no substantial risk of delayed.

3.4.5 Multi-Criteria Decision Analysis (MCDA)

Following the statistical analysis of the stakeholders' votes in each of the three questions per exercise, we aggregate the stakeholder input to calculate the voters' priorities over the technological and other game-changing innovations while emphasising the extent to which voters agreed with one another (consensus). For this, we employ APOLLO (see PARIS REINFORCE deliverable D4.3), a group decision-making and consensus analysis tool based on the 2-tuple TOPSIS multi-criteria decision aid (MCDA) methodology (Labella et al., 2020; Koasidis et al., 2021), to rank each alternative by aggregating answers to all three questions. The tool uses linguistic variables, both for the input and the calculated output; this makes it ideal for this type of exercise (instead of, e.g., aggregations based on average values), where stakeholders' preferences are provided in qualitative format. Here, a five-term linguistic scale {very low, low, medium, high, very high} is used, coded as {0, 1, 2, 3, 4}. This is in accordance with the previous statistical analysis, adapted to use only positive values required by TOPSIS. An additional explanation of MCDA methodology is detailed in Appendix 5.

Technological Innovations

Based on the MCDA analysis (**Figure 12**), we identify three groups of distinct priority levels among the 14 game-changing technologies considering their mitigation potentials, expected availability, and risk of delay.

The *top priority technological cluster* includes three technologies for industrial decarbonisation—including alternative building materials for steel and cement (TOPSIS 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 hyperloops (1.40), Direct Air Capture (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 are close for 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. Among different stakeholder groups, rankings do not differ markedly, with technologies for decarbonising industry and next-generation energy storage remaining of the highest priority.

When looking at *working capacity*, academics' ranking (the largest group) was expectedly similar to the global solution, despite slightly undermining top-priority technologies and boosting the moderate-priority technology cluster (slightly reducing the distance between the two clusters). In contrast, the gap between the top-priority cluster and the moderate-priority cluster was more accentuated for private-sector stakeholders, who furthermore prioritised aviation biofuels while showing relatively limited faith in iron ore electrolysis (essentially swapping aviation biofuels and iron ore electrolysis in the top priority cluster). 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 hydrogen; compared to all other groups, they also largely boosted CCS, bringing it closer to the top-priority technologies, and emphatically undermined nuclear fusion. NGO representatives featured the largest divergence from the global solution, clearly prioritising steel-sector hydrogen, increasing the importance of transport

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technologies (hyperloops, hydrogen aircraft), and showing less faith in CCS (with or without bioenergy), advanced biofuel supply, and biochar.

Figure 12: TOPSIS scores and consensus of evaluated technologies for the total stakeholder sample (global solution) and for different stakeholder groups.
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

In further analysing these expert assessments from a *regional* perspective, we follow the countries' classification by Income from the World Bank (World Bank, 2019). The lower-middle-income/lower income is merged based on the low number of representatives from the latter category. We find that stakeholders from high-income countries closely followed the global solution but overemphasised the top-priority technology cluster (and aviation biofuels), contrary to nuclear fusion.

Participants from upper-medium-income countries (most being 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 responders favouring the former and male responders favouring 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 (**Figure 12**),

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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.

Other Innovations (Non-Technological Innovations)

In contrast to technologies, clusters were less distinct for other disruptive game-changers (**Figure 13**), which showcased relatively even differences. The *top-priority DLCIs are* oriented toward mobility, including reduced demand for (2.95) and alternatives to auto-mobility (2.80), although alternative mobility models (e.g., car-sharing) received a lower priority score (2.56).

Figure 13: TOPSIS scores and consensus of evaluated DLCI for the total stakeholder sample (global solution) and for different stakeholder groups.
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.

DLCIs with 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, e.g., through demand response measures (2.42) and new (energy) service providers (2.37). Food-related innovations were perceived as *low priority DLCIs*; 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 on DLCIs (80.2%) was a bit lower than in the technological survey, reflecting higher competition among individual alternatives.

By *working capacity*, and as in the case of the technologies, members of academia 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. Industry representatives indicated measures to reduce demand for mobility as a top priority; they also

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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 optimal thermal performance in buildings with mobility measures following. Overall, NGO representatives favoured highly most DLCIs, in contrast to the other stakeholder groups, who instead displayed a clearer ranking of their preferences. NGO stakeholders 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. Overall, we found consistent prioritisation of mobility measures; at the same time, we identified conflicts between building and energy-supply measures among groups: for example, both academics and international institutions greatly prioritised optimal thermal performance in buildings, which was not the case with private-sector and national government stakeholders.

From a *regional* point of view, like the technological survey, we observed a large agreement between the global solution and stakeholders from high-income countries, favouring consumer integration into the power grid and new service provision (aggregators, third-party financing, etc.). Stakeholders from upper-middle-income countries gave the highest priority to smart interconnectivity and all mobility measures, notably including alternative forms of auto-mobility as well; they instead showed relative disbelief in 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 for reduced demand for mobility.

Finally, *gender*-wise, female stakeholders had higher evaluations for most DLCIs, although trends in their ranking remained close to the global solution; a notable difference was a higher preference for decentralised energy supply. Consensus on the DLCIs among stakeholder groups differed slightly more than that on technologies (**Figure 13**), ranging from 76.7% (lower-middle-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 the ranking of DLCIs based on the stakeholder preferences (e.g., interchanges between building-related measures and. energy supply-related measures, the high fluctuations in the role of alternative forms of auto-mobility, etc.). Much like (but lower than) that of the technological survey, the consensus among stakeholders of the same groups was at similar levels. Detailed numerical evaluation of the TOPSIS scores (and, consequently, the ranking) of technologies and DLCI according to each stakeholder group is given in **Table 7** and **Table 8** below.

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Table 7: TOPSIS scores and consensus of evaluated technologies for the total stakeholder sample (global solution) and for different stakeholder groups.

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.

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Table 8: TOPSIS scores and consensus of evaluated DLCI for the total stakeholder sample (global solution) and for different stakeholder groups.

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.

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3.4.6 Other Technologies & Non-Technological Innovations (open-ended question)

The survey also asked respondents about specific technologies and non-technologies innovations with potential mitigation of deep decarbonisation, outside those listed in the questionnaire. **Table 9** below summarises those notable mentions.

Table 9: Other Disruptive Low Carbon Innovations

NO	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 for New Products
5	Photocatalysis	Reduced Space of Commercial Buildings
6	Deep Geothermal	
7	Fourth Generation of Nuclear Power	
8	Electric Aircraft	
9	Ocean Energy	

3.5 Points Taken from The Survey

Three takeaways can be taken from the statistical analysis of the survey. First, respondents' opinions on potential technological innovations could be classified into three major classifications. 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 to be critical in decarbonisation. Following this, respondents put CCS and other biofuel-related technologies in a lower category with less strong mitigation potential predictions. On the other hand, both statistical analyses confirm Hyperloops, Ocean Liming, DAC, Hydrogen Aircraft, and Nuclear Fusion as the lowest prioritised technologies. Hyperloops and Ocean Liming face higher uncertainty compared to others, and respondents assessed their mitigations potentials as relatively low with a high potential of being delayed. These technologies are not expected until post-2050. Perceptions of DAC, Hydrogen Aircraft, and Nuclear Fusion tend to be less optimistic, with the latter being very dispersed. Our expert respondents project these technologies will not be available anytime soon.

Second, for non-technological innovations, most of the respondents assessed moderate-to-high mitigation potentials. Common assessments converge towards immediate implementations (shortly after 2030). Some are expected to be implemented sooner (before 2030) and are less likely to be delayed. These include Alternative

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Forms of Auto-Mobility (car-sharing, ride-sharing), Alternatives to Auto-Mobility (E-bike), and Reduced Demand for Mobility (Home- Working, Teleconference). Innovation related to Foods and Space Reductions is 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 to be feasible included in the mitigation pathway. Mitigation potentials are dispersed among respondents, and a longer timeline is to be adopted. Nevertheless, consistent respondents' projections on non-technological disruptive innovations substantiate the importance of including these demand-side factors in the integrated modelling approach, in line with the deep decarbonisation pathway.

Finally, there is a significant difference in perception of technologies' mitigation potentials, yet a common agreement between respondents on non-technological innovations (DLCI). Academics are more optimistic about the technologies' mitigation potentials, while this is not the case for energy experts from national governments. Respondents from emerging economies (upper-middle income countries) are more optimistic that certain technologies will be effective in mitigation, leading to considerable preference towards moderate-to-lower-priority technologies. This pattern is more evident among respondents coming from developing economies, while high-income countries tend to be more sceptical. All respondents seem optimistic that DLCIs have moderate-to-high mitigation potentials with no significant difference between working background or regional points of view.

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4 Analysis on Representations of selected results in the IAMs

4.1 Technologies Captured in Current IAMs and Potential Integration in Future Modelling Scenario

PARIS REINFORCE draws from a strong core of numerous integrated assessment models (IAMs), which present technologies that already exist or are in development. The uptake of these technologies depends to a large extent on the carbon prices implied in the Current Policies and NDC scenarios or developments of technology costs that are exogenous in most of the PARIS REINFORCE models.

Technological assumptions constitute a critical part of IAMs. The technological mapping or parameterisation proves to be crucial, especially when technology-rich bottom-up models are used to generate the energy pathways to low-carbon futures. The power sector technologies, of which parameters were shared across the models, are: onshore wind, offshore wind, solar photovoltaics (utility and rooftop), concentrated solar power, pulverised coal, oxyfuel coal, coal integrated gasification combined cycle, natural gas combined cycle, natural gas combined cycle oxyfuel, geothermal, nuclear, biomass combustion, and electricity storage.

The transport sector technologies, for which parameters were shared across the models, identified the key transport modes to target for the decarbonisation of the sector, such as buses, cars, light trucks, medium trucks, commercial trucks, and heavy trucks. Each transport mode was characterised using conventional fuels (either petrol, diesel, LPG, or natural gas), biofuels (either ethanol, methanol, or hydrogen), or electricity (battery or hybrid vehicles). As a general assumption to move from a cost-per-vehicle to vehicle-km, an average travelled distance in Europe equal to 13,000 (light), 37,000 (medium), and 52,000 (heavy) km per year was assumed respectively for each class of truck.

The focus was on technologies such as CCS in cement and steel manufacturing for the industrial sector. For the modelling approach, we first harmonised the assumption on capture rate, which is a crucial harmonisation parameter to determine the increased costs of capital and operational for technology, as evident in power generation (Van Vuuren et al., 2017). Then, we harmonised cost assumptions from available studies which have disclosed their techno-economic assumptions (Gardarsdottir et al., 2019; Schorcht et al., 2013).

In the residential and commercial building sector, heating, cooling, and cooking display a wide fragmentation across the models. Benchmark values were defined by calculating the additional costs due to the relative improvements of advanced technologies compared to the corresponding standard technology. This implied a process of cost normalisation over efficiency. Only a high-level alignment of costs and performance was requested for this sector due to the significant uncertainty of the benchmark values and the large variability of the representation of the sector across the models.

Tables 10, 11, 12, 13, 14, and **15** provide a detailed list of technologies already represented in the IAMs used by the PARIS REINFORCE consortium. The bold shaded area indicates represented technologies, while a clear distinction can be made between sectoral or national models with global models. The former usually have more technological richness. This is obvious for sectoral models that concentrate on one sector by definition and can devote more effort to technological granularity. National and regional models usually have a more detailed representation of technologies based on domestic circumstances. For example, dedicated to Russia, CONTO describes the Fusion option in the electricity generation sector, following the long history of Russian research on this option.

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Within global models, one must differentiate between bottom-up models and top-down models. Top-down models are usually based on national account statistics with poor technological detail. That is the case for ICES and GEMINI-E3, with an exception for their electricity generation sectors. Modellers have contributed to integrating more technological detail through the GTAP Power database (Peters, 2016). This allows these CGE models to have a comparable technological detail for this sector as the one used by bottom-up models. Nevertheless, for the other sectors, especially the non-energy sectors (Industry, Building, Agriculture), the bottom-up models have a much more detailed representation of the technologies.

It is interesting to compare the technologies mentioned in these tables with the ones listed in Section 2. Negative emissions technologies like BECCS are already well represented in our set of models. But Direct Air Capture, Ocean Liming, and Biochar are not yet integrated (except in TIAM, which already includes CDR/NET technologies). Also, Hydrogen is already well represented in our models as a new energy carrier and end-use energy demand (like hydrogen fuel cell vehicles). Some disruptive technologies like hydrogen planes (TIAM) or electric planes (EU-TIMES, CONTO, and MUSE) are also considered.

Following our statistical findings that reflect stakeholder preferences elicited by the survey, priority to integrate technological innovation into mitigation pathway should be directed to Alternative Building Materials, Next-Generation Energy Storage, Hydrogen in Steel Making, and Iron Ore Electrolysis. Integrating Hydrogen in Steel Making and Iron Ore Electrolysis is feasible as FORECAST, CGAM, TIAM, and MUSE since these models have process heat hydrogen-based technologies represented in their industries (**Table 14**). On the other hand, the Alternative Building Materials is not well integrated, yet further representation in current IAMS remains feasible. A top-down model such as GEMINI-E3 or NEMESIS could apply a similar approach as Winchester and Reilly (2020) by disaggregating EII and creating a constructing sector, followed by replacing inputs of building materials of cement and steels with alternative low carbon materials such as woods. This is one way to improve technical granularity for those models.

Brainstorming and further discussions are also needed to integrate the Next-Generation Energy Storage. This technology is not explicitly integrated with current IAMs, yet supports the development of energy-source Electricity Generation sectors. Their role in current modelling scenarios is implicitly captured through technological cost assumptions that increase the efficiency of renewables' electricity generations. Keeping this approach requires deeper harmonisation of assumptions for further modelling; otherwise, a certain type of energy storage should be integrated as a separate technology.

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Table 10: Technologies captured by PARIS REINFORCE models in upstream technology

			Sectoral or national/regional models													Global models					
Sectors	**Technology Classification**	**Technology Type**	ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Upstream Technology	Synthetic Fuel Production	Coal to Gas with CCS																	■		■
		Coal to Liquids with CCS													■			■	■		
		Gas to Liquids with CCS									■								■		
		Biomass to Liquids			■						■		■		■			■	■		
		Biomass to Liquid with CCS									■				■			■	■		
		Bio. Gas Comb. Circle (BIGCC)																			■
		BIGCC with CCS																			■
	Hydrogen Production	Electrolysis			■			■			■		■		■			■	■		
		Coal to Hydrogen with CCS			■			■					■		■			■	■		
		Gas to Hydrogen with CCS			■			■							■			■	■		
		Biomass to Hydrogen with CCS													■			■	■		
		Nuclear to Hydrogen			■																
		Thermal Splitting (Nuclear)													■						
		Fuel Cells																			■

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Table 11: Technologies captured by PARIS REINFORCE models in electricity generation

Sectors	Technology Classification	Technology Type	Sectoral or national/regional models											Global models							
			ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Electricity Generation	Electricity	Coal with CCS																			
		Gas with CCS																			
		Nuclear Fission																			
		Nuclear Fusions																			
		Hydro																			
		Biomass																			
		Biomass with CCS																			
		Geothermal																			
		Solar PV																			
		Solar CSP																			
		Onshore Wind																			
		Offshore Winds																			
	Heat	Coal with CCS																			
		Gas with CCS																			
		Oil with CCS																			
		Geothermal																			
		Biomass																			
		Biomass with CCS																			

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Table 12 Technologies captured by PARIS REINFORCE models in transport

Sectors	Technology Classification	Technology Type	Sectoral or national/regional models											Global models								
			ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Transport	Road	Gas (LNG / CNG) vehicles																			
		Hybrid electric vehicles																			
		Fully electric vehicles																			
		Hydrogen fuel cell vehicles																			
		Biofuels in fuel mix																			
		Efficiency																			
		Others																			
	Rail	Electric rail																			
		Hydrogen fuel cell rail																			
		Efficiency																			
		Other: Specify																			
	Aviation	Biofuels in fuel mix																			
		Hydrogen planes																			
		Electric planes																			
		Efficiency																			
		Other: Specify																			

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Sectors	Technology Classification	Technology Type	Sectoral or national/regional models												Global models						
			ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Transport	Shipping	Gas (LNG / CNG) vehicles				■		■			■								■	■	
		Hydrogen									■							■	■		
		Biofuels in fuel mix			■	■	■		■	■	■				■			■	■	■	
		Electric				■		■													
		Efficiency			■	■	■	■	■	■	■							■		■	
		Others																			
	Modal Shift				■		■		■	■			■		■		■	■			
	Other	Behavioural Changes			■		■				■		■		■	■	■	■			

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Table 13: Technologies captured by PARIS REINFORCE models in building

Sectors	Technology Classification	Technology Type	Sectoral or national/regional models											Global models							
			ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Building	Heating	Gas replacing oil / coal		■	■	■	■			■	■		■		■		■	■	■	■	
		Biofuels		■	■	■				■	■		■		■			■	■	■	
		Electricity		■	■	■	■	■		■	■		■		■		■	■	■	■	
		Hydrogen			■						■		■					■	■	■	
		Solar thermal		■	■	■	■			■	■		■					■	■	■	
		Building shell efficiency		■	■	■		■			■		■				■			■	
		Other																			
	Lighting	Efficient lighting		■	■	■			■	■	■		■				■	■	■		
	Appliances	Efficient appliances		■	■	■			■	■	■		■				■	■	■		
	Cooling	Electricity		■	■	■			■	■	■		■		■	■		■	■		
		Building shell efficiency		■		■					■		■								
	Other	Behavioural Changes		■	■		■				■		■		■	■		■			

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Table 14: Technologies captured by PARIS REINFORCE models in industry

			Sectoral or national/regional models											Global models							
Sectors	Technology Classification	Technology Type	ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Industry	Process Heat	Gas replacing oil / coal		■	■	■	■	■	■	■	■		■		■		■	■	■	■	
		Biomass		■	■	■	■	■		■	■		■		■			■	■	■	
		Hydrogen		■		■					■		■		■			■	■		
		Electricity		■	■	■	■	■		■	■		■		■		■	■	■	■	
	Machine Drives	Gas replacing oil/coal		■	■		■				■		■				■	■	■	■	
		Electricity		■	■		■				■		■				■	■	■	■	
	Steam	Gas replacing oil/coal		■	■	■	■			■	■		■				■	■	■		
		Electricity		■	■	■	■			■	■		■				■	■	■		
	CHP	Gas replacing oil/coal		■	■	■			■	■	■		■		■		■	■		■	
		Biomass		■	■	■			■	■	■		■		■		■	■	■	■	
	Overall Industry	CCS		■	■	■					■		■					■	■		
		CDR/NETs																■			
	Other	Behavioural Changes		■	■		■				■		■			■	■	■			

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Table 15: Technologies captured by PARIS REINFORCE models in agriculture and LULUCF

Sectors	Technology Classification	Technology Type	Sectoral or national/regional models											Global models							
			ALADIN	FORECAST	JRC EU-TIMES	LEAP	NEMESIS	CONTO	MARKAL	MAPLE	NATEM	SISGEMA	TIMES-CAC	DICE	GCAM	ICES	GEMINI	TIAM	MUSE	42	E3ME
Agriculture	Energy Use	Gas replacing oil / coal				■	■	■			■		■				■	■	■	■	
		Biomass				■	■	■			■		■					■	■	■	
		Electricity				■	■	■	■		■		■				■	■	■	■	
	Land Practices	Land yield maximisation													■						
		Organic fertilizer use																			
		No tillage																			
		Agroforestry																			
	Animal husbandry practices	Improved feeding practices									■				■						
		Manure management									■										
		Feed additives									■										
	Other	Behavioural Changes				■					■		■		■	■	■	■			
LULUCF		Afforestation				■						■	■		■			■	■		
		Land protection										■			■				■		
		Biomaterials													■						

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4.2 Integration of behavioural change into IAMs

Although the focus on demand-side solutions is increasing lately (Creutzig et al. 2019), research on climate change mitigation is still too much focused on supply-side technological solutions (Creutzig et al. 2018). However, several studies point out that achieving net-zero emissions in the middle of our century would require a significant transformation in the energy supply system and concurrent efforts on the demand side through behavioural changes.

In line with this, our survey results regarding non-technological innovation appear to be more homogeneous across all three evaluation criteria. Experts' assessment indicates the likelihood for positive mitigations potentials among almost all non-technological innovations. This implies that scenarios with non-technological innovations must be explored, especially for mobility (which respondents assessed as top-priority). Also, options related to electricity demand, such as demand-side management and smart grids, need to be integrated. Several IAMs, such as EU-TIMES, CGAM, and TIAM offer better representation with potential integration of these game changers in their transportation and energy sectors. For others, integrating these non-technological innovations remains a challenge.

Yet the survey results enhance a growing need to integrate behavioural changes into IAMs, in order to build bridges between social sciences (psychology, sociology), economics, political sciences, and energy system modelling, but also to provide a tractable research agenda between all these disciplines. The International Energy Agency (IEA 2020b) emphasises equally significant roles of non-technological innovations in achieving net-zero emissions besides energy efficiency, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy, and CCUS. Behavioural change is a key pillar of decarbonisation in the roadmap to net-zero by 2050 (IEA 2021). Trutnevyte et al. (2019) and Nikas et al. (2020), emerging from the NAVIGATE and PARIS REINFORCE projects respectively, also advocate for integrating social transformations in IAMs and propose a research plan based on interdisciplinary and transdisciplinary approaches. Literature on how to overcome these limitations is reviewed in the following subsection.

4.2.1 Building narratives

Integration is one of the strategies proposed by Trutnevyte et al. (2019). An illustrative example is the SSP narratives (Riahi et al., 2017). Different qualitative storylines integrating socio-economic development, sustainable development, inequality, and others are derived from quantitative input assumptions that define different scenarios. Among the SSP scenarios, SSP1 "Sustainability (taking the Green Road)" already integrates into its definition a behavioural change dimension that contributes to a global decoupling of energy demand from economic growth (Van Vuuren et al., 2016). These behavioural changes are present in three areas: residential, transport demand, and food consumption. In residential buildings, behaviour changes lead to less energy consumption for heating, cooking, and appliances. The SSP1 assumes fewer kms travelled and low penetration of faster modes associated with public transport and car-sharing preferences in the transport sector. At the same time, higher environmental and health concerns result in a dietary change to less meat-intensive diets.

It is interesting to highlight that most of these behavioural changes have been applied to a solution on the demand side, and few of them consider the supply side, where the focus is dedicated to technological diffusion. IEA (2021) noticed that companies could indirectly influence behavioural changes by promoting the use of public transport by employees and encouraging working from home. The most promising changes are probably to be expected in the way the production is organised: reuse of material, reorganisation of the supply chains, and the circular economy could merit additional consideration in the narrative constructions. For example, IEA (2020b) indicates that material efficiency strategies in the industry sector can reduce by 15% its direct emissions.

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Several IAMs use this methodology to analyse the impact of behavioural change on decarbonisation pathways. Van de Ven et al. (2018) use the GCAM model to assess the potential climate mitigation by behavioural change in the European Union. They compute from various studies the impacts of these changes on food mobility and housing demand. All these changes come from a voluntary approach by households without any costs. These impacts are translated into exogenous assumptions that are then integrated into GCAM. They find that modest to rigorous behavioural change could reduce accumulated European GHG emissions from 2011-2050 by 6% to 16%. The emissions decrease would contribute to reducing the EU mitigation costs by 13.5 to 30%.

Using the IAM IMAGE, Van Sluisveld et al. (2016) study the impact of lifestyle changes in mitigation scenarios. Again, they assume different sets of exogenous assumptions regarding the household (space occupied per capita, heating, appliance use, waste management) and transport domains (reduced vehicle use, shift to public transport, preference for slower modes) calibrated from existing studies. They simulate a 2-degree global warming scenario with and without lifestyle changes. By 2050, they find that the measures will reduce CO_2 emissions in the residential sector by about 13% and in the transport sector by approximately 35% compared to baseline emissions. But the lifestyle changes considered in this study are on their own insufficient to meet the 2 °C climate objective. Stehfest et al. (2009) use the same IAM (i.e., IMAGE) and the same methodology to analyse the impact of dietary change on ambitious climate policies.

In Pedinotti-Castelle et al. (2021), the authors study a "behavioural disruption scenario" consisting of a massive deployment of carpooling in Quebec (Canada), using the TIMES Energy framework. Their results highlight that a behavioural disruption can lead to the same GHG emission reductions (65%) by 2050 as an electrification policy.

4.2.2 Social science approaches in energy modelling

Mitigation pathways require a transformation in both energy supply and demand. Interaction between technology, economy, environment, policy and society are elemental in developing mitigation pathways to reach lower than two degrees at the end of the century. However, transformation in demand is mainly underrepresented as modelling practice focuses predominantly on the supply-side action space (Wilson et al., 2012). Despite certain factors that affect demand, such as values, choices, cohesion, culture, and lifestyle shift in society are indirectly narrated as assumptions (O'Neill 2017). Still, their interactions with technological flows and economic and environmental policies are minimal (Grubler 2018).

The study by Nikas et al. (2020) points out the importance of framing human choices and behaviours in influencing the energy transition. The first fundamental factor lies in understanding the diffusion of social innovations on an aggregated scale. People's social relations affect energy demand. While drivers of behavioural changes embodied in energy used, such as cuts in electricity and heat, building and transportation, influence energy sufficiency with potential escalation impacts at the industrial level. These interactions between key characteristics of behaviour affect heterogeneity in consumers' decisions. Computational modelling, especially IAMs, can play an influential role in simulating the decision-making processes of heterogeneous decision-makers (with different objectives, search strategies, and decision methods) in the energy system (Sach et al., 2019).

The second factor covers initiative-based learning to understand expectations and strategies of energy transitions. It includes evaluating how people perceive and contribute to transitions' complexities, such as the representation of global economic pathways, on different time and social scales. This also co-develops cutting-edge knowledge with societal end-users in combining horizontal (across diverse social groups, across space) and vertical (across time) towards shared futures on climate change from an interdisciplinary perspective. The underlined point is how theoretical modelling can provide a conditionally valid approximation to social changes.

In addition to orienting on different magnitudes of lifestyle changes across a diverse set of dimensions and

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socioeconomic groups, framing social sciences in the energy transition also needs to incorporate the criticisms and shortcomings of the current generation of models, in both the supply (Gambhir et al., 2018) and the demand side (Farmer et al., 2015). For instance, modelling work should distinguish voluntary behavioural changes from changes due to policy implementation—e.g., how people adapted to the COVID-19 reality and what part of this new norm was enforced by the policy response.

The application of this social science approach is reflected in Trutnevyte et al. (2019). The study introduces a "bridging strategy" as an option for a better representation of household behaviour in the model. There have been several attempts to bridge strategy, such as done by the model family MARKAL/TIMES (Loulou and Labriet, 2008).

One example is Fragnière et al. (2017) who link a MARKAL model with a sociological survey. The aim is to represent better household behaviours, which are exogenous and described through "energy service demands." Other approaches have been tested to make these demands endogenous, like TIMES elastic (Loulou and Lavigne, 1996) or by linking the Bottom-Up model with a Top-Down model (Labriet et al., 2015). The method combines technical methods from operations research with behavioural approaches from social sciences. This is called Metamodel, where a classical energy model and *share of choice* model (from a sociological survey) are coupled. Then, this is combined with the bottom-up model.

A bridging strategy is also done by Cayla and Maïzi (2015), who worked on integrating household behaviour and heterogeneity into the TIMES model. They also link surveys reflecting household energy demand in building and transportation. Focusing on France, they contend that this method can specifically address demand-side policies and low-carbon policies in household behaviour.

Costa et al. (2021) develop a new type of IAM, aiming for more transparent approaches to address the challenge of reducing carbon emissions. The model called EUCALC represents energy, resources, production, and food systems at the EU27, the UK, and Switzerland under pre-defined (but adjustable) levels of ambitions regarding technological deployment and consumption behaviour. These pre-defined adjustable levels called *lever* correlate with four lifestyle domains (travel, homes, diets, and consumption). In the travel domain, pre-defined adjustable levels cover the average distance of travel, mode of undertaken transport, occupancy, and utilization rates. Space becomes elemental scope in the home domain, where space occupancy, appliances, and cooling/ heating system are critical l*evers*. Diet and consumption domains are closely related, where the first particularizes in calories demand. The consumption domain is broader, covering the substitution rate of foods, travel, and energy-intensive products.

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5 Conclusion

Achieving the Paris Agreement goals and increasing climate ambition depend on rapid decarbonisation in all sectors. Reaching the target of net-zero emissions in 2050 requires transformative innovations of low-carbon technologies and fundamental changes to current lifestyles. Technological innovation is crucial to achieving the net-zero emission target. Also, the non-technological aspects of behavioural changes, such as reducing transport demand, are essential yet often neglected in modelling deep decarbonisation pathways.

This deliverable identifies and evaluates transformative innovations for a deep decarbonisation pathway through a worldwide online survey on selected technological and non-technological low-carbon innovations targeted to climate and energy experts. These technological innovations were selected based on their TRL and cover the transportation, industry, building, construction sectors, and technologies related to negative emissions. The non-technological innovations belong to disruptive and sustainable actions that trigger fundamental shifts in societal and individual behaviour affecting decarbonisation pathways. These include innovations on changes in mobility, building and interconnectivity, food consumption, and energy distribution.

For technological innovations, elicited perceptions show divergence in mitigation potential and likelihood/capacity to be part of deep decarbonisation pathways. Next-Generation Energy Storage, Alternative Building Material, Iron Ore Electrolysis, and Hydrogen in Steelmaking appear instrumental technologies, with respondents prioritising them. CCS and BECCS, typically emphasised in modelled net-zero emissions pathways, are found to have significant potential mitigation, but later (2040s). Ocean Liming Hyperloops, Nuclear Fusion, and DAC are expected to be unavailable before mid-century.

In contrast, survey results for non-technological innovations appear to be more convergent in terms of mitigation potentials, timing, and risks. Respondents indicated high likelihood of positive mitigation potential for almost all non-technological innovations considered in the study/survey.

These survey results provide elemental feedback for further modelling development. Despite representative technologies with a wider description being identified and shared across all models, the Current Policies and NDC scenarios (Sognnaes et al., 2021; Nikas et al., 2021) have not yet identified any non-technological innovations defined in this deliverable. This implies that scenarios with non-technological innovations (behavioural changes) must be explored, especially for mobility, when seeking to identify Paris-compliant mitigation ways forward. Options related to demand, such as demand-side management and smart grids, also need to be highlighted in such scenarios. The current methodologies of Building Narrative to analyse the impact of behavioural change on decarbonisation pathways, or Bridging Strategy as an option for a better representation of household behaviour, should be the pivotal foundation to develop a more adaptive approach to integrating non-technological innovations into IAMs.

As PARIS REINFORCE draws from a strong core of numerous IAMs presenting technologies that already exist or are in development, the role of hydrogen-based technology in industrial sectors, next-generation energy storage, and decentralised energy supply must be further investigated for their central role in deep decarbonisation pathways. An adjustment approach in modelling is needed, following the experts' common perception of CCS and BECCS as valid mitigation options but with delayed contributions to emissions cuts. Scenarios that consider an immense contribution of these technologies need to be dwindled to incorporate contributions of other transformative innovations. Finally, technologies like DAC, Hyperloops, Ocean Liming, and Nuclear Fusion are unlikely to be available before the middle of the century, thus insignificant in developing mitigation scenarios to 2050.

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6 Appendix 1: Survey Questions

6.1 Page 1: Presentation of the Consortium and the survey

PARIS REINFORCE

A survey on game-changing innovations towards net-zero emissions in 2050

About Us

PARIS REINFORCE is an EU-funded research and innovation project aimed at effectively supporting the design of climate policies and scenario analysis to meet the Paris Agreement. It started in June 2019 and is expected to run until the end of 2022.

The project is focused on developing demand-driven scenarios on how the world and different regions can decarbonise, using integrated assessment modelling and a range of other analytical and stakeholder engagement tools.

One central aspect of our scenario design work is to understand the range of measures that could contribute to rapid decarbonisation. This includes those technologies commonly included in mitigation analysis, as well as, new "game-changing" innovations (technological, behavioural and societal) that could accelerate the pace and scale of the low-carbon transition.

This survey is designed to elicit a range of experts' views on these game-changing innovations.

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About the survey

The objective of this survey is to understand the range of new technologies and of disruptive low-carbon innovations that could contribute to deep decarbonisation by 2050.

The survey is intended to take no more than 15 minutes – we understand your time is valuable and thank you for using it to take part.

All results will be made publicly available and shared with participants.

Ethics of the survey

The information provided in this form (email address, working capacity, country, gender) is collected by the PARIS REINFORCE Project Consortium partners responsible for the organisation of this survey. These partners are the Energy Policy Unit of the National Technical University of Athens (EPU NTUA, https://www.epu.ntua.gr/), École Polytechnique Fédérale de Lausanne (https://www.epfl.ch/labs/leure/), Grantham Institute of Imperial College London (https://www.imperial.ac.uk/grantham/), SEURECO (http://www.erasme-team.eu/), and Bruegel (https://www.bruegel.org/). This information will be used only in relation to this specific survey and as follows. The email address will be used to communicate information related to the outcomes of the survey (if the participants select to), as well as to ensure the survey has been filled in once per participant. Working capacity, country, and gender will be used for aggregated statistics on the participants and for differentiated the analysis of the results.

The anonymised survey results will be used in the scientific process of the PARIS REINFORCE research project, for the purposes of designing scenarios on game-changing technological, economic, and societal/behavioural innovations that respond to the needs identified by stakeholders, and therefore serve to enhance the societal/policy relevance and co-ownership of the produced outputs. The anonymised survey results may also be published as part of the peer-reviewed paper(s) documenting the scientific process and results.

The personal information included in the primary source of data (the survey's results) will be held for up to four years after the end of the PARIS REINFORCE Project based on its contractual obligation with the EC (30/11/2022), after which, they will be removed from the data set. In accordance with articles 14-17 of the EU-GDPR, we inform you that you have the right to access, rectify, delete or restrict the processing of your data at any time. You may withdraw this consent at any time. You may place any such request or ask for more information by emailing contact@paris-reinforce.eu, paris@epu.ntua.gr, or the Data Protection Officer of EPU NTUA from https://www.epu.ntua.gr/contact.

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6.2 Page 2: About the respondent

About you

Please indicate your e-mail (Your e-mail will not be shared with anybody, nor used to publicly attribute your responses to you. All responses will be treated anonymously.) *

Votre réponse

Please select the category that best describes your current working capacity. *

- ◯ Academia/Research
- ◯ Private Sector/Industry
- ◯ National Government
- ◯ Regional/Local Government
- ◯ International Institution
- ◯ NGO
- ◯ Press
- ◯ Civil society
- ◯ Autre : ____________

Please select your country *

Sélectionner ▾

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What is your gender? *

- ◯ Female
- ◯ Male
- ◯ I prefer not to say
- ◯ Autre :

6.3 Page 3: Backgound information

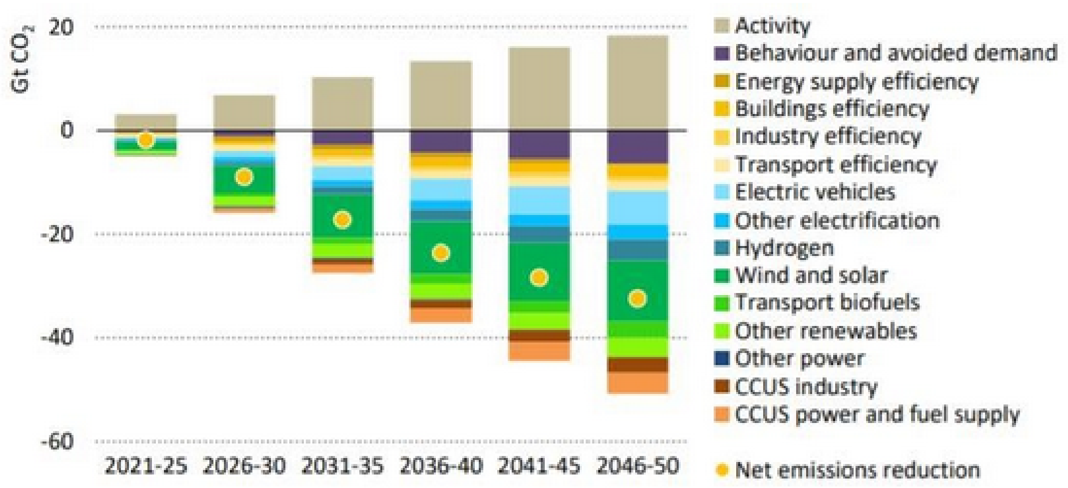
Background

In its recent Net-Zero pathways analysis, the IEA (2021) highlights the role of existing technologies (solar, wind, biofuels, heat pumps, etc...) and of early stage technologies (hydrogen aviation, next generation batteries, etc...) to fully decarbonise the global energy sector, with the latter covering almost half of the total emissions reductions required to achieve net-zero.

Below, we list three groups of technologies:

1. The principal technologies that are commonly included in low-carbon pathways analysis, which are mostly already commercially available.
2. Additional technologies which are increasingly being looked into as part of low-carbon pathways, but which are at an earlier stage of development.
3. Other disruptive low-carbon innovations, which are in general less technological-based, but which cover behavioural changes, market design and new business models.

Average annual CO2 reductions from 2020 in the Net Zero Emission



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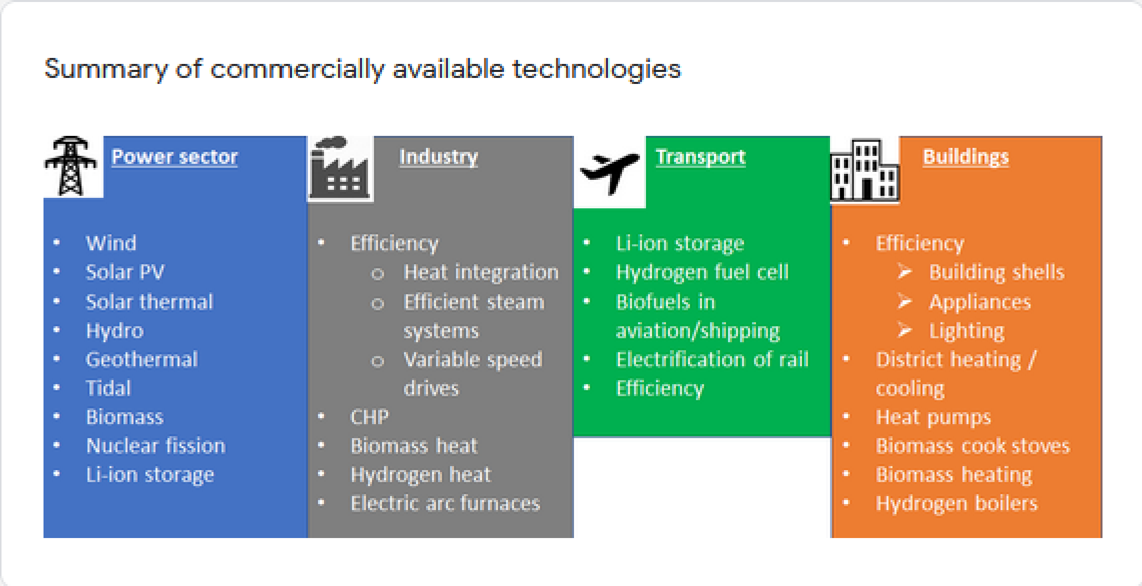
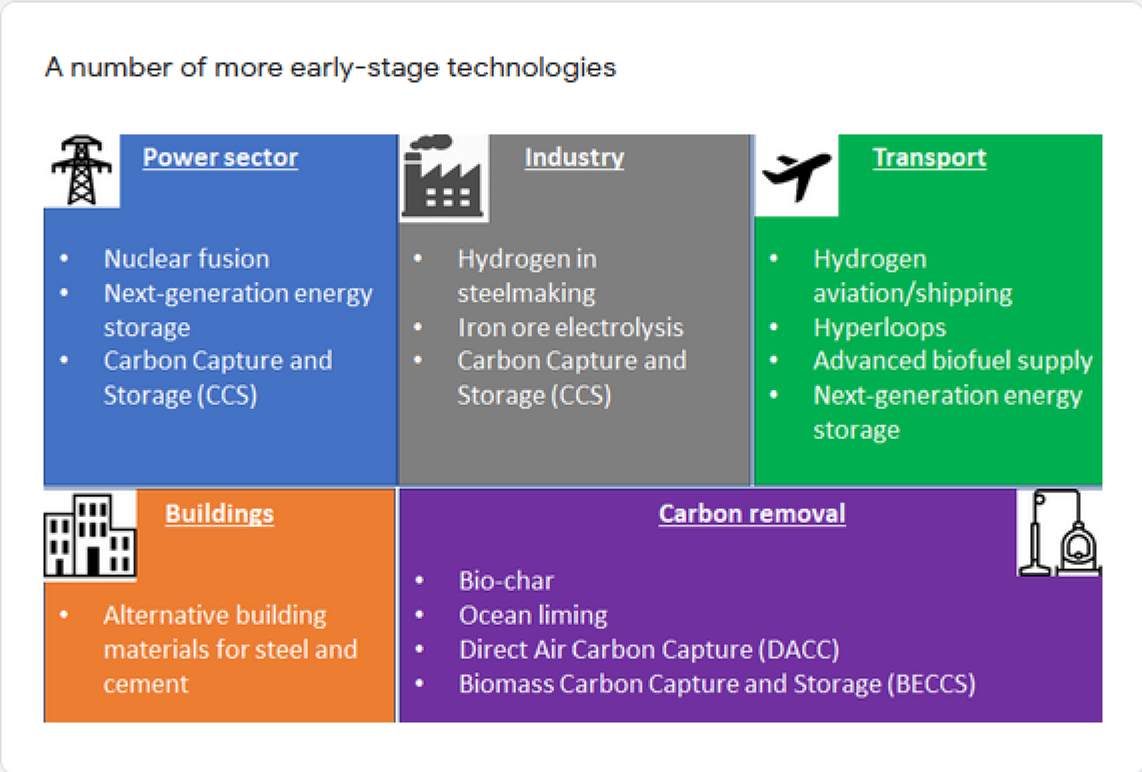
Source

IEA (2021), Net Zero by 2050 - A Roadmap for the Global Energy Sector, IEA, Paris.





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A number of other disruptive low-carbon innovations are also being looked into

Mobility

- 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.)

Buildings

- Interconnectivity for optimised usage (smart appliance, LED, smart homes, etc...)
- Optimisation of buildings thermal performance (Home energy management systems, smart heating controls, etc..)
- Reduced demand for space and materials (sharing)

Food

- Alternative dietary preferences (Reduced meat diet, etc.)
- Urban food production (own food growing, community farms, etc.)
- Producer-consumer relationships (local food distribution, etc...)
- Reduced demand for food (Food waste reduction, etc...)

Energy supply & distribution

- 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 + storage, Micro-wind turbines, etc...)

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Sources

The list of early-stage technologies is based on:

1. Napp et al., 2019a, "A survey of key technological innovations for the low-carbon economy", Grantham Institute - Climate Change and the Environment, Imperial College London, paper provided to the OECD in the context of the project "Growth, investment and the low carbon transition"
2. Napp et al., 2019b, "The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets", Applied Energy, 238(351-367). doi: 10.1016/j.apenergy.2019.01.033.

The list of other disruptive low-carbon technologies is based on Wilson et al., 2019, "The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation", Energy Efficiency, 12(423-440). doi: 10.1007/s12053-018-9679-8

6.4 Page 4: Mitigation technologies related questions

Survey: Mitigation technologies

In this section, we ask three questions about technologies which are at earlier stages of development or which are currently more speculative, according to Napp et al. (2019a) and Napp et al. (2019b):

1. How do you perceive each technology's mitigation potential up to 2050?
2. When do you think each technology will be available commercially?
3. How big do you find the risk of a technology delaying or not being eventually available?

We deliberately avoid defining—e.g., in terms of absolute or relative emissions cuts—what constitutes a "very low", "low", "moderate", "high" or "very high" potential, but rather rely on your judgement of a technology's potential contribution to delivering on the Paris Agreement's temperature goals.

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

1. What is the mitigation potential of these technologies up to 2050? *

	Very low	Low	Moderate	High	Very high	Not able to respond
Aviation biofuels (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 procude iron)	○	○	○	○	○	○
Alternative building materials for steel and cement	○	○	○	○	○	○

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Biomass Carbon Capture and Storage (BECCS)	○	○	○	○	○	○
Bio-char (soil amendment resulting from the pyrolysis of biomass)	○	○	○	○	○	○
Ocean liming (addition of calcium oxide powder in oceans)	○	○	○	○	○	○
Direct Air Capture (e.g. soda/lime process)	○	○	○	○	○	○
Next-generation energy storage (Power-to-Gas, Flywheels, new batteries, etc...)	○	○	○	○	○	○
Nuclear fusion	○	○	○	○	○	○

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2. When do you think the technologies will be available commercially ? *

	By 2030	Between 2031 and 2040	Between 2041 and 2050	Post-2050	Never	Not able to respond
Aviation biofuels (biojet or renewable jet fuel)	○	○	○	○	○	○
Hydrogen aircraft	○	○	○	○	○	○
Hyperloops	○	○	○	○	○	○
Advanced biofuel supply	○	○	○	○	○	○
Carbon Capture and Storage (CCS)	○	○	○	○	○	○
Hydrogen in steelmaking	○	○	○	○	○	○
Iron ore electrolysis (to procude iron)	○	○	○	○	○	○
Alternative building materials for steel and cement	○	○	○	○	○	○

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Biomass Carbon Capture and Storage (BECCS)	○	○	○	○	○	○
Bio-char (soil amendment resulting from the pyrolysis of biomass)	○	○	○	○	○	○
Ocean liming	○	○	○	○	○	○
Direct Air Capture (e.g. soda/lime process)	○	○	○	○	○	○
Next-generation energy storage (Power-to-Gas, Flywheels, new batteries, etc...)	○	○	○	○	○	○
Nuclear fusion	○	○	○	○	○	○

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2. When do you think the technologies will be available commercially ? *

	By 2030	Between 2031 and 2040	Between 2041 and 2050	Post-2050	Never	Not able to respond
Aviation biofuels (biojet or renewable jet fuel)	○	○	○	○	○	○
Hydrogen aircraft	○	○	○	○	○	○
Hyperloops	○	○	○	○	○	○
Advanced biofuel supply	○	○	○	○	○	○
Carbon Capture and Storage (CCS)	○	○	○	○	○	○
Hydrogen in steelmaking	○	○	○	○	○	○
Iron ore electrolysis (to procude iron)	○	○	○	○	○	○
Alternative building materials for steel and cement	○	○	○	○	○	○

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Biomass Carbon Capture and Storage (BECCS)	○	○	○	○	○	○
Bio-char (soil amendment resulting from the pyrolysis of biomass)	○	○	○	○	○	○
Ocean liming	○	○	○	○	○	○
Direct Air Capture (e.g. soda/lime process)	○	○	○	○	○	○
Next-generation energy storage (Power-to-Gas, Flywheels, new batteries, etc...)	○	○	○	○	○	○
Nuclear fusion	○	○	○	○	○	○

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

3. What is the risk of non-availability or delay of these technologies? *

	Insignificant	Low	Moderate	Important	Critical	Not able to respond
Aviation biofuels (biojet or renewable jet fuel)	○	○	○	○	○	○
Hydrogen aircraft	○	○	○	○	○	○
Hyperloops	○	○	○	○	○	○
Advanced biofuel supply	○	○	○	○	○	○
Carbon Capture and Storage (CCS)	○	○	○	○	○	○
Hydrogen in steelmaking	○	○	○	○	○	○
Iron ore electrolysis (to procude iron)	○	○	○	○	○	○
Alternative building materials for steel and cement	○	○	○	○	○	○

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Biomass Carbon Capture and Storage (BECCS)	○	○	○	○	○	○
Bio-char (soil amendment resulting from the pyrolysis of biomass)	○	○	○	○	○	○
Ocean liming	○	○	○	○	○	○
Direct Air Capture (e.g. soda/lime process)	○	○	○	○	○	○
Next-generation energy storage (Power-to-Gas, Flywheels, new batteries, etc...)	○	○	○	○	○	○
Nuclear fusion	○	○	○	○	○	○

Please indicate any other technologies that we failed to mention in the above questions

Votre réponse

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

6.5 Page 5: Other disruptive low-carbon innovations related questions

Survey: Other Disruptive Low-carbon Innovations

In this section, we will ask you to share your opinion over possible disruptive low-carbon innovations that go beyond the predominantly supply-side technologies and fuels covered in the previous section. Here, we mainly orient on behavioural changes, new economic practices and business models, etc. (list based on Wilson et al., 2019):

1. How do you perceive each innovation's mitigation potential up to 2050?
2. When this innovation will take off?
3. What is the risk of never adopting this innovation?

Again, we choose not to define—e.g., in terms of absolute or relative emissions reductions—what constitutes a "very low", "low", "moderate", "high" or "very high" potential, but rather rely on your judgement of a measure's potential contribution to a decarbonised future.

1. What is the mitigation potential of these disruptive low-carbon innovations up to 2050? *

	Very low	Low	Moderate	High	Very High	Not able to respond
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 (Reduced meat diet, etc.)	○	○	○	○	○	○
Urban food production (own food growing, community farming, etc...)	○	○	○	○	○	○

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Producer-consumer relationships (local food distribution, food box deliveries, etc...)	○	○	○	○	○	○
Reduced demand for food (Food waste reduction, etc...)	○	○	○	○	○	○
Interconnectivity for optimised usage (smart appliance, LED, smart homes, etc...)	○	○	○	○	○	○
Optimisation of buildings thermal performance (Home energy management systems, smart heating controls, etc..)	○	○	○	○	○	○
Reduced demand for space and materials (sharing)	○	○	○	○	○	○

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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 + storage, Micro-wind turbines, etc...)	○	○	○	○	○	○

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2. When do you think these disruptive low-carbon innovations will take off? *

	Already taken off	By 2030	Between 2031 and 2040	Between 2041 and 2050	Post-2050	Never	Not able to respond
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 (Reduced meat diet, etc.)							
Urban food production (own food growing, community farming, etc...)							

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Producer-consumer relationships (local food distribution, food box deliveries, etc...)	○	○	○	○	○	○	○
Reduced demand for food (Food waste reduction, etc...)	○	○	○	○	○	○	○
Interconnectivity for optimised usage (smart appliance, LED, smart homes, etc...)	○	○	○	○	○	○	○
Optimisation of buildings thermal performance (Home energy management systems, smart heating controls, etc..)	○	○	○	○	○	○	○
Reduced demand for space and materials (sharing)	○	○	○	○	○	○	○

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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 + storage, Micro-wind turbines, etc...)	○	○	○	○	○	○	○

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3. What is the risk of these disruptive innovations never materialising/being adopted? *

	Very low	Low	Moderate	High	Very high	Not able to respond
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 (Reduced meat diet, etc.)	○	○	○	○	○	○
Urban food production (own food growing, community farming, etc...)	○	○	○	○	○	○

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Producer-consumer relationships (local food distribution, food box deliveries, etc...)	◯	◯	◯	◯	◯	◯
Reduced demand for food (Food waste reduction, etc...)	◯	◯	◯	◯	◯	◯
Interconnectivity for optimised usage (smart appliance, LED, smart homes, etc...)	◯	◯	◯	◯	◯	◯
Optimisation of buildings thermal performance (Home energy management systems, smart heating controls, etc..)	◯	◯	◯	◯	◯	◯
Reduced demand for space and materials (sharing)	◯	◯	◯	◯	◯	◯

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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 + storage, Micro-wind turbines, etc...)

Please indicate any other non-technological innovations that we failed to list in the questions above:

Votre réponse

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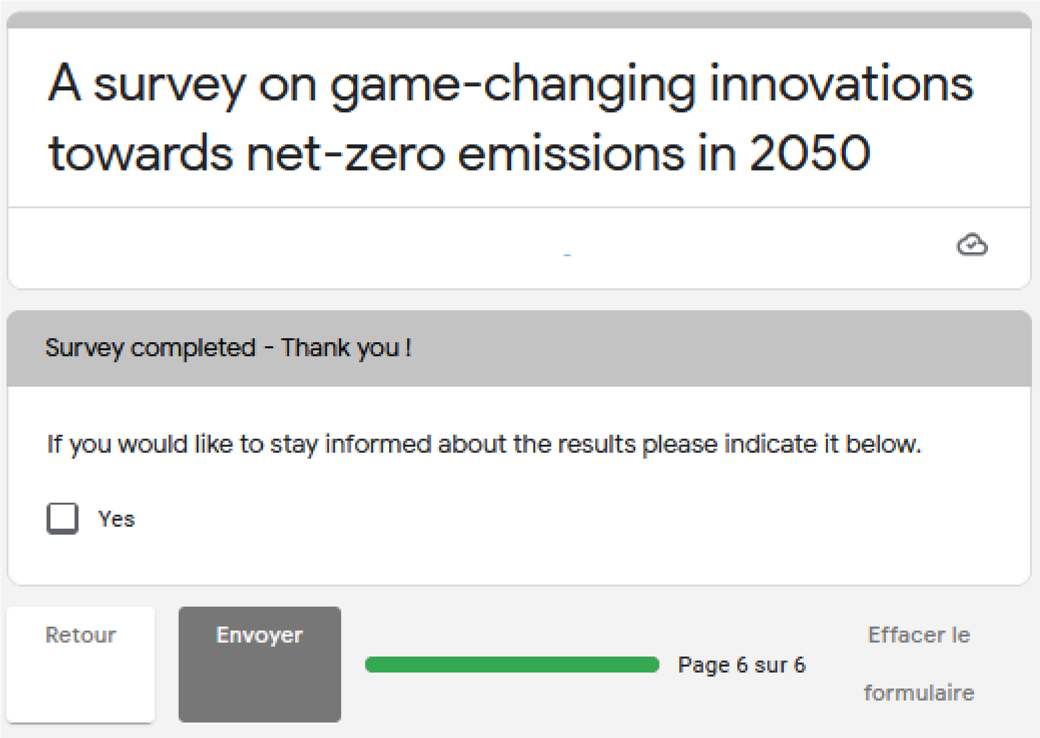
6.6 Page 6 : Submission part



A survey on game-changing innovations towards net-zero emissions in 2050

Survey completed - Thank you !

If you would like to stay informed about the results please indicate it below.

☐ Yes

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Envoyer

Page 6 sur 6

Effacer le formulaire

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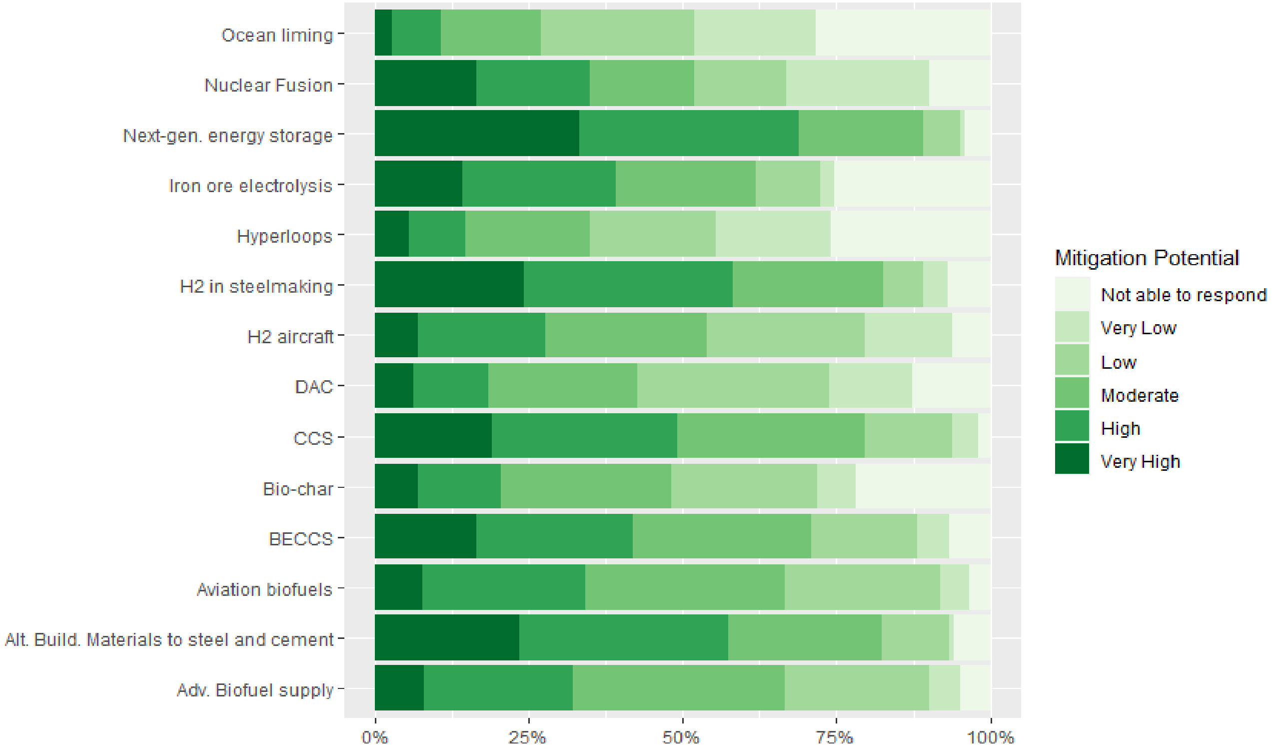
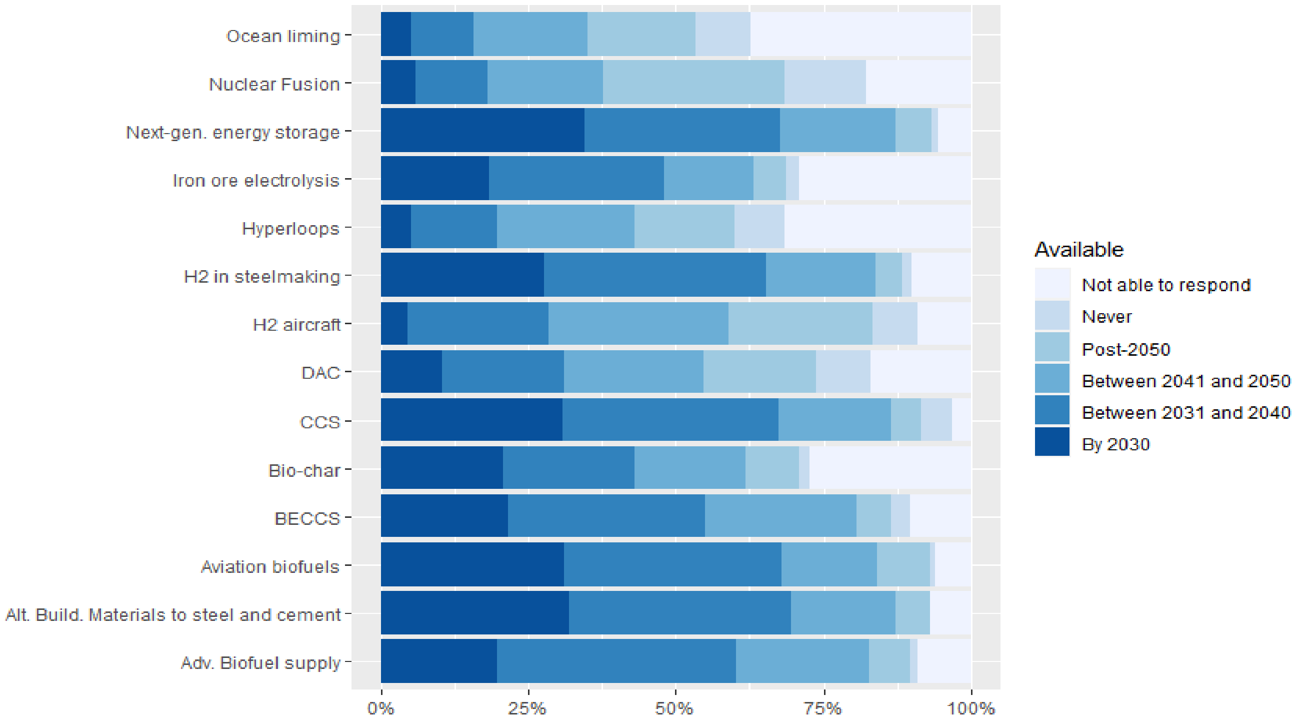
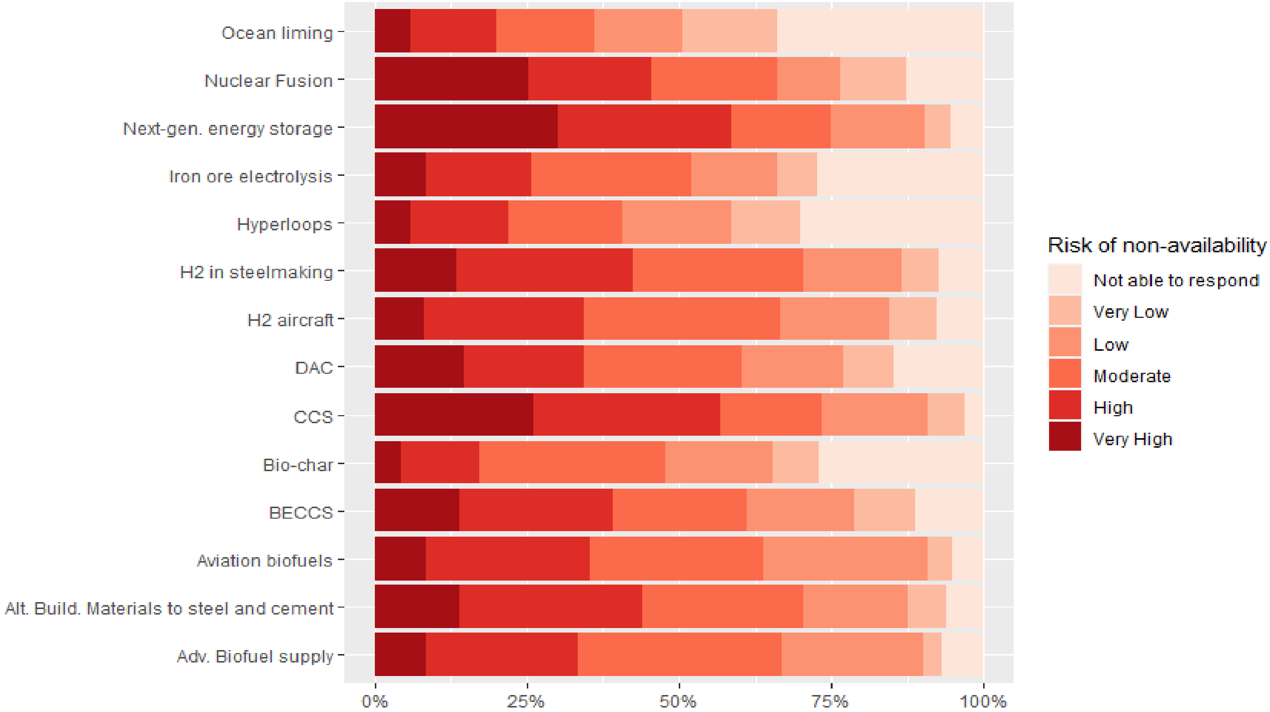
7 Appendix 2: Survey Responses

7.1 Stacked Bar Chart: Technological Innovations (All)

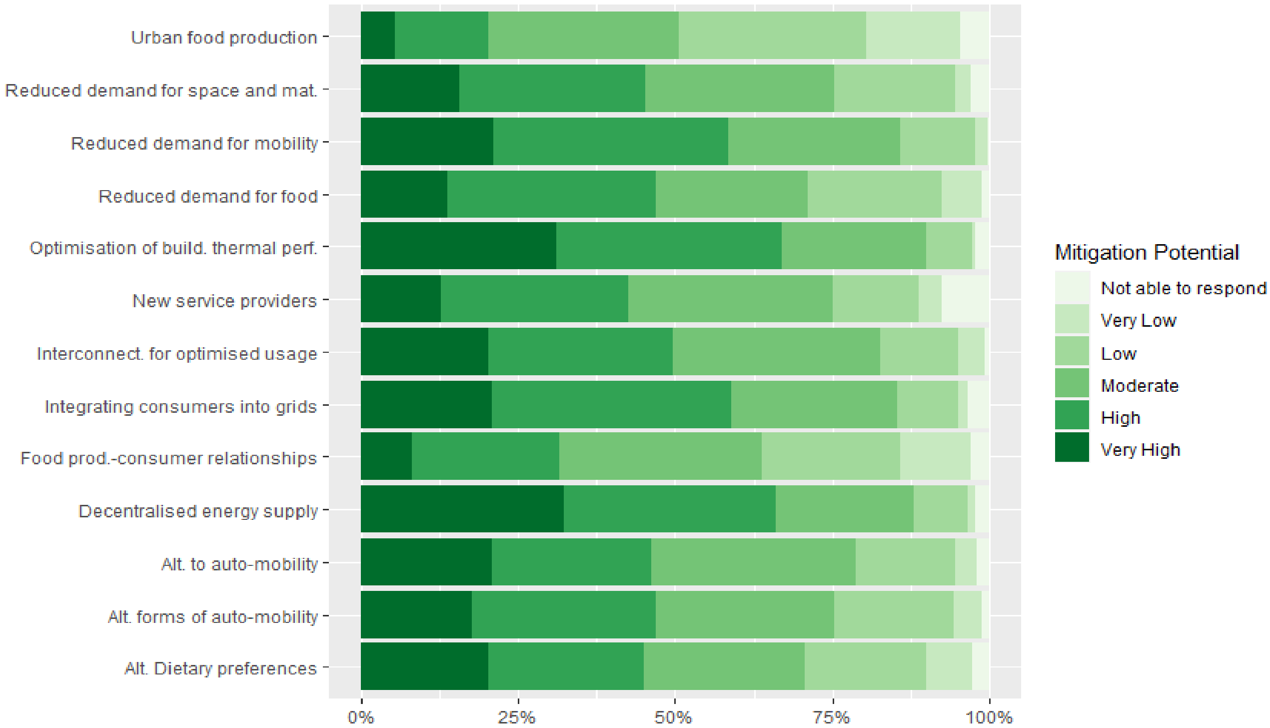




The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.



7.2 Stacked Bar Chart: Non - Technological Innovations (All)



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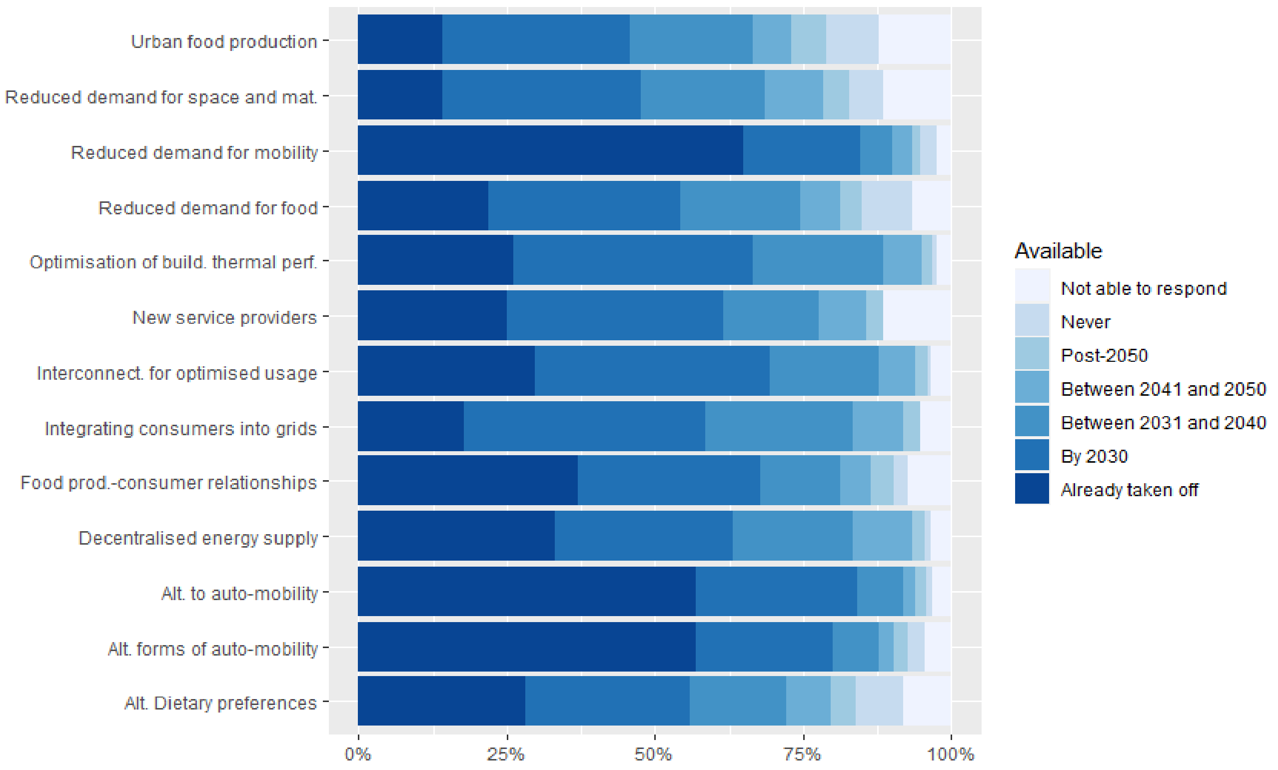

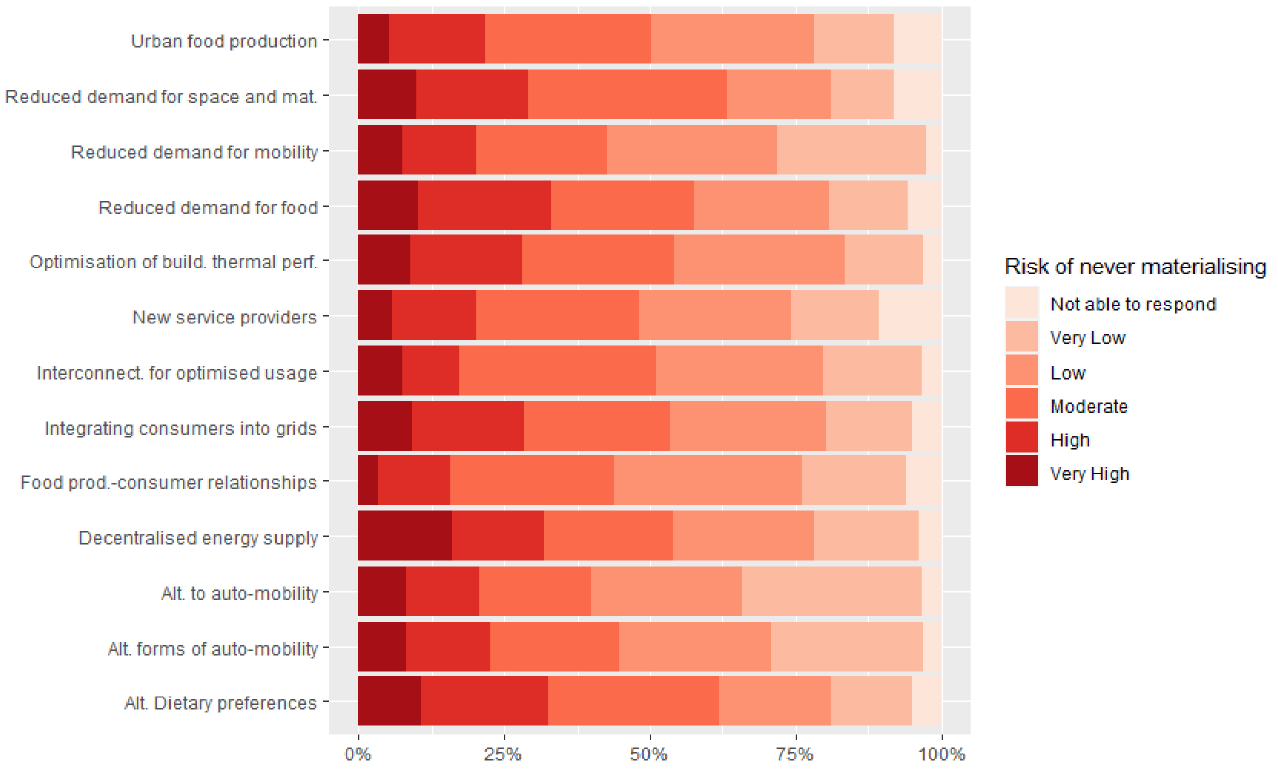

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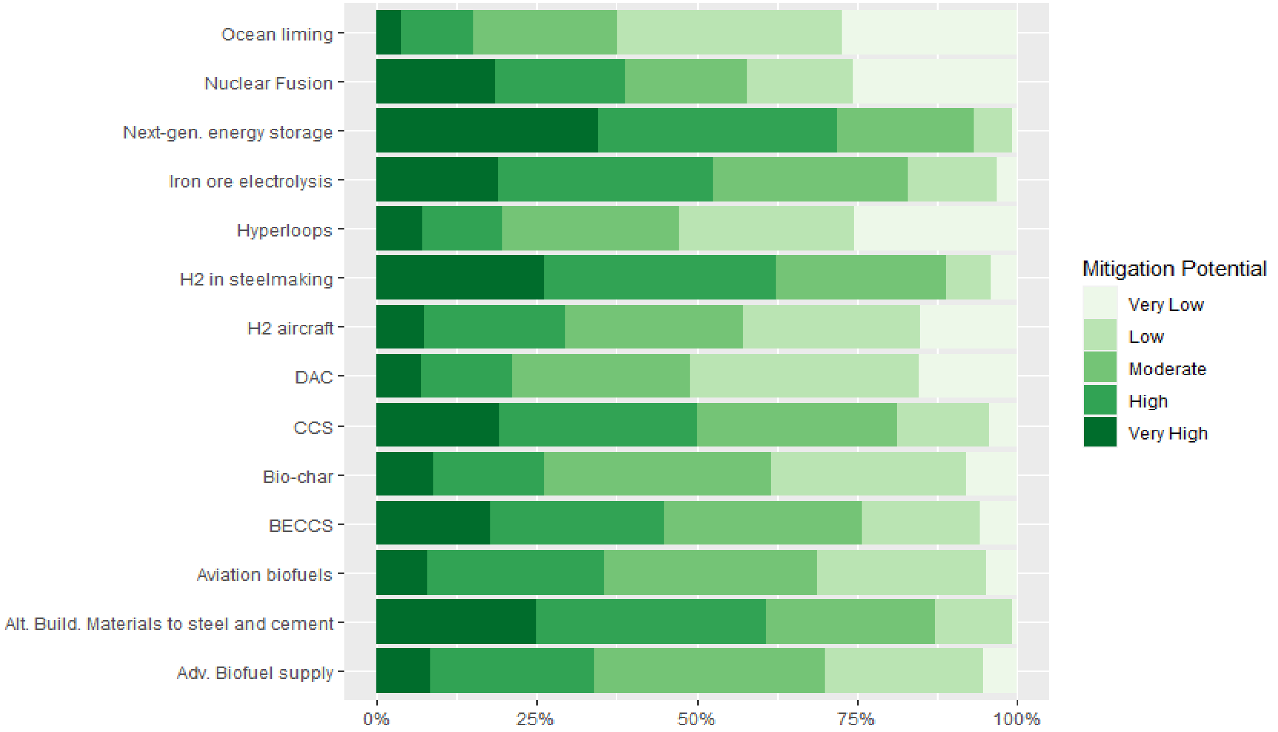
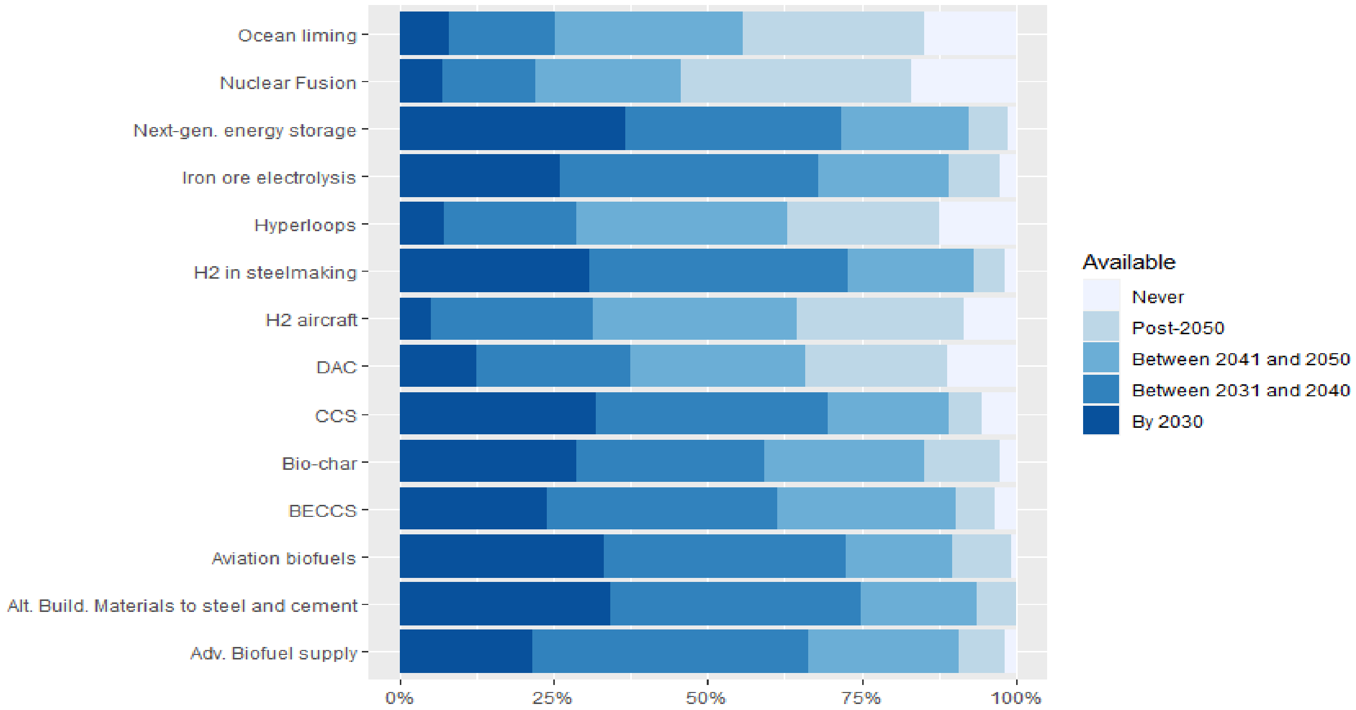
7.3 Stacked Bar Chart: Technological Innovations (NA-Handling)





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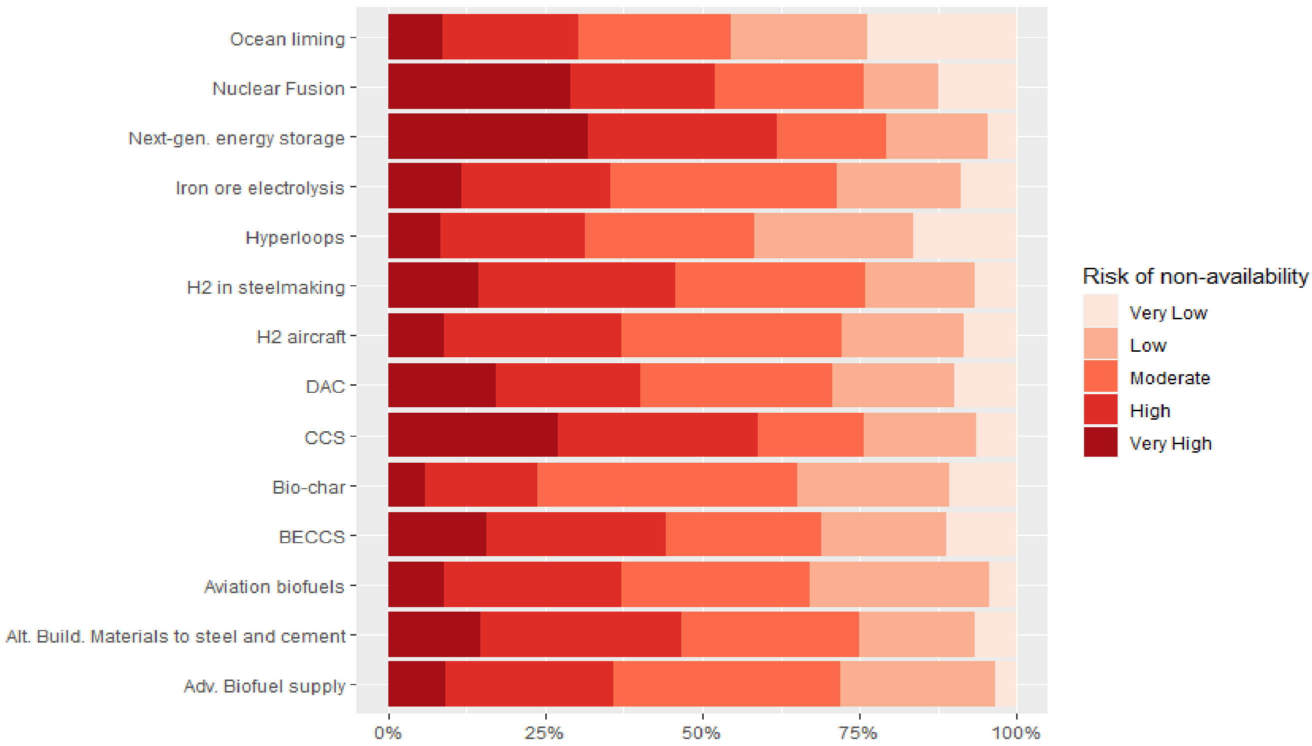
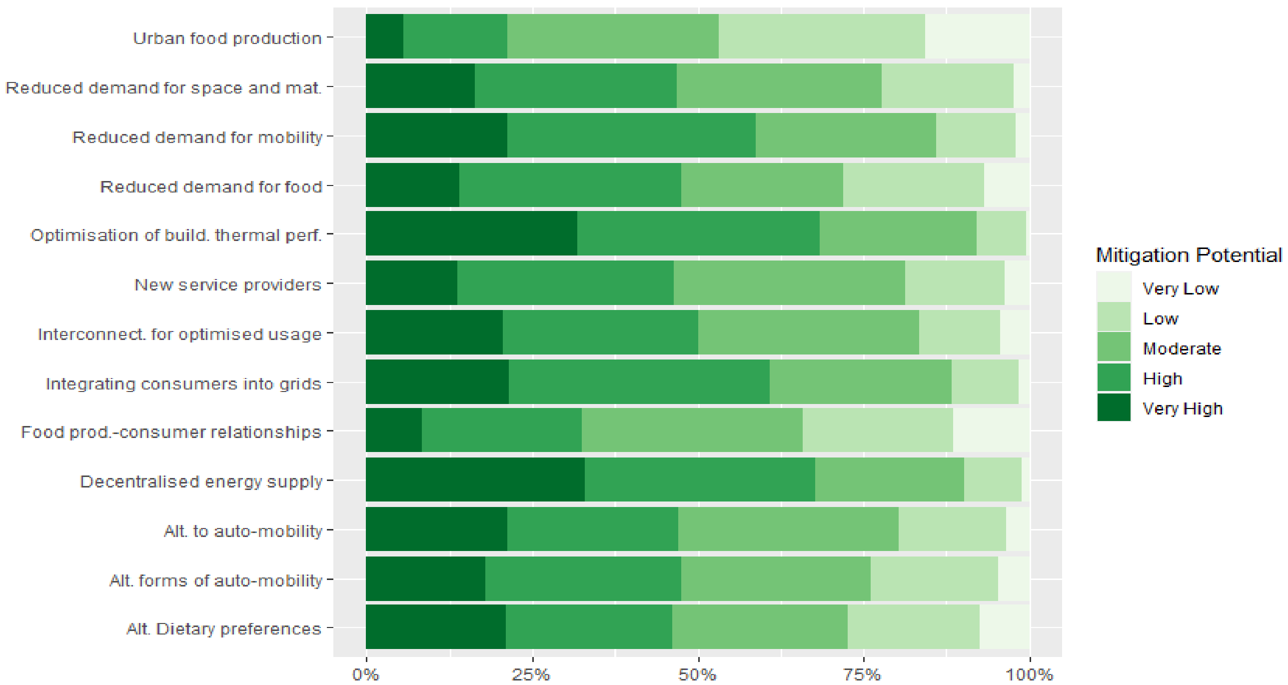


7.4 Stacked Bar Chart: Non-Technological Innovations (NA-Handling)



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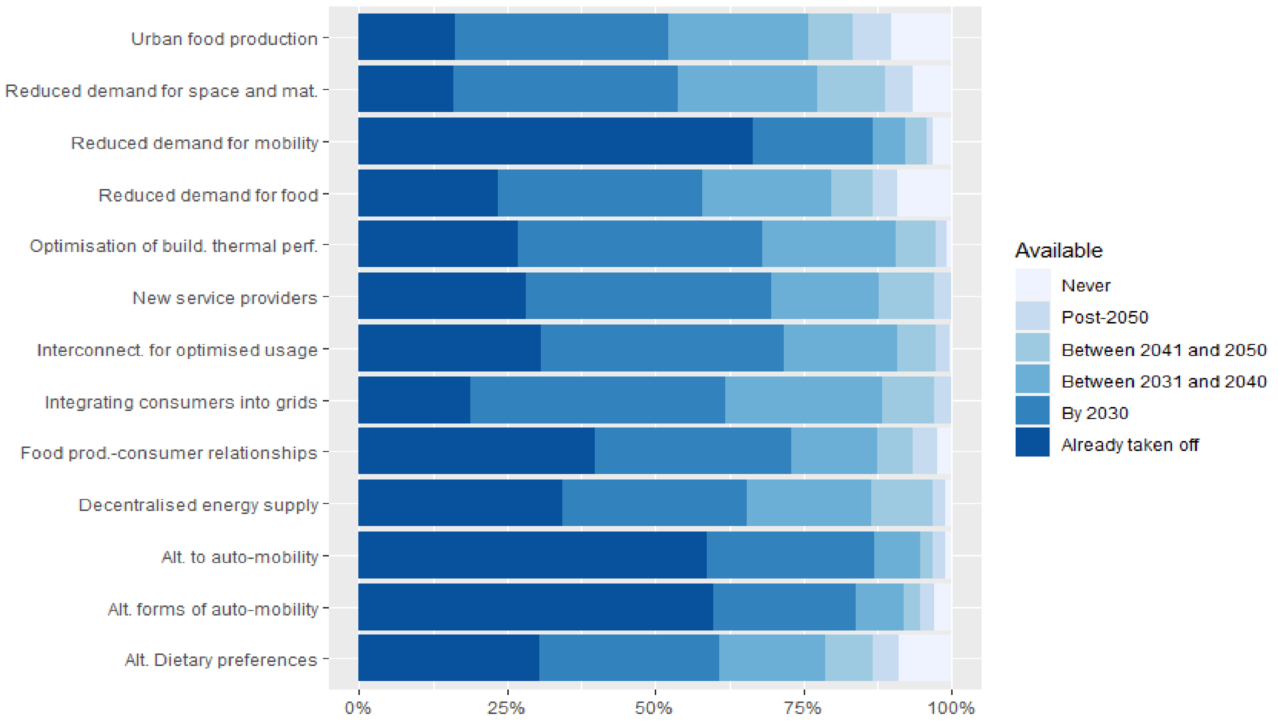

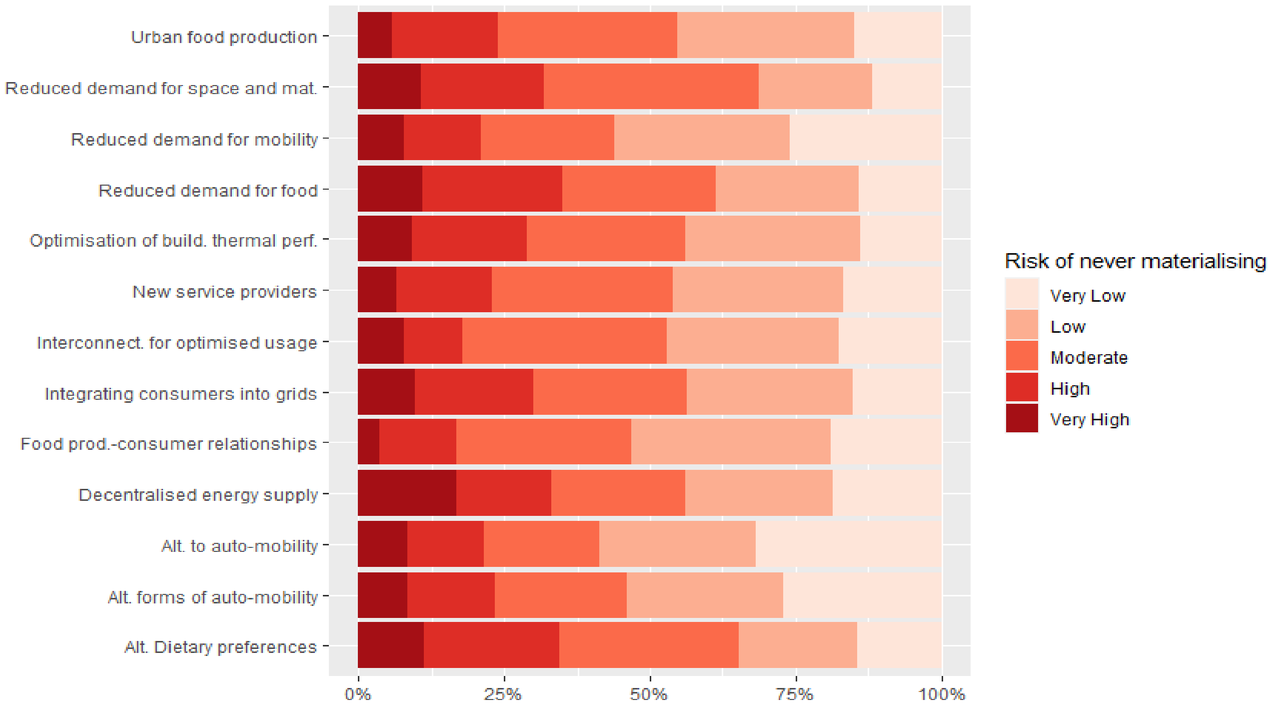

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8 Appendix 3: Numerical Scale of Survey Responses

Factors	Options	Scale
Mitigation Potentials	Very Low	-2
	Low	-1
	Moderate	0
	High	1
	Very High	2
Expected Adopting Time	Never	-
	Already Taken Off	2020
	By 2030	2030
	Between 2031-2040	2036
	Between 2041-2050	2046
	Post 2050	2075
Risk of Failure / Never Been Adopted	Insignificant/ Very Low	-2
	Low	-1
	Moderate	0
	Important/ High	1
	Critical/ Very High	2

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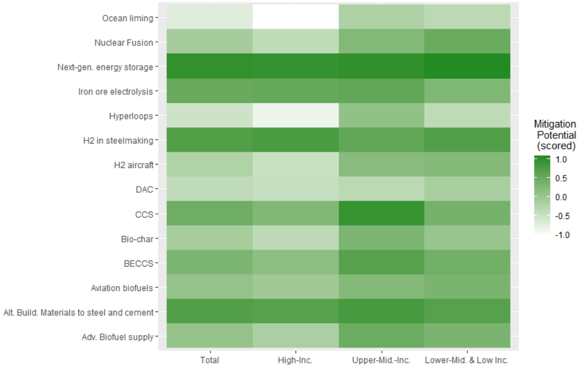
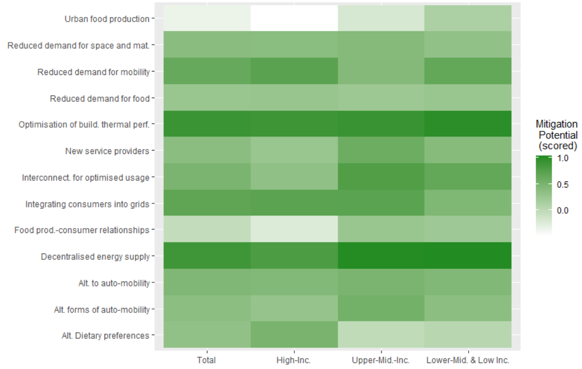
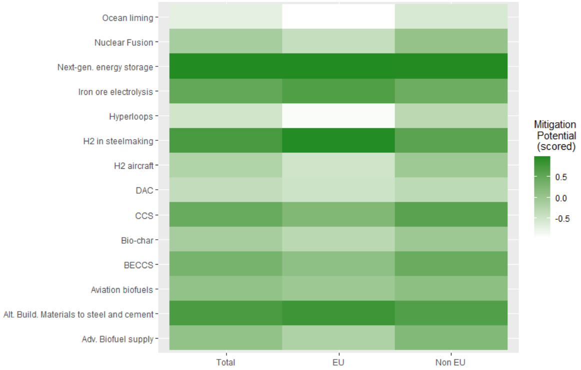
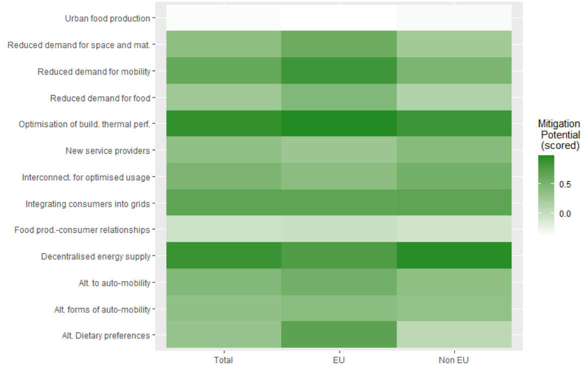
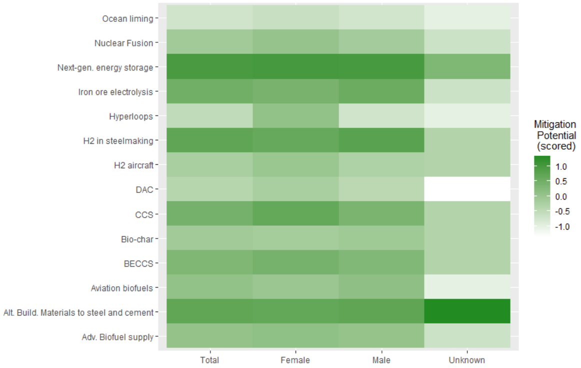
9 Appendix 4: Respondents' Responses Distribution

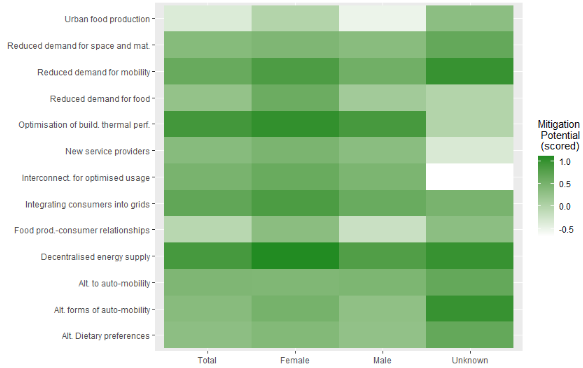


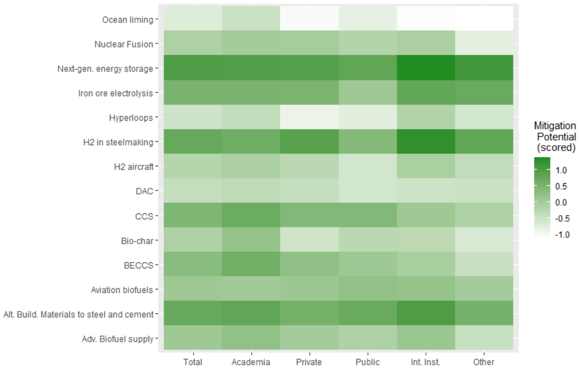


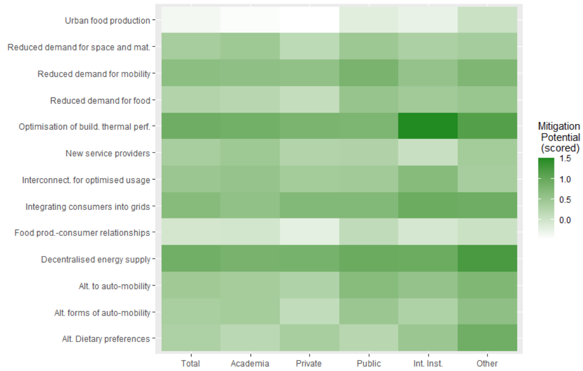












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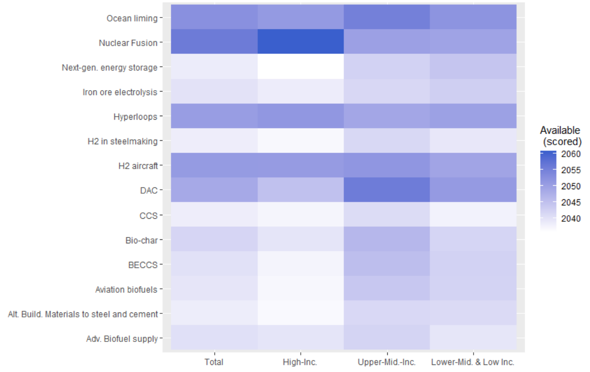

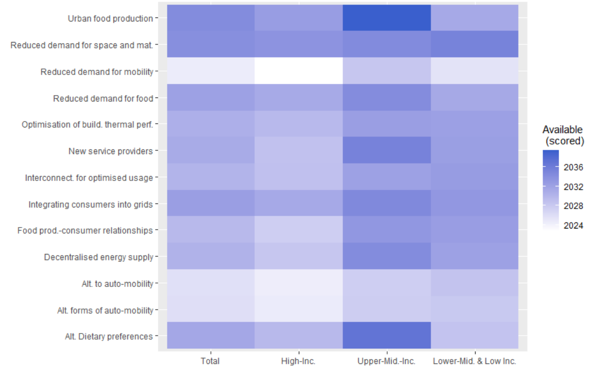

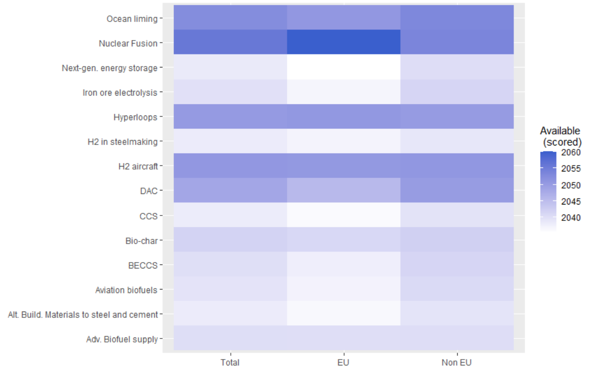

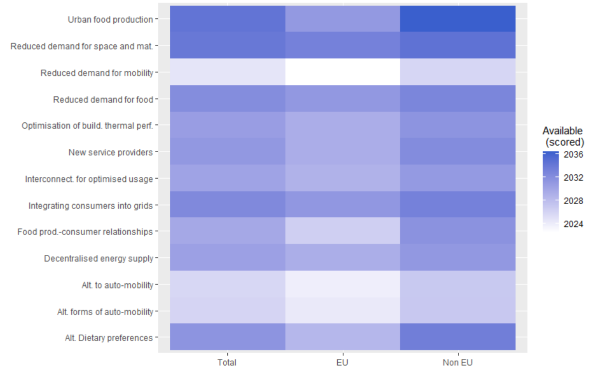

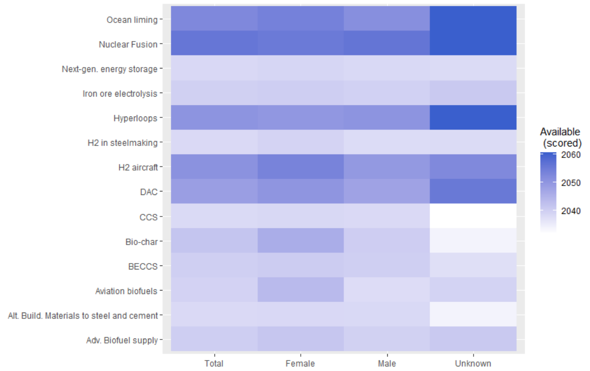

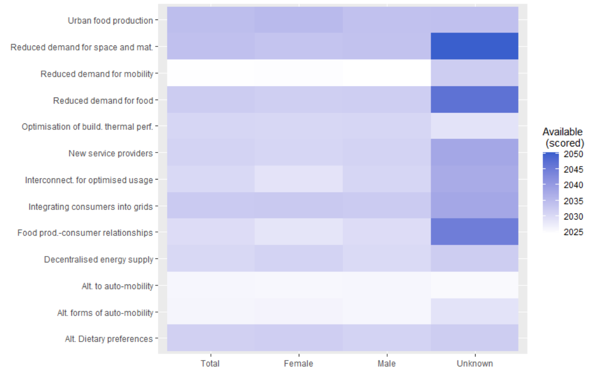

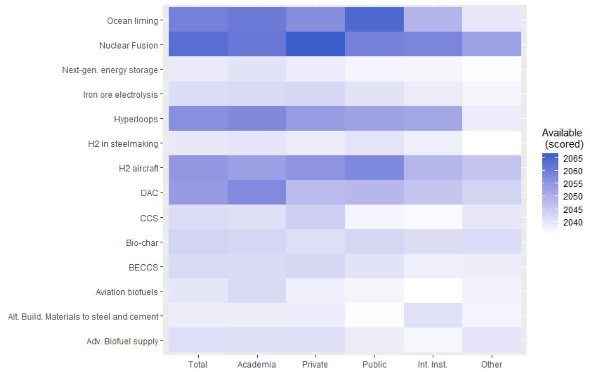

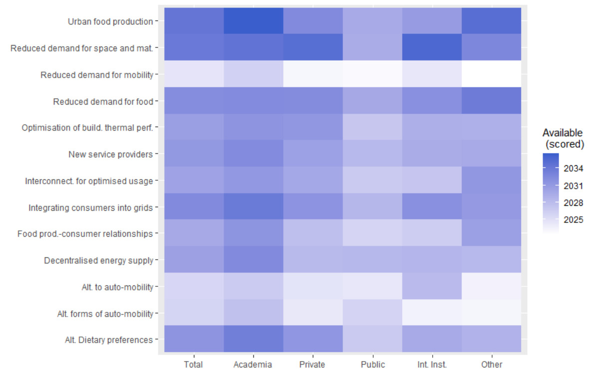

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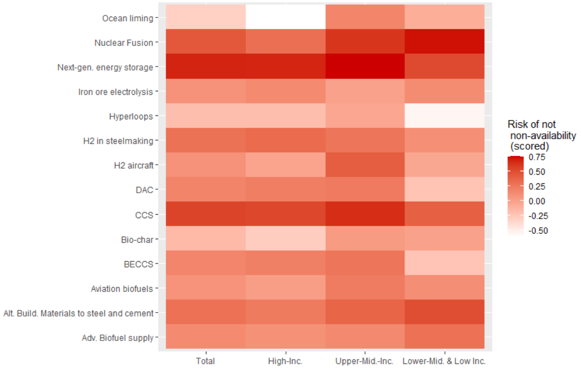

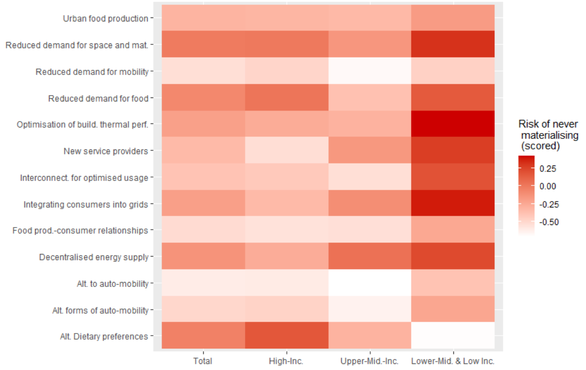

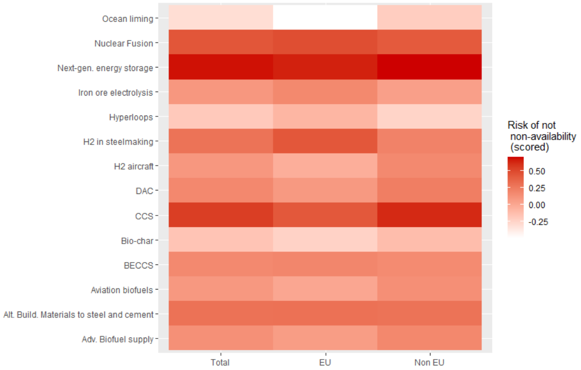

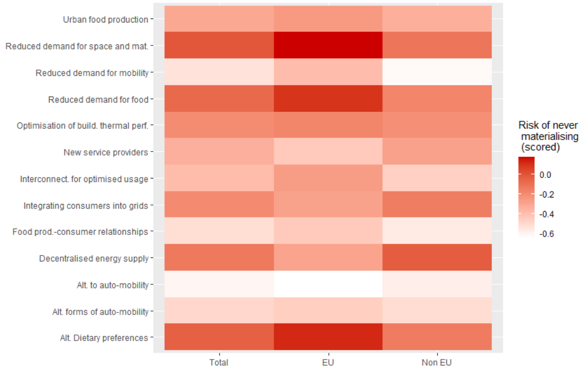

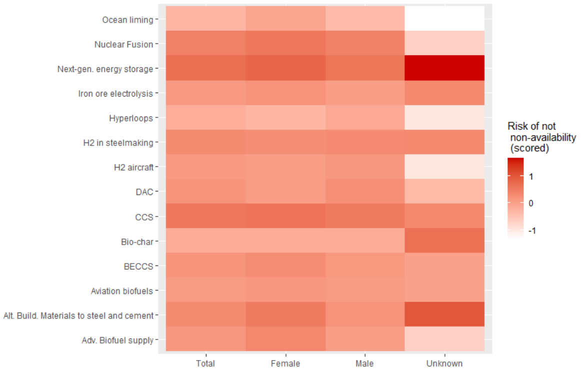

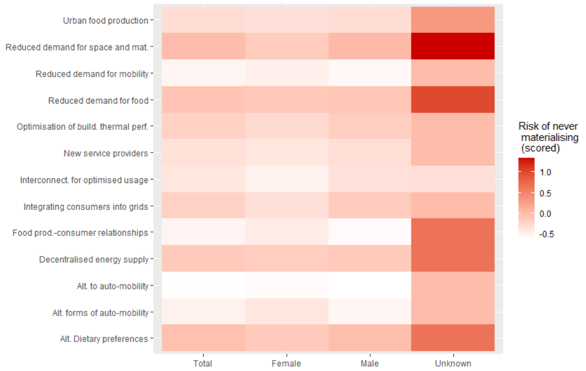

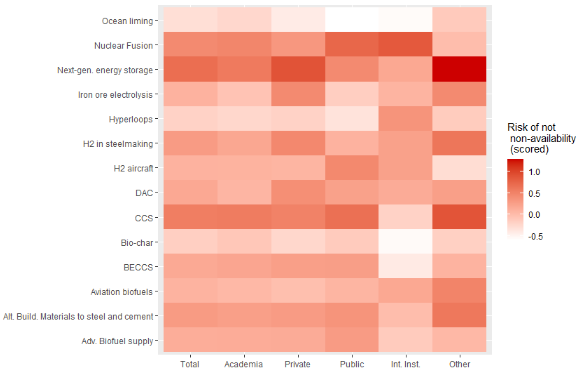

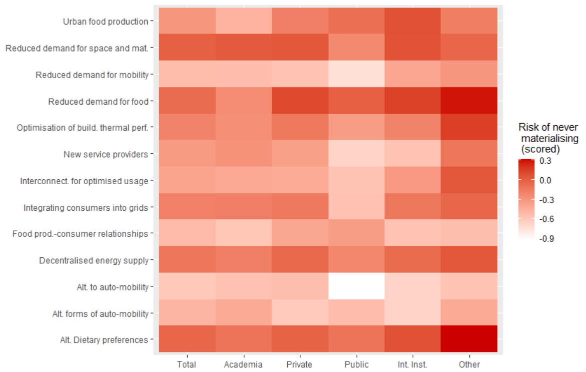

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10 Appendix 5: Additional Explanation of MCDA

Following previous statistical treatment, adjusted to MCDA, a five-term linguistic scale {very low, low, medium, high, very high} is used (coded as {0, 1, 2, 3, 4} hereinafter), with the very high scale indicating a technology/innovation that should be pursued/studied as top priority. This is the case for all three questions providing five possible choices (for handling "not able to respond" please see below). The only exception, in that case, is the "Expected Adopting Time" question for the DLCIs, where for the purposes of this analysis the "already taken-off and "By 2030" were treated as similar. Despite the model's ability to provide output in a linguistic format, the coding is performed to harmonise results with the previous statistical analysis, albeit adapted to use only positive values required by TOPSIS (instead of the {-2,2}). For the purposes of aggregating the three questions, the optimal innovation (i.e., which should receive top priority) 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 stakeholder's ranking of alternatives is calculated independently. Following that, the independent rankings of the individual stakeholders are synthesised in a new decision matrix, which is then used to calculate the final ranking. The choice of this group decision-making approach is based on two parameters.

First, different decision matrices can be synthesised additionally to the one for the entire sample of participants; these consist of the preferences of selected stakeholders grouped variably—here, based on their professional occupation/capacity, income level (regional), and gender. This enables to capture and comprehend how priorities shift depending on the different backgrounds of the engaged stakeholders, as well as to what extent different (groups of) stakeholders agree with one another (and internally within that group). We use three groupings reflecting occupation, geographic region, and gender, respectively: (i) academia/research, private sector/industry, international institutions, national governments, and NGOs; (ii) high-income, upper-middle-income, and lower-middle-income/lower-income countries (lower-middle-income/lower income are merged based on the low number of representatives from the latter category); and (iii) male and female. We did not consider other options, despite some few respondents providing "other" or "prefer not to say" answers; these stakeholders are included in the total and country analysis but excluded in the occupation and gender analysis.

Second, the employed approach allowed handling the "not able to respond" votes, which are typically excluded in multi-criteria decision analyses. These votes were substituted with the average (mean value) stakeholder vote per alternative. Correcting missing values (such as "not able to respond") based on information provided by the rest of the voters is common practice, especially in the presence of multiple experts (Alonso et al., 2008). However, we also introduced a metric to reflect how many valid responses (i.e., responses other than "not able to respond") each stakeholder provided to weigh stakeholders upon the synthesis of individual stakeholder preferences in APOLLO. It was assumed that stakeholders providing a "not able to respond" answer for more than half of the alternatives 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 stakeholders being omitted in the first questionnaire (technologies) and 4 in the second questionnaire (other disruptive game-changing innovations), from a total of 260 respondents.

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