Tyndall°Centre
for Climate Change Research

Disruptive Low Carbon Innovations Workshop Report

Two back-to-back workshops were held in London in March 2017 to explore the potential contribution of disruptive innovation to reducing carbon emissions. The innovator workshop on March 7th focused on innovations and markets, bringing together leading firms, investors, market intermediaries, and policymakers in different domains including mobility, cities, energy supply, and food. The researcher workshop on March 8th focused on research needs and challenges, bringing together leading thinkers and researchers working on disruption, system transformation and innovation, particularly in the energy domain. Discussions from the two workshops were compiled, analysed and synthesised as a series of key findings under eleven themes. Insights from the workshops will feed into: (1) further Future Earth activities as part of an international forum process on disruptive innovation and decarbonisation; (2) scientific publications for assessment by the IPCC Special Report on Global Warming of 1.5^{o}C; (3) advisory work on 1.5^{o}C and 2^{o}C mitigation by the Tyndall Centre for the UK government.

April 2017

Tyndall Centre for Climate Change Research

Working Paper 164

Disruptive Low Carbon Innovation Workshops: Executive Summary

Two back-to-back workshops were held in London in March 2017 to explore the potential contribution of disruptive innovation to reducing carbon emissions. The workshops were organised by the Tyndall Centre and Future Earth, with financial support from the UK Science & Innovation Network. The innovator workshop on March 7th focused on innovations and markets, bringing together leading firms, investors, market intermediaries, and policymakers in different domains including mobility, cities, energy supply, and food. The researcher workshop on March 8th focused on research needs and challenges, bringing together leading thinkers and researchers working on disruption, system transformation and innovation, particularly in the energy domain.

Discussions from the two workshops were compiled, analysed and synthesised as a series of key findings under eleven themes. These are summarised here in the Executive Summary, and explained in full in an accompanying Synthesis Report.

Insights from the workshops will feed into: (1) further Future Earth activities as part of an international forum process on disruptive innovation and decarbonisation; (2) scientific publications for assessment by the IPCC Special Report on Global Warming of 1.5^{o}C; (3) advisory work on 1.5^{o}C and 2^{o}C mitigation by the Tyndall Centre for the UK government.

UK Science & Innovation Network

futurearth research for global sustainability

SILCI Social Influence and *disruptive* Low Carbon Innovations

Tyndall°Centre® for Climate Change Research

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Summary of Key Findings from Workshop Discussions

Insights from the innovator workshop are in normal font. Insights from the researcher workshop are in italics and framed as research questions (Q). Further explanations of all the insights, as well as a comparison between the two workshops, are in the full Synthesis Report.

1. Meaning & interpretation of disruptive low carbon innovation
1.1. What's distinctive about 'disruptive' low carbon innovation is not always clear.
1.2. Disruptive innovation involves business models as well as technologies.
1.3. Innovation is also high-carbon and non-disruptive.
1.4. Q: Is it useful to have a singular definition of disruptive innovation?
1.5. Q: How can the different relationships between disruptive innovation and low carbon be identified, measured and benchmarked?
1.6. Q: How can a systems perspective help understand and analyse disruptive innovation and its impacts?

2. Innovation environment
2.1. Knowledge sharing among networks of innovation actors is essential.
2.2. Intellectual property protection is a double edged sword for disruptive innovation.
2.3. Small-scale innovations face lower barriers to market.
2.4. Integrating disruptive innovations into existing markets and infrastructures is costly.
2.5. Q: Are more distributed patterns of innovation activity impacting disruptive innovation?
2.6. *Q: How do the characteristics and drivers of disruptive innovation vary between countries?*

3. Innovation actors
3.1. Cities are an important site for disruptive innovation.
3.2. Disruptive innovation is generated by a diversity of innovators and competences.
3.3. Investors, insurers and the media play a role in disruptive innovation.
3.4. Q: What roles do different types of companies, investors, and other stakeholders play in disruptive innovation?

4. Innovation drivers & barriers
4.1. Education, communication and positive stories are powerful drivers of disruptive innovation.
4.2. Market forces support cost and performance improvements in disruptive innovations.
4.3. Investors can pressure incumbents to adapt.
4.4. Q: What effect will disruption from climate change have on low carbon innovation?
4.5. Q: How can incumbent high carbon systems be most painlessly closed down?
4.6. Q: Does disruptive innovation reinforce a problematic emphasis on economic growth?

5. Markets & demand
5.1. Disruptive innovations need new markets or new market arrangements.
5.2. Early adopters of disruptive innovations play a key role.
5.3. Disruptive innovation faces strong social resistance.
5.4. Q: What are the drivers and dynamics of social resistance to change?

6. Value propositions for end users
6.1. Disruptive innovations must be designed and marketed to serve user needs.
6.2. Disruptive innovations can improve quality of life.
6.3. Moving from owning to accessing creates opportunities for disruptive innovation.

7. Innovation finance

7.1. Dedicated funding for disruptive low carbon innovation is needed, particularly for SMEs.
7.2. Investors in disruptive innovations need certainty, particularly from policy frameworks.

8. Innovation governance

8.1. Disruptive low carbon innovation cannot be left to the market.
8.2. There are unresolved tensions for policymakers in supporting disruptive innovation.
8.3. Innovators need to trust governments.
8.4. Cost-benefit analysis should recognise the future potential of disruptive innovations.
8.5. Q: How do power and politics shape the dynamics and outcomes of disruptive low carbon innovation?

9. Innovation policy

9.1. Supportive policy for disruptive low carbon innovation requires a mix of instruments.
9.2. Policy should enable fair access to markets and users for disruptive innovators.
9.3. The energy system needs regulatory reform.
9.4. It is unclear if policy should directly support disruption.
9.5. Q: How can coordinated policies stimulate systems-level change?

10. Impacts & outcomes of disruption

10.1. Disruptive forces arise from within the current system.
10.2. Disruption implies risk and a potentially uneven distribution of benefits and costs.
10.3. Q: What kinds of disruption are desirable, and who gets to decide?
10.4. Q: How can the impact of disruptive innovation on CO_2 emissions be analysed empirically?
10.5. Q: What unintended consequences can disruptive innovation have?
10.6. Q: Are current modelling tools sufficient for estimating the impacts of disruptive innovation on CO_2 and other system outcomes?

11. Research practice

11.1. Q: Are current approaches to research suited to the challenge of understanding system change?


MOBILITY
CITIES & HOUSING


DRIVERS
of disruptive
low C innovation


BARRIERS
to disruptive
low C innovation


POLICIES
for disruptive
low C innovation


RESEARCH NEEDS
RESEARCH NEEDS

Disruptive Low Carbon Innovation Workshops: Synthesis Report

Workshop Aims & Objectives

Two back-to-back workshops were held in London in March 2017 to inaugurate an 'international forum on disruptive low carbon innovations' under the auspices of Future Earth. The workshops brought together leading firms, intermediaries, policymakers and researchers to explore the role disruptive innovations can play in low carbon transformation.

The aims of the workshops were to:
(1) identify generalisable characteristics and challenges for disruptive low carbon innovation across sectors and systems;
(2) develop a global scientific research agenda around disruptive low carbon innovation;
(3) establish dialogue and networks among leading practitioners and thinkers.

Workshop Organisation

The innovator workshop was held on March 7, 2017 focusing on firms, markets and policy. The researcher workshop was held the following day on March 8, 2017 focusing on science and research. Insights from the innovator workshop were fed into the researcher workshop by the facilitators and wall collages (see below).

Both workshops were held at the Crystal in the London Docklands. The Crystal is a sustainable building showcase built by Siemens to coincide with the 2012 London Olympics and which now hosts an exhibition and educational resource on sustainable cities.

The workshops were organised as a joint initiative between Future Earth, the Tyndall Centre for Climate Change Research (and the SILCI project), with the financial support of the UK Science & Innovation Network. The organising committee comprised Charlie Wilson (Tyndall Centre), Asher Minns, Erik Pihl, Sabine Fuss (Future Earth) and Mikael Allan Mikaelsson (UK Science & Innovation Network).

UK Science & Innovation Network
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SILCI Social Influence and *disruptive* Low Carbon Innovations
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Workshop Participants

The innovator workshop was by invitation only. Invitation lists were compiled from contact networks, recent conference & event participant lists, targeted search, and snowball methods (e.g., within-firm recommendations). Invitation lists were designed to ensure a diversity of innovation actors (e.g., innovators, incumbents, facilitators), domains (e.g., mobility, cities & housing) and geographies (e.g., UK, EU, US).

46 participants confirmed attendance, with 40 attending on the day. Participant affiliations indicated the workshop roughly comprised of: innovators (6), incumbents (6), investors & funders (7), advisors & facilitators (6), other intermediaries (5), policymakers & regulators (5), researchers (5). Participant expertise was spread across different domains, principally mobility and energy supply & distribution, but also cities & housing, and food & agriculture.

The researcher workshop included invited participants and participants responding to an open announcement advertised through research networks including Future Earth. 38 participants confirmed attendance, with 35 attending on the day.

Both workshops also involved an overall workshop process facilitator (Asher Minns, Future Earth), an overall workshop content facilitator (Charlie Wilson, Tyndall Centre), and 6 facilitator-rapporteurs (1 per table).

Pre-Workshop Survey

A pre-workshop online survey was circulated to participants the week prior to the workshops. The survey asked participants to select 1 of 4 domains in which they were most experienced: mobility, cities & housing, energy supply & distribution, food & agriculture. In their selected domain, they were then asked to rank a set of 10 low carbon innovations according to their potential disruptiveness and their potential impact on CO_2 emission reductions. The full set of 4 * 10 low carbon innovations were compiled by the workshop content facilitator from literature search. Participants were also asked to suggest additional low carbon innovations to those in the predefined set.

A total of 32 (of 40) participants from the innovator workshop and 24 (of 35) participants from the researcher workshop completed the survey (response rates of 80% and 63% respectively). Average survey completion time was 4 minutes.

The potentially disruptive low carbon innovations from the pre-workshop survey, including both those identified from literature search and those suggested by participants, were all transcribed onto post-it notes, and compiled into a wall collage prior to the workshop. The wall collage was readily visible by participants during the workshop and served both as a cue for discussion, and also to avoid the workshop discussions becoming too focused on specific disruptive low carbon innovations (*d*LCIs). The *d*LCIs, organised by domain and type, are shown in full in the Appendix (Table A1), along with their average rankings from the pre-workshop surveys (Table A2). These average rankings were also presented to workshop participants during the introductory talks by the workshop content facilitator.

Note: *d*LCI = *disruptive* low carbon innovation

Workshop Structure & Talks

Workshop discussions were roundtable with 6-8 participants and 1 facilitator-rapporteur per table. Discussions were structured in 3 separate sessions. For the innovator workshop, participants changed seating in each session to ensure each table had a diversity of roles and domains represented. For the researcher workshop, participants were encouraged to mix their seating to vary table composition per session.

Each session was framed by a question setting the overarching theme (Table 1), and was further specified by topic prompts. Full details of the session themes and topic prompts are available in the workshop agendas available here or www.futureearth.org/europe/disruptivelowcarboninnovations_synthesisreport

TABLE 1. WORKSHOP STRUCTURE.

	Innovator Workshop	**Researcher Workshop**
Session 1 (plenary then roundtable)	* *3 introductory talks* **examples of *d*LCIs**	* *2 framing talks, then:* **meaning of *d*LCI**
Session 2 (roundtable then wrap-up)	**drivers & barriers of *d*LCI**	* *2 framing talks, then:* ***d*LCI and system transformation**
Session 3 (roundtable then wrap-up)	**policies to support *d*LCI**	* *2 framing talks, then:* **estimating CO_2 impact of *d*LCI**

* *see text for details of introductory & framing talks*

The innovator workshop began with 3 introductory talks:

- Corinne Le Quéré (Committee on Climate Change, Future Earth) on the magnitude of emission reduction targets and the urgent need for low carbon innovation;
- Charlie Wilson (Tyndall Centre) on Christensen's canonical definition of disruptive innovation as offering novel attributes to end-users, often through low-tech, low-end goods and services;
- Kathryn Myronuk (Singularity University) on disruptive trends including exponential improvements in computing technologies, widespread data capture from cheap sensors with linked AI-training applications, democratisation and distribution of innovation expertise and activity away from traditional competences and organisations.

The researcher workshop had 2-3 framing talks per session. Session 1 on the meaning of *d*LCI was framed by:

- Kathryn Myronuk (Singularity University) on disruptive trends including exponential technologies, big data and data analytics, and the democratisation of innovation expertise;
- Charlie Wilson (Tyndall Centre) on insights from the previous day's innovator workshop, and a reminder of Christensen's canonical definition of disruptive innovation;
- Frank Geels (University of Manchester) on systems theories of sociotechnical change and the systemic nature of disruption.

Session 2 on *d*LCI and system transformation was framed by:

- Paul Ekins (UCL) on adverse consequences of system disruption and the potential for incumbent technologies to realign with decarbonisation aims;
- Benjamin Sovacool (University of Sussex) on open vs. closed systems of innovation, and disruptive innovations observable in the energy system.

Session 3 on the CO_2 impacts of *d*LCI was framed by:

- Gert Jan Kramer (Utrecht University, formerly Shell Scenarios Group) on scenario biases towards current thinking and the challenges of anticipating novel futures;
- Mark Winskel (Edinburgh University) on the UK Energy Research Centre's current project on system disruption.

Slides from the workshop talks are available here or www.futureearth.org/europe/disruptivelowcarboninnovations_synthesisreport

Workshop Data
Ideas and insights from workshop discussions were recorded on post-it notes which were collated in wall collages during each session by the workshop content facilitator. Similar ideas from different tables were clustered in the wall collages to help identify common topics. These clusters then served to summarise the main discussion points back to plenary at the end of each session. Additional data on key discussion points were recorded by the facilitator-rapporteurs per table.

At the end of each workshop, participants were given five dots to distribute as 'votes' on the wall collage notes they considered the highest priority to work on.

Workshop Data Analysis
Both post-it notes with key ideas and insights, and the additional notes recorded by facilitator-rapporteurs, were inductively coded into a set of themes and subthemes (Table 2). The full data analysis process is shown in Figure 1.

The themes that emerged from the two workshops were broadly comparable, with some exceptions resulting from the different workshop compositions and structures (e.g., innovator workshop had more discussion of examples of *d*LCIs, researcher workshop had more discussion of modelling CO_2 impacts of *d*LCIs). Data within each theme were clustered, and then summarised as a series of key findings (see below). The aim of the key findings was to enshrine the main ideas & insights discussed without exhaustively listing all the data captured.

Workshop Outputs & Outcomes
Workshop outputs include:
(1) this synthesis report with analysis and key findings;
(2) a workshop website hosted by Future Earth with agendas, talks, and video;
(3) initial dialogue between innovation stakeholders on disruption + low carbon.

Insights from the workshops will also feed into ongoing science and policy initiatives, including:
(1) further Future Earth activities as part of an international forum process on disruptive innovation and decarbonisation;
(2) scientific publications for assessment by the IPCC Special Report on Global Warming of 1.5°C (including the possibility of a viewpoint series in *Energy Research & Social Science*);
(3) advisory work on 1.5°C and 2°C mitigation by the Tyndall Centre for the UK government.

FIGURE 1. ANALYSIS OF WORKSHOP DATA

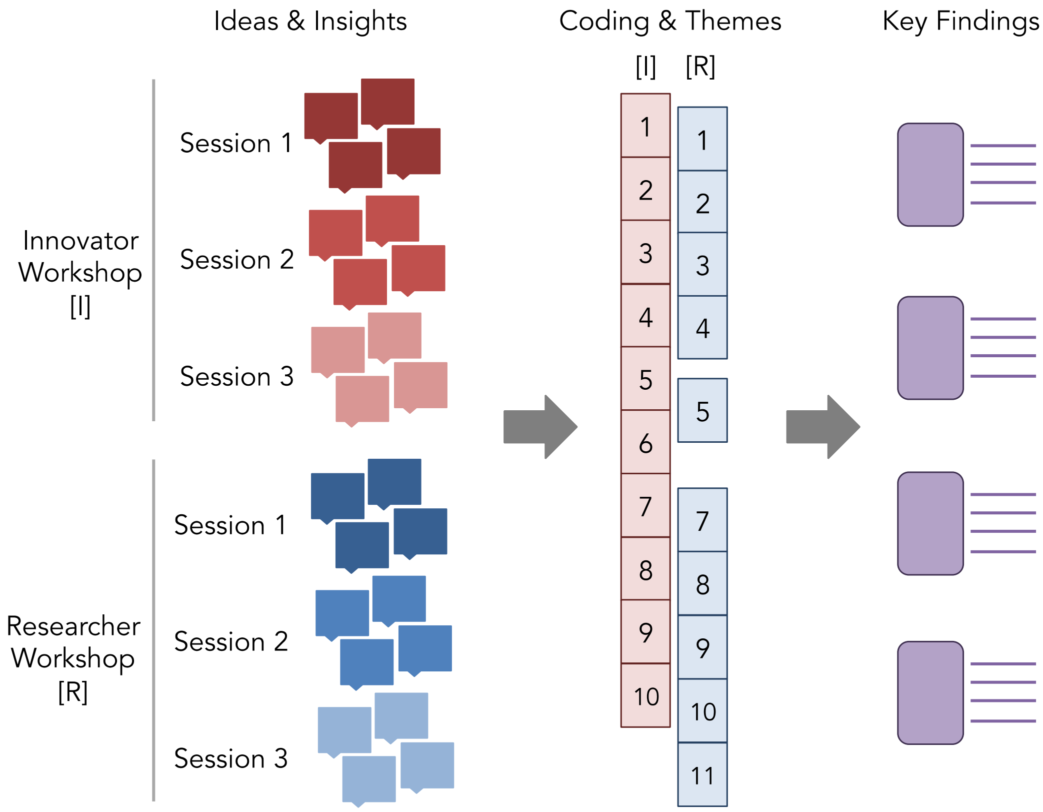

TABLE 2. CODING OF WORKSHOP DISCUSSIONS. NOTE: CODES DENOTED BY [I] FROM INNOVATOR WORKSHOP, [R] FROM RESEARCHER WORKSHOP. *D*LCI = *DISRUPTIVE* LOW CARBON INNOVATION.

Emergent Themes		**Innovator Workshop**	**Researcher Workshop**
1	meaning & interpretation of dLCI	[I1a] what is *d*LCI [I1b] examples of *d*LCIs	[R1a] definitional questions [R1b] system transformation [R1c] evaluative questions
2	innovation environment	[I2a] innovation environment [I2b] innovation dynamics	[R2a] innovation environment [R2b] geographies & contexts
3	innovation actors	[I3a] innovators [I3b] intermediaries [I3c] other innovation actors	[R3] innovation actors
4	drivers & barriers	[I4a] drivers of *d*LCIs [I4b] motivations for *d*LCIs [I4c] barriers to *d*LCIs	[R4a] needs & values [R4b] strategies & approaches [R4c] incumbent systems
5	markets & demand	[I5a] market characteristics [I5b] demand for *d*LCIs	[R5] users & adopters
6	value propositions for end users	[I6a] novel attributes [I6b] business models	-
7	innovation finance	[I7a] funding approach [I7b] finance mechanisms	[R7] funding approach
8	innovation governance	[I8a] governance & strategies [I8b] policy environment [I8c] policy framework	[R8] governance
9	innovation policy	[I9a] policy characteristics [I9b] policy instruments	[R9] policy
10	impacts & outcomes of disruption	[I10a] impacts [I10b] risk & distribution	[R10a] impacts on CO_2 [R10b] other, general impacts [R10c] modelling & estimation
11	research practice	-	[R11a] cognitive routines [R11b] research approaches

Key Findings

The ideas & insights from the workshops are synthesised below, grouped into eleven themes (see Table 2):

- points in plain text are from the innovator workshop;
- points marked by * are from the researcher workshop, and are summarised as a research question (Q);
- boxes labelled 'Workshop comparison' compare and contrast discussions on each theme between the two workshops.

1. MEANING & INTERPRETATION OF DISRUPTIVE LOW CARBON INNOVATION

1.1. What's distinctive about 'disruptive' low carbon innovation is not always clear. Despite the framing of the workshop around *disruptive* low carbon innovation, how this differed from low carbon innovation more generally was not always evident in workshop discussions. By implication, disruption was seen as an inherent characteristic or consequence of innovation. More restrictive and specific definitions of disruptive innovation, such as Christensen's, were not shared by participants.

1.2. Disruptive innovation involves business models as well as technologies. Although the importance of business models was firmly expressed, only circular economies and sharing economies were raised as specific types of business model for disruptive innovation. More general discussions on business models emphasised the importance of supportive policy environments, particularly as the economic benefits of low carbon innovations tend to accrue at the systems level and are hard to capture by individual actors. Although participants tended to downplay the importance of technological innovation, discussions frequently anchored on physical hardware or applications (e.g., electric vehicles).

1.3. Innovation is also high-carbon and non-disruptive. Participants clearly identified innovation activity which ran counter to both disruptive trends and low-carbon outcomes.

****1.4. Q: Is it useful to have a singular definition of disruptive innovation?*** For researchers, disruptive innovation is a contested concept. Many definitional questions were raised about the relationship between disruptive innovation and other innovations: incremental, game-changing, transitional, and transformational. Some argued that generalising a definition of disruptive innovation was inappropriate as disruptiveness varied in different contexts, and the kinds of innovation that lead to transformation was unclear. Moreover, innovations may have disruptive effects on being introduced, or not until they are deployed at scale. It is also important to recognise what is being disrupted, and over what timescale.

****1.5. Q: How can the different relationships between disruptive innovation and low carbon be identified, measured and benchmarked?*** Whether disruptive innovation is low carbon is an important research question. Not all disruptive innovation is low carbon; not all low carbon innovation is disruptive. Disruptive innovation may affect emissions intentionally or unintentionally, and directly or indirectly. Disruption may only be identifiable after the fact. Low carbon disruption seems most evident in the energy sector, but may also be possible in other sectors. It's also possible that disruption may adversely affect incremental change towards low carbon targets.

****1.6. Q: How can a systems perspective help understand and analyse disruptive innovation and its impacts?*** For researchers, disruption is primarily understood in terms of system transformation. Researchers emphasised the importance of a systems perspective from the outset. Identifying how to catalyse whole system transformation in a way that meets human needs and is consistent with deeply-held values sets the context for disruptive innovations. In this sense, system transformation drives disruptive innovation rather than the other way round. Placing system transformation centre stage also shifts the focus away from a narrow technical framing of the problem which disruptive innovation is trying to solve.

Workshop comparison: Meaning & interpretation of disruptive low carbon innovation. The two workshops took markedly different perspectives on disruptive innovation. In the innovator workshop, there was little reflection on what disruptive innovation meant and discussions tended to be about low carbon innovation in general (with its inherently disruptive characteristics). Conversely, in the researcher workshop, there were many different interpretations of disruptive innovation and questioning of its assumptions. The most prominent view was that disruptive innovation needed to be seen from a systems perspective. Neither workshop 'bought into' Christensen's canonical definition of disruptive innovation which emphasises novel attributes for end users who are marginalised from, or oversupplied by, mainstream markets. In the researcher workshop, some argued that Christensen's definition was difficult to apply to low carbon innovation as it emphasises private not social benefits.

2. INNOVATION ENVIRONMENT

2.1. Knowledge sharing among networks of innovation actors is essential. This was one of the most commonly discussed themes. 'Friction-free coordination' and a stronger consensus around the value of network-building help support disruptive innovation. However various forces work against this, including the complexity and diversity of inter-relationships between innovation actors, and the lack of incentives for knowledge exchange. [Editor's note: Workshops such as this are designed to help!]

2.2. Intellectual property protection is a double edged sword for disruptive innovation. Open source business models facilitate innovation and knowledge exchange, but potentially undermine innovators' ability to appropriate the returns on their innovation investments.

2.3. Small-scale innovations face lower barriers to market. Short lead times and rapid learning cycles - often associated with small-scale, modular innovations - improve the feasibility of scaling up to meet market demand. Conversely, innovations with 'no room to fail' (e.g., aircrafts or power grids) face additional barriers which discourage risk-taking experimentation.

2.4. Integrating disruptive innovations into existing markets and infrastructures is costly. Prevailing systems are structured in favour of incumbents. It is in incumbents' interest to block disruption and maintain strong relationships with government. Moreover, it is often disruptive innovations rather than existing practices which are 'painful' in terms of transitional or switching costs.

2.5. Q: Are more distributed patterns of innovation activity impacting disruptive innovation? Researchers discussed whether and how science and innovation activities were opening up to a new set of actors and so being distributed away from traditional R&D competences centralised in firms and labs. This 'democratisation' of innovation was linked to similar trends towards more distributed governance and ownership of technologies, enabled by low-cost innovations for data collection and processing. How these background trends may impact disruptive innovation is an important research question.

2.6. *Q: How do the characteristics and drivers of disruptive innovation vary between countries? Researchers discussed how disruptive innovation varies geographically. This raises interesting questions about why disruptiveness varies spatially, what facilitates disruption in different contexts, and why certain cultures appear to be more innovative in transitioning towards low carbon (e.g., Germany and Denmark for renewables). However, researchers also expressed the importance of a global view and of research focusing on rapidly-growing developing countries.

Workshop comparison: Innovation environment.
The two workshops focused on different aspects of the broader innovation environment. In the innovator workshop, discussions centred around important enabling elements of innovation: knowledge sharing, intellectual property protection, learning, and systems integration. Conversely, researchers considered deeper underlying forces: the democratisation of science and innovation activity, and both national and cultural differences. In sum, innovators were concerned with the instrumental question of 'how can we best innovate …' whereas researchers were interested in underlying contexts and conditions.

3. INNOVATION ACTORS

3.1. Cities are an important site for disruptive innovation. Many participants cited the key role of cities as incubators and test beds for innovations, as more stable and consistent policy environments, and as places where social norms at a community level can potentially be harnessed. 'Cities as drivers of change' was one of the most voted on ideas & insights from the wall collages.

3.2. Disruptive innovation is generated by a diversity of innovators and competences. Market success stories, iconoclastic leaders, start ups, and citizen groups were all cited as potentially important sources of disruptive innovation.

3.3. Investors, insurers and the media play a role in disruptive innovation. However, investors were seen as lacking relevant expertise and appropriate risk-return criteria. The media were considered to be helpful in raising awareness of disruptive innovation, but this was being undermined by an increasingly fragmented media space.

****3.4. Q: What roles do different types of companies, investors, and other stakeholders play in disruptive innovation?*** Researchers did not focus in any depth on specific actors involved in disruptive innovation. There was some discussion around how disruptive low carbon innovation could be made relevant for businesses and investors. The importance of other stakeholders in large socio-technical systems was also noted. Otherwise, discussions about innovation actors was largely focused on policy and governance.

Workshop comparison: Innovation actors.
Both workshops discussed how cities, investors, the media and other actors played important supporting roles in disruptive innovation, alongside innovator firms and policymakers. The innovator workshop focused in more depth on the different types of innovators involved, particularly at the local level.

4. INNOVATION DRIVERS & BARRIERS

4.1. Education, communication and positive stories are powerful drivers of disruptive innovation. 'Enable innovation through education' was the most voted on idea & insight from the wall collages. Related discussion points emphasised how clear and effective communication was needed to bridge the different languages used in business, finance and policy, and to create a clear narrative of positive change.

4.2. Market forces support cost and performance improvements in disruptive innovations. Natural competition between companies has driven down costs in technologies such as solar PV and electric vehicles. Reliable projections of market potentials for such innovations makes them bankable, and exerts a pull on supporting regulation.

4.3. Investors can pressure incumbents to adapt. Whether through external pressure to address climate risks or internal corporate social responsibility initiatives, it is in the economic self-interest of major companies to recognise disruptive trends (including climate change). However, incumbent firms benefit from low marginal cost production from depreciated assets which creates a barrier to change.

4.4. Q: What effect will disruption from climate change have on low carbon innovation? Understanding how to manage complexity in bringing about change is an important research challenge. Researchers were concerned with how to understand the system interactions which generate emergent phenomena and which in turn may support or hinder innovation. As an example, background disruption from climate change could help drive disruptive low carbon innovation. But conversely, innovation in response to disruption might prevent change.

4.5. Q: How can incumbent high carbon systems be most painlessly closed down? Research is needed on how to disrupt incumbency. Why incumbent high carbon systems and organisations are so resilient is also an important research question. This includes end-user demand for incumbent aspirations such as vehicle ownership, as well as institutional support for large-scale centralised technologies like nuclear power. Research should also focus on how resulting systems inertia can be most effectively disrupted.

4.6. Q: Does disruptive innovation reinforce a problematic emphasis on economic growth? Researchers saw disruptive innovation as being driven by values which are not narrowly economic. Sustainable consumption, circular economies, and carbon accounting in products and services were all cited by researchers as strategies consistent with this view. More broadly economics needs be internalised within societal and environmental goals. Education may have a role to play in building support for aspirational change, and resetting goals to a higher level of ambition.

Workshop comparison: Innovation drivers & barriers.
Both workshops viewed education as important, but with different emphases: shaping positive narrative of change for the innovators; and shifting deeply-held values and aspirations for the researchers. This led the researchers to question the domination of economic values, and even the growth paradigm, whereas the innovators placed greater emphasis on market forces for stimulating disruption. Both workshops discussed incumbents as a barrier to disruptive innovation, and the mechanisms by which inertia could be overcome.

5. MARKETS & DEMAND

5.1. Disruptive innovations need new markets or new market arrangements. Participants discussed the need to find new markets globally, but also identified both China and younger generations as key potential targets. China's striving for stronger geopolitical prestige, and Millenials' shifting away from ownership (including of vehicles), were cited as opening up possibilities for disruptive innovation. New market arrangements can also open up existing markets to disruptive innovation (e.g., moving away from prioritising low marginal cost production in electricity markets).

5.2. Early adopters of disruptive innovations play a key role. Consumers were considered to be more ready targets for new goods and services, not least because they are more easy to sway (than business users) and present a defined target market. Fragmentation of the media space may accelerate social influence through early-adopter networks.

5.3. Disruptive innovation faces strong social resistance. Many different participants raised social acceptance, trust and fear of new technologies as a major barrier to change. The public, writ large, was seen as being inert, potentially fuelled by misconceptions about innovations.

5.4. Q: What are the drivers and dynamics of social resistance to change? Social science research can help understand public responses to low carbon disruption. Possible avenues for research include the effect of media narratives, how to give people 'ownership' of innovations, and why people seem 'inattentive' to low carbon or energy-efficient technologies. Whether there are examples of disruption removing consumer choice but enhancing lifestyle is also of interest.

Workshop comparison: Markets & demand.
Both workshops identified a strong social resistance to low carbon disruption. The innovator workshop saw this in terms of trust, fear, and misconceptions, with a potentially key role to be played by new markets and early adopters in reducing perceived risks. The researcher workshop was interested in the underlying dynamics which generated this social resistance, linked to aspirational lifestyles and product ownership.

6. VALUE PROPOSITIONS FOR END USERS

6.1. Disruptive innovations must be designed and marketed to serve user needs. The lack of a clear value proposition undermines many new technologies. End users may also face higher financial costs in adopting disruptive innovations.

6.2. Disruptive innovations can improve quality of life. The 'co-benefits' or non-climate-related attributes of disruptive innovations are attractive to end users. Co-benefits include taste and health (in the case of food) and cleaner air (in the case of mobility). These must be clearly communicated as part of efforts to educate consumers.

6.3. Moving from owning to accessing creates opportunities for disruptive innovation. Service-based business models challenge embedded patterns of ownership; but these patterns run deep and are not easily changed. Policy has an important role to play in incentivising flexible payment for services, and supporting trusted, open source platforms for bundling services together to enhance the value proposition for consumers. Peer-to-peer innovations like blockchain show promise in helping to connect consumers and enable distributed governance.

Workshop comparison: Value propositions for end users.
Only the innovator workshop examined value propositions and end users in any depth,

emphasising the importance of non-carbon attributes ('co-benefits') which improved quality of life. The potential for peer-to-peer business models in supporting a move from owning to accessing was another important cross-cutting theme.

7. INNOVATION FINANCE

7.1. Dedicated funding for disruptive low carbon innovation is needed, particularly for SMEs. Participants also discussed how funding should be more flexible, available across different scales, simpler to access, and avoid locking in redundancy. Innovation prizes can create strong incentives, but funding is also needed for sustainable business models.

7.2. Investors in disruptive innovations need certainty, particularly from policy frameworks. Participants expressed strong views on this point. Policies should be flexible but credible. Prescriptive policy erodes flexibility in meeting defined targets and adaptability to changing best practices. However policy flip-flops are damaging. Residential energy efficiency and feed-in tariffs are recent UK examples. Policies subject to political populism also erode market confidence.

Workshop comparison: Innovation finance.
Only the innovator workshop considered innovation funding approaches and financing mechanisms, emphasising the importance of stable, credible funding streams tailored to innovators' needs. This perspective seems common to innovation in general, rather than disruptive innovation specifically, and links to wider points made about innovation governance and policy instruments.

8. INNOVATION GOVERNANCE

8.1. Disruptive low carbon innovation cannot be left to the market. Policies, funding, and governance strategies dominated discussions throughout the day. Disruptive low carbon innovation is clearly not generated by market dynamics alone. It is unclear whether this is specific to low carbon outcomes, or whether it's generic to disruptive innovation in the sectors represented (mobility, cities & housing, energy supply & distribution, food & agriculture). Many participants voiced the need for new strategies and policies to open up markets to low carbon innovations, particularly in sectors and niches in which low carbon is also profitable. Some participants called for dirigiste planning (e.g., energy efficiency as a strategic infrastructure issue) or for a clear industrial strategy to help innovations bridge the valley of death between R&D and market diffusion. Others called for less regulation to create space for more private investment. A broader point is that disruptive low carbon innovation is not narrowly about low carbon; enabling just social transitions provides an alternative, complementary basis for supporting low carbon innovation.

8.2. There are unresolved tensions for policymakers in supporting disruptive innovation. The diversity of policy-related ideas revealed clear trade-offs in the governance strategy 'required' to support disruptive low carbon innovation. Three clear examples of these tensions were: the need for flexibility vs. the importance of stability (particularly for investors); the importance of collaboration vs. the need to protect intellectual property; the need for a clear industrial strategy vs. the importance of not picking winners. On this last point, policy can target desired outcomes rather than technologies, but this is also problematic as it implicitly favours more market-ready options.

8.3. Innovators need to trust governments. Better links between policymakers and innovators, clear advanced signalling of policy intentions, and independent enforcement of existing policies, can all help strengthen innovation governance. However, both institutional lock-in and a lack of substantive expertise in government can undermine these trust-building efforts.

8.4. Cost-benefit analysis should recognise the future potential of disruptive innovations. The regulatory requirement for cost-benefit analysis is blocking disruptive innovation, unless option values are recognised.

8.5. Q: How do power and politics shape the dynamics and outcomes of disruptive low carbon innovation? What types and levels of governance are most strongly related to disruption are important research questions. Researchers had similar discussions to the innovators around how governance systems affected low carbon innovation (e.g., open vs. closed), what levels of governance were best suited to accelerated transformation (e.g., national vs. local), and when governments should start but also stop supporting an innovation (e.g., stability vs. adaptability). Researchers were also concerned with regulatory capture by incumbents which created the need for governments to disrupt themselves.

Workshop comparison: Innovation governance.
The innovator workshop was deeply concerned with innovation governance, reflecting both the composition of the workshop and the market-oriented outcomes being discussed. A strong general consensus was that disruptive low carbon innovation should not be left solely to the market. However this belied an inconsistent set of more specific recommendations on governance structures and approaches. These unresolved tensions between views expressed were unsurprising given the range of innovation actors and domains represented. Questions raised in the researcher workshop focused on the many possible variants of governance systems for disruptive innovation.

9. INNOVATION POLICY

9.1. Supportive policy for disruptive low carbon innovation requires a mix of instruments. A wide range of specific policy instruments and strategies were discussed, with a clear consensus around the need for a comprehensive policy mix rather than any silver bullet approach. 'All policies listed here' was the second most voted on idea & insight from the wall collages. Specific policies recommended by participants spanned both technology-push (e.g., R&D funding, demonstrators) and market-pull strategies (e.g., carbon pricing, subsidies, public procurement, personal carbon allowances). Several participants also called for standards and regulations tailored to specific industry structures.

9.2. Policy should enable fair access to markets and users for disruptive innovators. Consumers should be supported in making low carbon choices on a level playing field. Policies forcing combinatorial innovation (e.g., all autonomous vehicles must be zero carbon) can enhance value propositions. Policy can also force transparency in supply chains (e.g., by disclosing CO_2 emission impacts or using consumption-based emissions accounting) which supports the effectiveness of price incentives (e.g., through carbon taxes).

9.3. The energy system needs regulatory reform. The energy supply and distribution system was a specific focus of several discussions, with calls for greater clarity and independence in how energy networks are regulated and operated, and new market arrangements to support disruptive innovations. Standards can also enable more effective information exchange between system operators on the one hand, and end users and appliances on the other.

9.4. It is unclear if policy should directly support disruption. Whether it is appropriate or necessary for policy to directly support disruption was raised … but not answered.

9.5. Q: How can coordinated policies stimulate systems-level change? For researchers, policies should establish framework conditions to guide disruptive innovation towards low carbon. Such efforts should be aligned to emission reduction objectives in the Paris Agreement. A specific example discussed by researchers was how policy could ensure big data, algorithms, and AI could drive societal behaviour towards low carbon outcomes.

Workshop comparison: Innovation policy.
Only the innovator workshop discussed policy characteristics and instruments in any depth. Regulatory reform to enable fair access to markets for disruptive innovations was a common refrain. Innovators also recognised the need for a comprehensive mix of policy instruments to tackle many different market barriers, although potential trade-offs within such a mix were not discussed. The researcher workshop similarly discussed policy mixes for system-level change, but focused on framework conditions rather than instrument choice.

10. IMPACTS & OUTCOMES OF DISRUPTION

10.1. Disruptive forces arise from within the current system. One source of potential disruption (e.g., solar PV) may open up opportunities for other sources of disruption (e.g., blockchain). Future disruptions from climate change under business-as-usual trajectories are also widely under-recognised.

10.2. Disruption implies risk and a potentially uneven distribution of benefits and costs. Adverse social consequences of disruption may be strongly felt in communities which 'lose' as the relative strength of different sectors changes.

10.3. Q: What kinds of disruption are desirable, and who gets to decide? As in the innovator workshop, discussions in the researcher workshop identified how the potential benefits from disruption may not be evenly or equitably distributed. Although disruption may work better when benefits are more visible locally, some researchers also questioned whether disruption was desirable or needed.

10.4. Q: How can the impact of disruptive innovation on CO_2 emissions be analysed empirically? Historical evidence of disruptive innovations impacting CO_2 trends is important for researchers. How disruption impacts CO_2 emissions is an empirical question. However, researchers are also concerned with characterising and quantifying future potential contributions of disruptive innovation to decarbonisation. But this should not be analysed in isolation from other types of innovation and low carbon strategies.

10.5. Q: What unintended consequences can disruptive innovation have? Both the positive and negative outcomes of disruptive low carbon innovation need researching. System change has pervasive impacts, and can both open up or close down innovation pathways. Disruption may also occur at different scales: from users and households up to countries and technological systems. These disruptive effects may not always be intended.

10.6. Q: Are current modelling tools sufficient for estimating the impacts of disruptive innovation on CO_2 and other system outcomes? Scenarios and models used by researchers to explore future emission pathways need to incorporate disruption. One of the most highly voted on ideas and insights from the researcher workshop was that scenarios were too conservative and that modelling disruption was not seen as credible. Researchers also set out various criteria for scenario analysis, including the importance of transparent assumptions, and the inclusion of wider socio-technical outcomes. Developing new, more complex models should be premised on a clear understanding of what prior models or methods missed.

Workshop comparison: Impacts & outcomes of disruption.
The impacts and outcomes of disruptive low carbon innovation were only discussed in depth during the researcher workshop. This was in part due to the workshop structure which focused attention on the methods and tools for estimating impacts on CO_2 emission reductions. However researchers emphasised the importance of other system outcomes, and both innovators and researchers saw risks and distributional issues as important.

11. RESEARCH PRACTICE

11.1. Q: Are current approaches to research suited to the challenge of understanding system change? Researchers were concerned that their own methods and mindsets were part of the problem. Some argued that prior assumptions and established approaches to disruptive innovation were themselves an obstacle to transformative change. Consequently, disruption to low carbon research agendas was also needed to broaden them out. This may need new institutional structures supporting researchers to retrain and cross-fertilise between fields, learning about and developing new toolkits.

Workshop comparison: Research practice.
One topic of discussion specific to the researcher workshop was whether the cognitive routines, methodological knowledge, and daily practices of the research community itself needed disrupting, to break out of established ways of thinking and doing research. No clear conclusion was reached!

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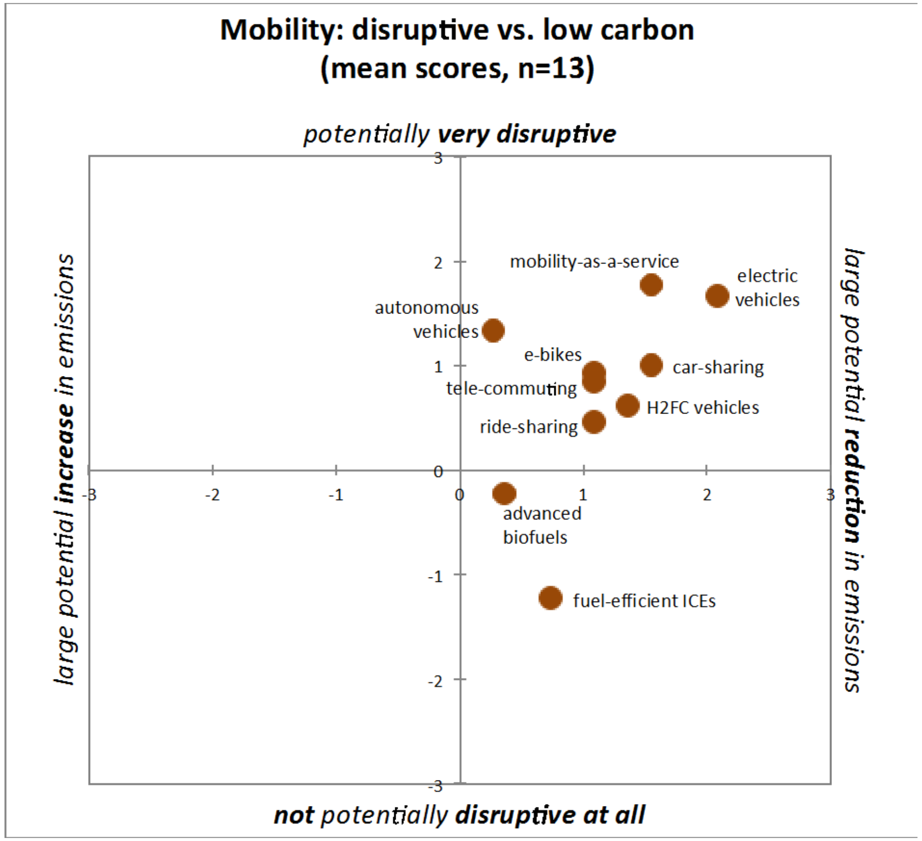
Appendix.

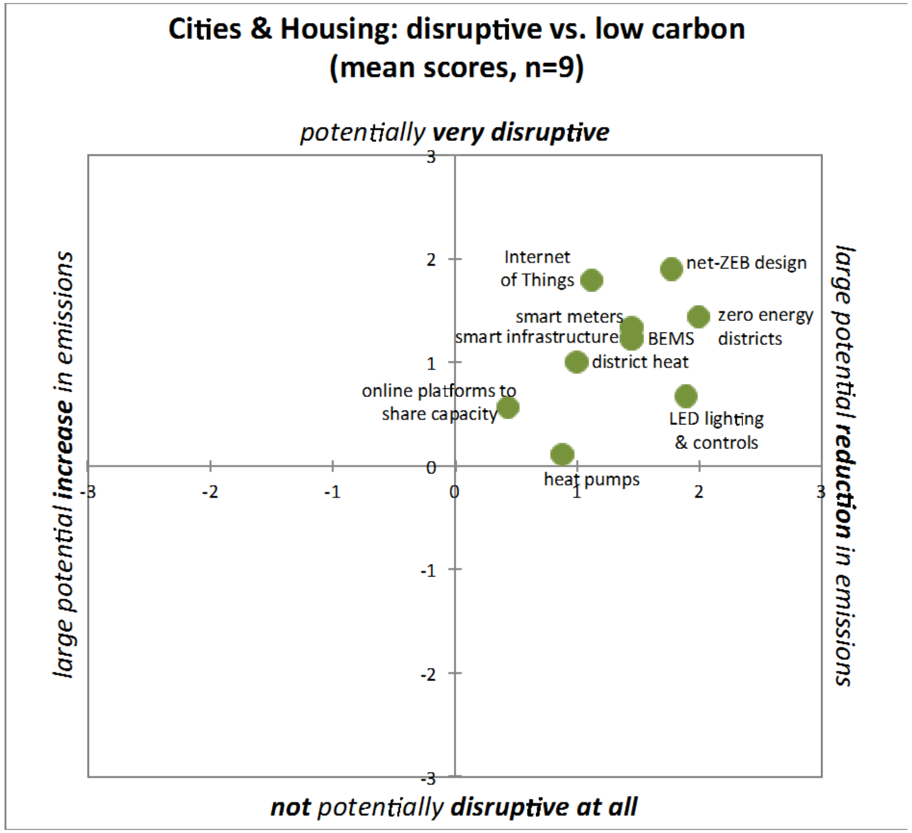
Table A1. Examples of potentially disruptive low carbon innovations (from pre-workshop survey and workshop discussions). Colour Code: duplicated in different domains | cultural shifts (nonmarket goods & services) | not in collage but discussed

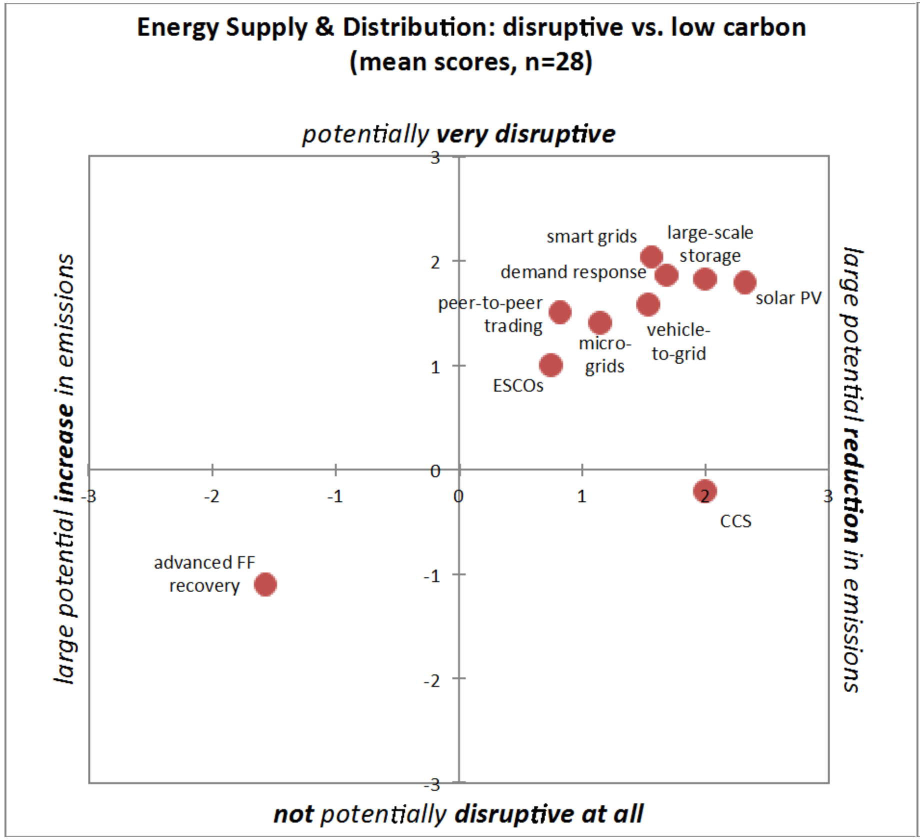
		end-use good or service (direct impact on emissions)		*upstream, B2B, enabling environment (indirect impact on emissions)*		
DOMAIN	**END-USE SERVICE**	**primarily service or business model innovation**	**primarily technology or product innovation**	**production, supply or manufacturing innovation**	**structural innovation in markets, infrastructures, cultural norms**	**meta-innovations, underpinning or cross-cutting**
cities & housing	- using stuff	- online platforms to share spare capacity		- 3d printing	- circular economy - sharing economy (from owning to accessing) - sharing & rental networks	- digital infrastructure - data analytics, AI - big data + distributed sensors, imaging - algorithms, optimisation + distributed control - electrification + distributed control - block chain (decentralised transactions) - education - distributed expertise + democratisation of innovation - microcomposites + advanced materials - synthetic biology - advanced biotech
	- heating & cooling - lighting	- SME en.eff. home improvements	- smart appliances - electric garden equipment - LED lighting & controls - building energy management systems (BEMS) - heat pumps + thermoelectric coolers - heat storage	- new insulation materials - prefab. renovations - building integrated energy production - zero-energy building (ZEB) design - C negative housing	- Internet of Things - smart meters - smart infrastructure - district heat - zero energy districts	
mobility	- moving people	- car sharing - ride sharing - mobility-as-a-service (MaaS) - on demand public transit	- autonomous vehicles - electric vehicles (EVs) - e-bikes - fuel efficient vehicles - fuel cell vehicles (H_2FCVs)		- vehicle-to-grid (V2G) - telecommuting + telepresence - bike highways - high speed rail - pricing fuel externalities	
	- moving stuff		- airships - rotor (Flettner) ships			
energy	- empowering	- demand response (DR or DSR) - energy service companies (ESCOs) - renewables or storage as service - peer-to-peer electricity trading	- solar PV - micro wind turbines - distributed fuel cell generation - domestic battery storage - electrification of heating	- advanced biofuels + algal biofuels - load flexible biomass energy - carbon capture & storage (CCS) - CO_2 utilisation - advanced fossil fuel recovery - vertical axis wind turbines	- micro-grids - smart grids + power electronics for new networks - large scale grid storage + advanced thermal storage + power-to-gas - vehicle-to-grid (V2G) - high voltage DC grids	

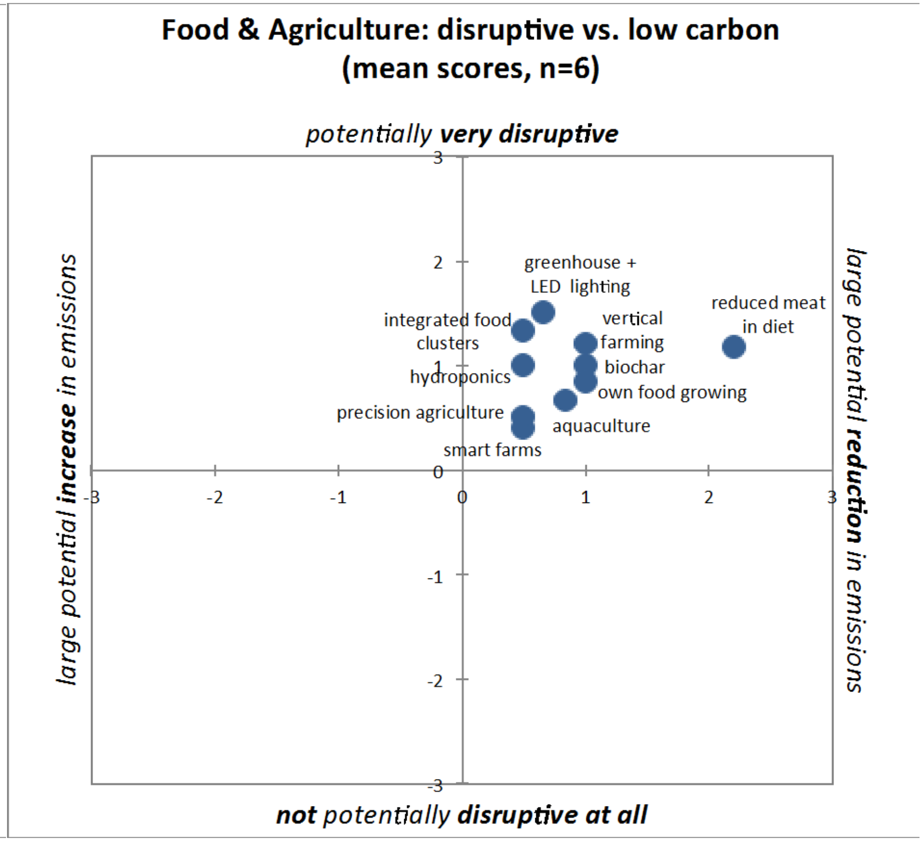
		- business models to lower switching costs for consumers			- H_2 gas supply network	
food	- eating & drinking			- hydroponics - aquaculture - vertical farming - farming pods - greenhouse & LED lighting - tropical staple trees - silvopasture (grazing + forestry)	- smart farms + digital optimisation of farm infrastructure - precision agriculture - integrated food clusters + localisation of food production - dietary shift away from meat - own food growing - reduced food waste - biochar soil C enhancement	

Table A2. Rankings of potentially disruptive low carbon innovations from pre-workshop survey (combining results from innovator workshop, total n=32, and researcher workshop, total n=24).






Energy Supply & Distribution: disruptive vs. low carbon
(mean scores, n=28)
potentially very disruptive
not potentially disruptive at all
large potential increase in emissions
large potential reduction in emissions
smart grids
large-scale storage
demand response
solar PV
peer-to-peer trading
vehicle-to-grid
micro-grids
ESCOs
CCS
advanced FF recovery


Food & Agriculture: disruptive vs. low carbon
(mean scores, n=6)
potentially very disruptive
not potentially disruptive at all
large potential increase in emissions
large potential reduction in emissions
greenhouse + LED lighting
reduced meat in diet
integrated food clusters
vertical farming
biochar
hydroponics
own food growing
precision agriculture
aquaculture
smart farms