Report for BEIS on Disruptive Low Carbon Innovations

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Summary

Innovation is integral to 1.5oC mitigation. Policy and modelling analysis tends to focus on low carbon innovations which are upstream (not directly consuming facing) and *sustaining* - they improve upon existing attributes like affordability, efficiency or cleanliness currently valued in mainstream markets. *Disruptive* innovations are distinctive in offering novel product or service attributes to end users. Disruptive low carbon innovations challenge prevailing technologies or practices and may lead to step change reductions in emissions if adopted at scale. Many potentially disruptive low carbon innovations exist today, but in small numbers. As examples, car sharing, reuse networks and community food-growing challenge mainstream consumer attributes of ownership, autonomy and status.

This report investigates the potential for disruptive innovations to transform the market for energy-related goods and services in line with the step change reductions in emissions required for 1.5oC mitigation.

First, we consider the key concepts of disruption innovation, and propose a set of characteristics that define disruptive low carbon innovations. Second, we review numerous studies of low carbon innovation in three domains: mobility; food; buildings & cities. We use our set of characteristics as screening criteria to identify potentially disruptive innovations in each domain. *We find a wide range of consumer-facing innovations that offer goods or services with novel attributes currently valued only in small market niches or not at all.*

Third, we draw on market research and consumer behaviour studies to identify the novel attributes offered by these potentially disruptive low carbon innovations. We assign rankings to these attributes and map how they compare across different innovations. *We identify sixteen attributes which cluster into subsets shared by multiple potentially disruptive innovations. These attribute clusters describe consumer value propositions around service-based business models, flexibility, useability, connectedness, as well as more conventional sources of value such as cleanliness and time saving. These clusters represent the basis of potential growth in consumer demand if current early adopters support cost and performance improvements so the innovations move mainstream.*

Fourth, we survey innovation experts to evaluate the potential impact of disruptive low carbon innovations on emissions. We also draw on select innovation-specific studies quantifying potential step changes in emissions consistent with the rapid reductions needed for 1.5oC mitigation. *We identify various innovations in each domain of particular interest to 1.5oC mitigation. Taking mobility as an example, innovations which experts considered to be disruptive and emission-reducing are: mobility-as-a-service, car clubs, and electric vehicles. These are predominantly characterised by a shift towards mobility becoming a pay-per-use service.*

Acronyms

*d*LCI = disruptive low carbon innovation
ICE = internal combustion engine

Introduction

The energy system has undergone many transformations historically of which end users have been the driving force. End-user demands for the attributes of new and improved energy services have stimulated a virtuous cycle of innovation, novel services, efficiency and performance gains, cost reductions, and so more demand (Fouquet 2010). However this virtuous cycle begins with energy services which were either wholly new (rapid long-distance mobility provided by airplanes, flexible on-demand access to communication and information provided by mobile computing) or qualitatively improved with novel performance attributes (mobility provided by cars substituting for horses, illumination provided by electric lighting substituting for gas lights). Historical energy transitions are indelibly stamped by novel and better energy services.

Global IAMs do not model novel energy services. In many IAMs, particularly those from a macroeconomic tradition or with a CGE core, energy demand is often a highly aggregated function (e.g., of GDP and income elasticities calibrated to historical data). IAMs are not designed to explore nor useful for exploring the emergence of novelty in energy end-use. In 2100, long-distance mobility is still by jet aircraft; short-distance mobility is still by car; residential construction still uses steel & concrete; buildings still need heating and cooling; food is still grown extensively using land; and so on. A backward look to 1930 tells us it is not science fiction to imagine that portfolios of mitigation options in 2017 may look very different in 2100.

Some IAMs like AIM-Enduse or POLES have more detailed representations of energy end-use technologies: buildings, vehicles, appliances, bulbs. Scenario assumptions about climate policy, demographics, or technological innovation can then feed through the modelling to affect the marginal production of these consumer goods and how these flows affect more inert stocks with their systemic consequences (like energy use, emissions, and commodity prices). But modelling change in energy end-use is hard. End-use technologies are smaller in scale, orders of magnitude larger in number, more dispersed, and highly heterogeneous compared with the pits, pipelines and power plants of the energy supply. Data are correspondingly patchy or unavailable. Many end-use technologies are also consumer goods with a variety of attributes over which end-user preferences vary. Efficiency may be traded-off against style, speed, safety. These 'behavioural' characteristics of end-use technology adoption pose greater problems for modellers and analysts seeking reduced-form and context-independent expressions of cause and effect.

Consequently the representation of end-use technologies and energy services in IAMs is highly limited. Low carbon alternatives are typically centred around like-for-like substitutes with current mainstream technologies: alternative fuel vehicles for internal combustion engines; exterior wall insulation for non-insulated buildings; and so on (Table 1). These substitution technologies do not offer novel energy services; but they are low carbon.

Low carbon innovations from solar PV and offshore wind, to smart grids and large-scale storage, to electric vehicles and energy efficient homes are strongly emphasised in modelling studies (Rogelj et al. 2015), mitigation scenarios (Clarke et al. 2014), roadmaps (Dixon et al. 2014), national climate plans (UK_CCC 2010), and R&D initiatives like Mission2020 (King 2017). Yet these low carbon innovations offer few novel attributes to end users. As a consequence, decarbonisation is predominantly upstream (away from end users) and reliant on climate policy or technological change driving cost and efficiency improvements. Consumers are a missing constituency in energy-system transformation for stringent mitigation.

Table 1. Representation of consumer-facing non-mainstream low carbon innovations in IMAGE. Source: adapted from p174 of (van Sluisveld 2017).

<table>
<tr><th></th><th>none</th><th>implicit*</th><th>explicit</th></tr>
<tr><td rowspan="4">electricity</td><td>fuel cells</td><td>demand response</td><td>LED lighting</td></tr>
<tr><td>rooftop PV</td><td>-</td><td>-</td></tr>
<tr><td>small-scale wind</td><td>-</td><td>-</td></tr>
<tr><td>virtual power plant</td><td>-</td><td>-</td></tr>
<tr><td rowspan="4">mobility</td><td>vehicle-to-grid</td><td>mobility-as-a-service</td><td>alternative fuel vehicles (electric, bio, H2)</td></tr>
<tr><td>smart charging e-vehicles</td><td>teleworking</td><td>-</td></tr>
<tr><td>active modes including cycling</td><td>-</td><td>-</td></tr>
<tr><td>inter-modality</td><td>-</td><td>-</td></tr>
<tr><td rowspan="5">buildings & heat</td><td>smart control systems</td><td>district heating</td><td>net zero energy buildings</td></tr>
<tr><td>waste water heat recovery</td><td>exterior building insulation</td><td>-</td></tr>
<tr><td>micro-CHP</td><td>-</td><td>-</td></tr>
<tr><td>heat pumps</td><td>-</td><td>-</td></tr>
<tr><td>power to heat</td><td>-</td><td>-</td></tr>
</table>

* implicitly only as part of aggregate sectoral demand, i.e., not resolved nor represented in model and so analysable only by proxy by varying aggregate assumptions or parameterisations (e.g., income or price elasticity)

Disruptive innovations

Disruptive innovations are remarkable for being uncompetitive in conventional terms of price or performance. Rather, they offer potential adopters a wholly new set of attributes. If successful, they effectively create a new market, a new set of demands and preferences. As a result their transformative potential is large. Microcomputers are the classic example used by Clayton Christensen in his seminal work on disruptive innovations published in 1997 as 'The Innovator's Dilemma' (Christensen 1997). The mainframe computing industry in the late 1970s failed to anticipate how microcomputers could challenge their market dominance. The attributes valued by mainstream users - large firms and institutions - were processing speed, storage capacity, cost per MB, reliability. Microcomputers performed relatively poorly on all these attributes. However they offered something new: portability (small volume, lower weight), versatility (ruggedness), low unit costs, low power consumption. As a disruptive innovation, the microcomputer had worse product performance than the incumbent mainframes, but brought to the market a very different value proposition than had been previously available. The novel attributes of the microcomputer created its own market in an entirely new segment of users: individuals and small firms. The resulting explosive growth is history.

An important distinction can therefore be made between disruptive and sustaining innovations (Walsh and Linton 2000). Whereas *sustaining* innovations improve on the existing product or service attributes valued by end users, *disruptive* innovations offer novel attributes and so create a new value proposition for end users. The challenge with disruptive innovations is not technological but about finding a market. Early microcomputers largely used off-the-shelf components put together in a product architecture that was simpler than previous approaches. They disrupted incumbent manufacturers as they created a new market.

Disruptive *low carbon* innovations

Characterising disruptive low carbon innovations

Our aim is to identify potentially disruptive low carbon innovations (*d*LCIs) and their novel attributes. This is the necessary first step for exploring the role of disruptive innovations in rapid and pervasive emission reductions in line with ambitious climate stabilisation goals. Disruptive innovations can potentially strengthen market demand for low carbon goods and services, and engage users as an active constituency in climate change mitigation efforts.

The business and management literature on disruptive innovation is principally concerned with firm strategy and performance, and the distinctions between disruptive and incumbent firms. However, Christensen and others have also defined the characteristics of disruptive innovations and their potential attractiveness of disruptive innovations for end users (Christensen 1997, Govindarajan and Kopalle 2006, Lambert 2014). These are summarised in Table 2.

Table 2. Characteristics of disruptive low carbon innovations. Note: * = most emphasised attributes.

	***Christensen*: disruptive innovation**	***Seba*: disruptive innovation**	**d*LCIs*: disruptive low carbon innovations**	***in general & in IAMs*: low carbon innovation**
novel application of knowledge (i.e., innovation!)	✔	✔	✔	✔
initially attractive in a market niche then performance improves	✔	✔	✔	✔
disrupts mainstream firms, markets or regulatory frameworks	✔*	✔*	-	-
combines technological & business model innovation to create value	✔	✔*	✔	-
offers novel attributes to end users	✔	✔	✔*	-
appeals to low-end price-sensitive users or non-users	✔*	-	✔	-
simple, low-tech alternatives to over-performing mainstream goods	✔*	-	✔	-
appeals to high-end price-insensitive risk-tolerant users	-	✔*	✔	-
radical technological breakthroughs which improve exponentially	-	✔*	✔	-
reduces greenhouse gas emissions if adopted at scale	-	-	✔*	✔*

Here we are interested in how potentially disruptive innovations may shape one particular system outcome: GHG emissions. Disruptive *low carbon* innovations must have the potential to substantially reduce greenhouse gas emissions if adopted at scale. This depends not just on the energy-using characteristic of the innovation, but also on what it displaces or substitutes for. Our definition of disruptive low carbon innovations is also shown in Table 2. We relax various of Christensen's defining characteristics in line with more recent literature on disruptive innovation. In particular, following (Seba 2014), we allow for high-end and/or high-tech sources of disruption, as well as the canonical 'bottom-of-the-pyramid' form of disruption in which continual improvements in goods and services along the performance attributes valued by mainstream users outstrips expectations and needs, so opening up the lower end of the market to cheaper, simpler alternatives. In the particular case of disruptive low carbon innovations, there are some examples of performance over-supply opening up the potential for simpler, cheaper alternatives. This is perhaps clearest among the many low-tech substitutes for automobile-based mobility: e-bikes, neighbourhood electric vehicles, bike-share schemes. But disruption can also come from above in the form of superior products and services which have more capabilities and functionality than what mainstream markets provide, but are also more expensive and so appeal initially only to a high-end market niche. They are disruptive because their cost and performance improvement curves are on a rapid (exponential) trajectory so they rapidly outcompete incumbents. Solar PV and battery technologies (for EVs and distributed storage) are widely-cited current examples (Seba 2014, Farmer and Lafond 2016); as are a whole host of ICTs relying on processors, sensors, wireless transmission, and data storage. As a result, high-tech challenges to established goods, services and practices tend to integrate ICTs into traditional energy hardware, opening up possibilities for algorithmic control and automation, distributed (peer-to-peer) networking, and real-time data provision for feedback or machine learning. This is perhaps clearest in the 'smartness' of appliances, homes and grids.

In sum, we use the term 'disruptive low carbon innovations' (dLCIs) to mean low carbon innovations that (1) offer novel attributes or functionality not currently valued by mainstream users, and (2) can significantly reduce GHG emissions if adopted by mainstream users by displacing or substituting for more carbon-intensive goods and services. In other words, our dLCIs fulfil both a consumer need (for novel and better energy services) and a social need (for reduced GHG emissions).

Identifying disruptive low carbon innovations

What are examples of disruptive low carbon innovations? McKinsey (2012) identify ten disruptive innovations which are or will affect energy productivity: unconventional natural gas production; electric vehicles; advanced internal-combustion engines (ICE); solar PV; LED lighting; grid-scale storage (batteries, flywheels, and ultracapacitors); digital transformers (for large-scale high-voltage power conversion); compressor-less air-conditioning and electro-chromic windows; clean coal (cheap CCS); biofuels and electrofuels (cellulosic and algal-based biofuels). Dixon et al. (2014) identify disruptive technologies relevant to urban energy retrofits. Examples include: LEDs; phase change materials (for thermal storage and AC); plastic electronics (lighting, PV, integrated smart systems); nanotechnology membranes (for water purification and grey water reuse); smart biometric materials; community and city-scale heat and power networks, hydrogen networks.

Despite the potential impacts of these technologies on existing businesses and forms of energy production, it is unclear what novel attributes are offered to users. McKinsey (2012) characterise disruption in terms of impact on energy productivity. Dixon et al. (2014) point to potential disruptions to utility profits, peak prices, and electricity system operation. However, this is largely the result of major technological advances. This conflates the important distinction between disruptiveness (about markets and users) and radicalness (about technological improvements).

We surveyed recent literature on low carbon innovation including sectoral and economy-wide reports, modelling and scenario studies, innovation case studies, and synoptic views of energy innovation, including: McKinsey Global Institute, Energy = Innovation (McKinsey 2012); New Scientist, Gamechanger (New_Scientist 2016); McKinsey Global Institute, Disruptive Technologies (McKinsey 2013); UK Government, 8 Great Technologies (HMG 2013); Mission Innovation, Clean Energy R&D Focus Areas (King 2017); The Global Energy Assessment (Johansson et al. 2012); Energy & Climate Change Committee of the UK House of Commons, The Energy Revolution (House_of_Commons 2016); Tony Seba, Clean Disruption (Seba 2014).

In each case, we used the characteristics of *d*LCIs set out in Table 1 to identify potential *d*LCIs cited in the literature. In particular, we are interested in innovations offering novel attributes to end users in four domains: mobility; buildings & cities; food; and energy supply.

Examples of *d*LCIs relating to *mobility* include car clubs, car sharing and car-free communities. These innovations perform poorly on valued mainstream attributes associated with car ownership. However they offer novel attributes to end users including service use, collaboration, inter-dependent exchange, and no maintenance or care obligations.

Examples of *d*LCIs relating to *buildings & cities* include smart homes, net zero energy homes, and networked PV-storage systems. These innovations perform poorly on valued mainstream attributes such as low upfront cost, convenience, passive end-user roles, and dependence on centralised networks or utilities. However they offer novel attributes to end users including control, automation, active involvement, and autonomy.

Examples of *d*LCIs relating to *food* include urban and community-based growing, reduced food waste schemes, modular hydroponic and aquaponic systems. These innovations perform poorly on valued mainstream attributes such as year-round availability, scale economies and standardisation (at one-stop shop centralised retailers). However, they offer novel attributes to end users including relationships, identity-signalling, and social benefits (localisation),

We also mention two further sets of *d*LCIs relating to *energy supply* and *consumer goods* which are not analysed further in this report. *d*LCIs relating to *energy supply* include peer-to-peer trading, vehicle-to-grid, and community or district energy networks. These innovations perform poorly on valued mainstream attributes such as passivity (as an electricity consumer), time-invariant rates, and dependence on external systems of provision. However, they offer novel attributes to end users including active involvement, control and autonomy. *d*LCIs relating to *consumer goods* include reuse networks (e.g., Freecycle) and service economies. These innovations perform poorly on valued mainstream attributes of ownership, newness, and brand status. However, they offer novel alternative attributes to end users including use value, reciprocity, and collaboration.

It is important to emphasise that these are broad-brushed examples of how the novel attributes of *d*LCIs for different energy end-uses contrast with mainstream valued attributes. As few of these *d*LCIs are simply substitute products, it is not as easy to neatly delineate the attributes or characteristics that appeal to end users.

Mobility-related disruptive low carbon innovations

In this section we present more detailed results for mobility-related *d*LCIs, characterising the novel attributes for each innovation. Table 3 shows potential *d*LCIs identified in the literature and linked to an 'incumbent' form of mobility for which they offer a substitute (this in turn determines their potential impact on GHG emissions). They are grouped into four: alternative vehicles technologies substituting for ICEs; alternative forms of auto-mobility substituting for car ownership; alternatives to auto-mobility substituting for car use altogether; and reducing mobility demand. This final grouping are structural approaches (e.g., in urban planning) and so not strictly *d*LCIs but are included for comparison purposes.

Table 3. Potentially *disruptive* low carbon innovations relating to mobility. Note: * *d*LCIs included in survey of innovation experts, see below; + other *d*LCIs; ~ denotes additional low-carbon mobility strategies).

type of innovation or strategy		potentially disruptive low C innovations or low C strategy	displaced incumbent
alternative fuel or vehicle technology	*	electric vehicles (EVs)	conventional ICE vehicles
	*	autonomous (self-driving) vehicles	conventional ICE vehicles
	*	fuel efficient ICEs	conventional ICE vehicles
	*	hydrogen fuel cell vehicles	conventional ICE vehicles
	*	advanced biofuels	conventional ICE vehicles
alternative form of auto-mobility	*	car clubs, car sharing	car ownership & use
	*	mobility-as-a-service (MaaS) [a]	car ownership & use
	*	ride-sharing	car ownership & use
alternative to auto-mobility	*	e-bikes	bikes, motorbikes
	+	neighbourhood EVs	walking, public transport
	~	modal shift to public transport	car use
	~	active modes (walking, cycling)	car use, public transport
reduced demand for auto-mobility	*	telecommuting, video- or teleconferencing	commuting
	+	interactive virtual reality [b]	commuting, teleconferencing
	~	disappearing traffic [c]	road infrastructure
	~	car-free communities	car-dependent suburbs

Some of the less familiar dLCIs are further defined here:
[a] *mobility-as-a-service* (also *inter-modality*) refers to app-based scheduling, booking and payment systems for multiple transport modes (ride-sharing, bus, train) through a single gateway or account;
[b] *interactive virtual reality* can be used for immersive interaction by remote (e.g., currently used in medical diagnosis or surgery);
[c] *disappearing traffic* refers to the removal of road infrastructure and restoration of car-free urban environments (e.g., express freeways in Seoul, South Korea).

Food-related disruptive low carbon innovations

In this section we present more detailed results for food-related *d*LCIs, characterising the novel attributes for each innovation. Table 4 shows potential *d*LCIs identified in the literature and linked to an 'incumbent' form of food consumption, production or retail for which they offer a substitute. They are grouped into four: alternative forms of diet (i.e., consumption); alternative forms of food production; alternative business models of food retail (linking consumers and producers); and reduced food waste. As with the mobility-related innovations, some of these blur the line between *d*LCIs and broader strategies for reducing emissions from food.

Table 4. Potentially *disruptive* low carbon innovations relating to food. Note: * *d*LCIs included in survey of innovation experts, see below; + other *d*LCIs; ~ denotes additional low-carbon food & agriculture strategies).

type of innovation or strategy		potentially disruptive low C innovations or low C strategy	displaced incumbent
alternative forms of diet	*	reduced meat in diet	animal agriculture
	+	cultured meat [a]	

	*	aquaculture	wild fish stocks
alternative forms of food production	*	hydroponic growing systems	soil-based growing systems
	+	aquaponic (fish-plant) systems [b]	
	*	greenhouse horticulture and LED lighting	traditional lighting solutions
	*	urban and community based growing schemes	large-scale rural agriculture
	*	urban indoor farms [c]	
alternative business models of food retail	+	farm shops	large-scale food production & retail
	+	farmers' markets	
	+	food box schemes	
	+	community supported agriculture	
	~	food links schemes [d]	
reduced food waste	~	upstream community food redistribution	

Some of the less familiar dLCIs are further defined here:
[a] *cultured meat* is animal meat that is grown using a bioreactor;
[b] *aquaponic systems* create a natural cycle between fish and plants with an enclosed 'pod' system;
[c] *urban indoor farms* include vertical farming, stacked greenhouses, modular food pods;
[d] *food links schemes* connect producers directly with consumers;
[e] *upstream community food redistribution* schemes link local retailers (or end users) with surplus food to charities or end users.

Buildings & cities-related disruptive low carbon innovations

In this section we present more detailed results for buildings and cities-related *d*LCIs, characterising the novel attributes for each innovation. **Table 5** shows potential *d*LCIs identified in the literature and the incumbents to which they offer a substitute. They are grouped into four: interconnectivity for efficient usage (of devices, appliances, assets, capacity); efficient thermal performance (of buildings); improved design & construction (of buildings); and enabling infrastructure at a city scale (collecting & analysing data, connecting users with system performance, optimising usage). As with the buildings & cities-related innovations, some of these blur the line between *d*LCIs and broader urban and industry-scale strategies for reducing emissions from buildings and cities.

Table 5. Potentially *disruptive* low carbon innovations relating to buildings & cities. Note: * *d*LCIs included in survey of innovation experts, see below; + other *d*LCIs; ~ denotes additional low-carbon food & agriculture strategies).

type of innovation or strategy		potentially disruptive low C innovations or low C strategy	displaced incumbent
interconnectivity for efficient usage	*	online platforms to share capacity [a]	stand-alone assets or devices non-responsive to system needs
	*	smart appliances	
	*	internet of things	assets or devices with limited user control functionality
	*	LED lighting and smart controls	
efficient thermal performance of buildings	*	building energy management systems	
	*	heat pumps	centralised gas network & in-home boilers
	+	heat storage [b]	
improved design & construction of buildings	*	net zero energy buildings (ZEBs)	high transaction cost home construction & retrofit industry
	+	pre-fab high-spec (low energy) new build	
	+	pre-fab high-spec (low energy) renovations	
enabling urban infrastructure	*	smart meters	information-poor built environment
	*	smart infrastructure [c]	
	~	urban sensing [d]	
	~	urban greening	weakly integrated natural & built environment

Some of the less familiar dLCIs are further defined here:
[a] *online platforms to share capacity* include peer-to-peer networks such as AirBnB (sharing homes) or Streetbank (sharing stuff).
[b] *heat storage* to match energy supply to heating and cooling demand allows efficient transfer of heat from point of production and storage to point of use.
[c] *smart infrastructure* includes connected traffic signals, street lights, and a host of other urban infrastructure allowing optimised traffic and people flows

[d] *urban sensing* refers to distributed sensor networks collecting real-time data to monitor performance metrics (air quality, parking availability, etc) to support smart infrastructure and urban management

Novel attributes of disruptive low carbon innovations

As emphasised above, our interest in potential *d*LCIs lies in the novelty of their attributes and so their attractiveness to end users. We identified relevant and salient attributes using market research, consumer-facing marketing material, consumer behaviour studies, and early adopter surveys. These attributes are summarised in general terms in
Table 6.

Table 6. Novel innovation attributes potentially attractive to end users.

attribute	generic description	I want ...
pay per use	having a usage-based cost structure without requirement for capital or other one-off investment	*just to use*
service based	accessing a useful service (rather than owning a good with associated maintenance responsibilities)	
multiple uses	diversifying the range of functions provided by a good or service	*flexibility*
choice variety	having the ability to choose alternative forms of a good or service to suit different needs or contexts	
convenience	making a good or service less hassle, more convenient, or more easy to use	*useability*
control	improving the ability to control, manage or influence how a good or service is provided	
autonomy	reducing dependence on third party service providers, infrastructures or systems of provision	
relational	strengthening interactions with others' using a good or service (either directly or indirectly)	*something more than me*
active involvement	deepening the active role in, engagement with, or contribution to how a good or service is provided	
identity signal	supporting desirable aspects of users' individual or social identity (and how this is communicated)	
social benefits	contributing to social, shared or collective benefits (e.g., less pollution, less congestion)	
clean at point of use	causing low or no emissions (or other pollution) directly from the use of a good or service	*all the usual benefits*
healthy	supporting healthy living or health outcomes by the use of a good or service	
safety & security	supporting safety & security by the use of a good or service	
time-saving	saving time or making use of time more efficient or productive when using a good or service	
cost-saving	saving money or making use of finances more efficient or productive when using a good or service	

To help interpret what these attributes tell us about the potential direction of new consumer value propositions relating to energy-using goods and services, the final column in Table 6 organises the 16 attributes shown into five clusters. Each cluster offers a simple characterisation of adopters' preferences and why they may be attracted to the innovations:

- As a user, I want *just to use* - this captures a movement away from owning goods and towards using services either on an as-needs basis or through membership of a service provider (attributes = pay per use, service based);
- As a user, I want *flexibility* - this captures a desire for usage which can be varied depending on need or context, and is enabled by a technology having multiple functionality (attributes = multiple uses, choice variety);
- As a user, I want *useability* - this captures the key concerns of user-centred design to ensure goods or services are easy to use, controllable, and do not create dependencies on external service providers to run or maintain the technology (attributes = ease of use, control, autonomy);
- As a user, I want *something more than me* - this captures a movement away from a passive role as an energy consumer of an always-available invisible commodity and towards a more active and engagement role as producer, trader, social network or community member, or citizen concerned with collective outcomes (attributes = relational, active involvement, identity signal, social benefits);
- As a user, I want *all the usual benefits* - this captures the set of attributes which have strongly characterised user preferences in observed historical energy transitions towards cleaner, more affordable, and more readily available energy services (attributes = clean at point of use, healthy, safety & security, time saving, cost saving).

Clearly the 16 attributes and 5 clusters of attributes shown in Table 3 will vary greatly in their applicability to specific innovations. Figure 1 maps the novel innovation attributes shown in
Table 6 onto the potentially disruptive *mobility-related* innovations shown in Table 3. The mapping distinguishes positive (green) or negative (red) associations, and scores each association with a simple 1 (weak) or 2 (strong). Associations are also coded +/- (grey) if they are ambiguous (e.g., negative or positive depending on context or interpretation).

The mapping in Figure 1 is based on the attributes, functionality, service features or performance characteristics identified cited in the literature reviewed. The novelty of these attributes in all cases is *relative to* the incumbents displaced (see Table 3). So, for example, although an EV may offer its owner and user 'control' (over when and where to go), this is not distinct from a conventional ICE vehicle so these attributes are not novel.

Following the same basic method, Figure 2 maps the novel innovation attributes onto the potentially disruptive *food-related* innovations shown in Table 4, and Figure 3 maps the novel innovation attributes onto the potentially disruptive *buildings & cities-related* innovations shown in **Table 5**. In both cases, the mappings are based on the attributes, functionality, service features or performance characteristics identified cited in the literature reviewed, with the novelty of these attributes in all cases being *relative to* the incumbents displaced.

Figure 1. Novel attributes of *mobility-related innovations* relative to displaced incumbents. Notes: +2 (red) & +1 (light red) = strong & weak positive associations between novel attribute and innovation; -2 (green) & -1 (light green) = strong & weak negative associations; +/- = contingent association; blank = no association.

As a user, I want …	*just to use*		*flexibility*		*useability*			*something more than me*				*all the usual benefits*				
novel attributes (relative to displaced incumbent) ->	**pay per use**	**service based**	**multiple uses**	**choice variety**	**ease of use**	**control**	**auto-nomy**	**rela-tional**	**active involve-ment**	**identity signal**	**social benefits**	**clean at point of use**	**healthy**	**safety & security**	**time saving**	**cost saving**
electric vehicles (EVs)			1[a]		-1[b]				1[c]	1	1	2				
autonomousvehicles			2[d]		-1[b]	-2				1	1	1		+/-	2[d]	
fuel efficient ICEs											1	1				1
H2FC vehicles					-1[b]					1	1	1				
advanced biofuels					-1[b]					1	1	1				
car clubs, car sharing	2	2	2[e]	2[e]	1	-1[f]		2		1					+/-[g]	1
mobility-as-a-service		2		2	2		1	1	1							1
ride-sharing	2	2		2		-1[g]	-1	2	1						+/-[h]	2
e-bikes					1				1			2	1		1	1
neighbourhood EVs			1			1	2			1		2		1	1	1
modal shift to transit	2	2	1			-1[i]	-1[i]	1			1				-1[i]	
active modes		2	1[k]	1[k]		1	1		2	1	1	2	2		+/-[k]	2
telecommuting	1	1	1	1	1	2	1	1		1		2			2	1
interactive virtual reality	1	1	1			1		2		1		2			2	
disappearing traffic			1[l]					1[l]	1		2	2	2	2		
car-free communities			2[l]			1		2		2	2	2		1	1	

Figure 2. Novel attributes of *food-related* innovations relative to displaced incumbents.

As a user, I want …	*just to use*		*flexibility*		*useability*			*something more than me*				*all the usual benefits*				
novel attributes (relative to displaced incumbent) ->	***pay per use***	***service-based***	***multiple uses***	***choice variety***	***ease of use***	***control***	***auto-nomy***	***rela-tional***	***active involve-ment***	***identity signal***	***social benefits***	***clean at point of use***	***healthy***	***safety & security***	***time saving***	***cost saving***
reduced meat in diet		-1		1	-1		1	1		2	2	1	2			1
cultured meat							2					2	1	-2		-2
aquaculture						-1					2	1	2			
hydroponic growing						2							1			
aquaponics			1	1	1		1		2		1	1	2			
greenhouse + LEDs				2		2						2				2
community growing			1	1	1	1	1	2	2	1	2	1	2	1		2
urban indoor farms				2								2				2
farm shops				2	-1	1	1	2	1	2	2	1	1			-1
farmers' markets		1		2	1	2	1	2	1	2	2	1	1			1
food boxes	1	2		2	2	1	1	1	1	1	1	-1	1		2	1
community agriculture	1						1	2	1		2					
food links		1			1											
upstream redistribution				-1	2			1	1	2	2	1	-1			1

Figure 3. Novel attributes of *buildings & cities-related* innovations relative to displaced incumbents.

As a user, I want …	*just to use*		*flexibility*		*useability*			*something more than me*				*all the usual benefits*				
novel attributes (relative to displaced incumbent) ->	**pay per use**	**service-based**	**multiple uses**	**choice variety**	**ease of use**	**control**	**auto-nomy**	**rela-tional**	**active involve-ment**	**identity signal**	**social benefits**	**clean at point of use**	**healthy**	**security & safety**	**time saving**	**cost saving**
sharing spare capacity	2	2	1	2	1	1		1	1							1
smart appliances			1		2	1	-1		1	1				1[a]	1	1
internet of things			1		+/-	1	-1	1	1	1				1[a]		1
LED lighting																2
building energy management			1			1	-1									1
heat pumps					-1											-1
heat storage					-1		1									
net ZEBs						-1	1			1	1		+/-[b]			+/-[c]
pre-fab low-e new build					1					1			+/-[b]			+/-[c]
pre-fab low-e retrofit				-1	1					1			+/-[b]			+/-[c]
smart meters						1	+/-[a]		2		-1		1			1
smart infrastructure			1		1	1		1								
urban sensing			2			1								1		
urban greening			1								2	2	2			

Footnotes to Figure 1: [a] grid services, [b] home charging, [c] while driving, [d] different vehicle types, [e] if vehicles unavailable, [f] booking & access time though no maintenance time, [g] if rides unavailable, [h] dependence on schedules & access, [i] exercise, [j] depends on distance, [l] restoration of public (car-free) space.

Footnotes to Figure 3: [a] security & assisted living applications but data privacy concerns, [b] low airflow vs. comfort & warmth, [c] capital costs (higher) vs. operating costs (lower).

Linkages between disruptive low carbon innovations

Each innovation varies in the novel value proposition it offers to end users. This is clearly evident in the mappings in Figures 1-3. There are also noticeable differences between domains.

Mobility-related innovations tend to offer value across many different attributes, both in terms of service provision and in establishing a deeper, more connected and involved role for mobility users (Figure 1). This is strikingly different to the incumbent model of private car ownership and use. Alternative vehicle types which could sustain this incumbent model albeit with lower emissions offer relatively less novelty, and perform poorly on useability attributes, linked to issues such as refuelling infrastructure and range anxiety.

Food-related innovations also tend to offer value across many different attributes, although not with service-based business models (Figure 2). Rather potential disruption to incumbent centralised models of food production and retail seem more likely to come from consumers pursuing healthier, cleaner, more localised, more interconnected food systems. This is already an established market niche, and is less reliant on technological innovation than is the case for mobility.

Buildings & cities-related innovations offer the least novelty to end users. Moreover many of the innovations perform poorly on useability attributes, particularly because they tend to increase the dependence of buildings and building performance on external service providers and infrastructures, hence reducing autonomy (Figure 3). This is often the trade-off for enhancing control functionality through, for example, internet-connected devices and building systems.

Despite these differences between domains, there are also some commonalities across domains. Certain attributes perform consistently well. Attributes clustered under the "*As a user, I want ... something more than me*" are consistently cited in market research and marketing literature for mobility and food-related innovations. These are a reaction to the incumbent goods and services which distance production from largely passive consumers, supporting the extension of Toffler's (1980) 'prosumer' concept from the social media realm (in which it has been overwhelmingly evidenced) into broader realms of everyday life.

Another interesting commonality among innovations across all three domains is in the attributes clustered under the "*As a user, I want ... flexibility*". This refers to the availability of choice, variety, and need-specific or context-dependent flexibility in how a good or service is consumed. Again, this is a reaction to incumbent models of ownership which effectively lock users into a specific way of providing a service. As alternatives, car clubs offer multiple vehicle types, mobility-as-a-service offers intermodal combinations optimised for specific journey requirements, greenhouse or urban farming systems offer artificial growing conditions for non-seasonal produce, and internet-of-things opens up a range of control functionality for appliances and devices beyond a simple on/off switch.

These ‘robust’ sources of value offering the hint of novel and better energy services across multiple innovations in different domains of life are of particular interest for 1.5oC mitigation as early adoption of one innovation could spillover into early adoption of others if adoption is motivated by shared novel attributes. Clearly this depends on who early adopters are, and the context in which they adopt, but this is fertile ground for further research.

Further, certain attributes are also of interest in that they challenge incumbent carbon-intensive modes of service provision to end users. These attributes (and the incumbents they challenge) include:

- *multiple uses*: versatility and diversity of applications from a single innovation (rather than having a single purpose or function);
- *choice variety*: opportunities to use variants or trial alternatives, including through single gateways or platforms (rather than being locked-in to a specific model or option based on ownership);
- *control*: availability of more or greater modalities of control over energy, end-use services or lifestyle (rather than being scripted or circumscribed within a defined role);
- *relational*: connections with other end users through networks, relationships, or shared commitments (rather than individual autonomy);
- *active involvement*: skilled or practiced engagement in the creation, provision or consumption of an end-use service (rather than passively having or owning);
- *identity signal*: defining, reinforcing or communicating some aspect of identity (rather than being socially ‘invisible’ or neutral).

Potential emission reductions from disruptive low carbon innovations

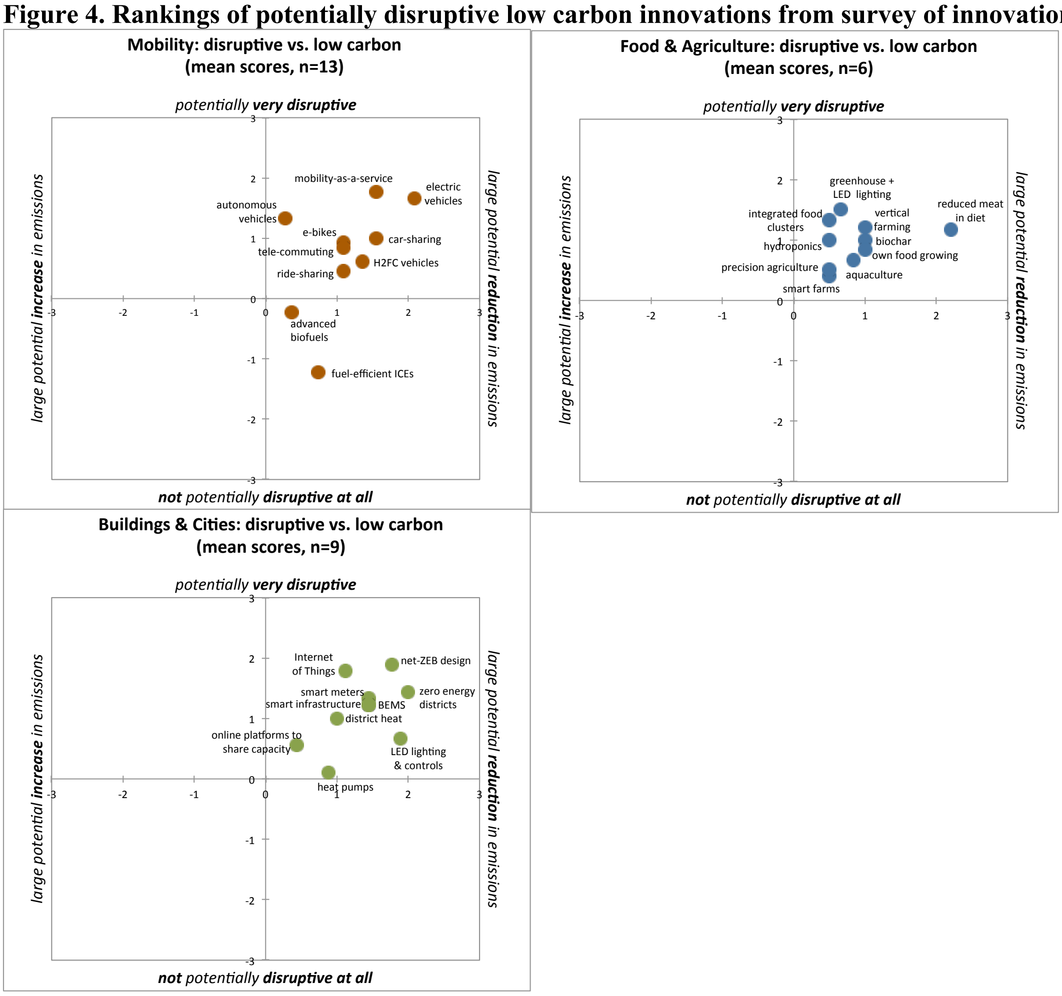
We noted from the outset that system modelling tools like IMAGE and other global IAMs are not designed to represent potentially disruptive consumer-facing innovations that shape the quality and performance attributes of end-use services. In this final section, we use both a survey of experts, and specific sectoral studies to provide initial indications of emission reduction potentials and so relevance of *d*LCIs to 1.5oC mitigation.

Survey of innovation experts

Innovation stakeholders and researchers were surveyed prior to two workshops on disruptive low carbon innovation held in London in spring 2017. A total of 28 respondents scored innovations in one of the three domains (mobility, food, buildings & cities). This is a small sample size and provides illustrative results only. The innovations are listed above in Tables 4-6 (and are marked by * to denote they were also included in the survey).

Respondents scored the innovations on two 7 point scales: potential disruptiveness (+3 = potentially very disruptive, -3 = potentially not disruptive at all); and potential emission reductions (+3 = large reduction in emissions, -3 = large increase in emissions). Figure 4 plots the mean scores on potential disruptiveness (y-axis) and potential impact on GHG emissions (x-axis) for innovations in each of the three domains. The scores are contingent on the innovations being adopted at scale in the market, so take into account both the size of the potential user segment, the incumbent form of the good or service being substituted, and the resulting effect on energy use and emissions.

Figure 4. Rankings of potentially disruptive low carbon innovations from survey of innovation experts.



The innovations in the *top half* of the Figure 4 plots are more strongly consistent with the key characteristic of *d*LCIs in offering novel attributes to end users. Those innovations in the *top right quadrant* of the Figure 4 plots also offer potentially large emission reductions if widely commercialised.

According to experts, the *d*LCIs towards the upper right corner of the plots are the most promising in being both potentially disruptive and potentially emissions-reducing. Focusing particularly on potential impact on emissions as required by 1.5oC mitigation, the top three *d*LCIs in each domain are:

- *mobility*: mobility-as-a-service, electric vehicles (EVs), car-sharing (or car clubs);
- *food*: reduced meat in diet, vertical farming, own-food growing;
- *buildings & cities*: net zero-energy buildings, building energy management systems, LED lighting.

These offer promising avenues for consumer-facing innovations to reduce emissions.

Innovation-specific studies of emission reductions

Detailed studies of specific innovations have also quantified emission reduction potentials using a variety of bottom-up modelling and other tools. Here we provide select examples, focusing on the three potential dLCIs in each of three domains identified as most promising by the experts surveyed. All these examples confirm the emission-reducing potentials of *d*LCIs in different domains.

- *mobility*: mobility-as-a-service, electric vehicles (EVs), car-sharing (or car clubs).

Two recent studies by the International Transport Forum (of the OECD) estimated the city-scale impacts of shared mobility using an agent-based simulation model of Lisbon, Portugal, based on real mobility and network data. The first study simulated shared mobility using a combination of shared taxis (on-demand, door-to-door) and taxi-buses (30 minute pre-book, flexible route, near door-to-door). This study found that 3% of the existing car fleet could provide a flexible, cheap, available, comfortable alternative to private vehicle ownership and use (ITF 2016). CO_2 emissions fell by 34%. Activity (vehicle.km) fell by 23%. The cost of urban journeys fell by >50%. Congestion fell to close to zero. The size of the car fleet fell by 97% freeing up enormous infrastructure for repurposing to parks, playgrounds, walking and cycling infrastructure. High load factors for on-road vehicles also meant more rapid fleet turnover with rapid substitution of cleaner, more efficient vehicle types. A second study examined the impacts of an autonomous shared vehicle fleet comprising both shared ('Taxibots') and single passenger ('Autovots') self-driving passenger cars (ITF 2015). This study found that 10-20% of the existing car fleet could provide a viable alternative to both private cars and buses, with commensurate benefits for freed-up road infrastructure. A similar study for the US by RethinkX found that autonomous electric vehicles providing Mobility-as-a-Service ('MaaS') could - by 2030 - reduce the size of the car fleet by over 75%, lower energy demand by 80% (although with an 18% rise in electricity demand, principally off-peak) and reduce CO_2 emissions by 90% (assuming a decarbonising grid) (Arbib and Seba 2017).

- *food*: reduced meat in diet, vertical farming, own-food growing.

A recent study by Springmann et al. (2016) analysed the health and environmental benefits of reducing the fraction of animal-sourced foods in diets. Using a region-specific global health model based on dietary and weight-related factors they found that moving toward more plant-based diets could reduce global mortality by 6-10% and food related GHG emissions by 29-70% in 2050 compared to a reference scenario. A study by Scarborough et al. (2014) analysed the diets of large samples of meat-eaters, fish-eaters, vegetarians and vegans in the UK. They found that GHG emissions were high for meat-eaters (up to 7.19 kgCO2e/day), medium for fish-eaters (3.91 & 3.81 kgCO2e/day for fish-eaters and vegetarians respectively), and low for vegans (2.89 kgCO2e/day). In a study based on a life cycle assessment (comparing an animal to a laboratory) Tuomisto and Teixeira de Mattos (2011) analysed the environmental impacts of cultured meat production (grown in a bioreactor) as an alternative to conventionally produced European meat. They estimated that cultured meat involves 7-45% lower energy use compared to animal production resulting in 78-96% lower GHG emissions, 99% lower land use and 82-96% lower water use. Vertical farming involves the provision of fresh food in and around towns and cities through greenhouses that use a fraction of the resources used by traditional farms. Drury (2017) found that greenhouse horticulture has the potential to reduce energy consumption by around 71% with resulting GHG emission savings. Emission reductions from own-food growing is highly variable and context-specific, but certainly reduces the carbon footprint of globally sourced, out of season food from large out of town retailers.

- *buildings & cities*: net zero-energy buildings, building energy management systems, LED lighting.

In a recent study of smart cities, Kylili and Fokaides (2015) found that net zero energy buildings (nZEBs) reduce energy consumption by up to two thirds that of a traditional building. The Green Investment Bank estimate that large scale switching to LED street lighting in the UK would save 50 to 80% of energy costs saving GHG emissions equivalent to taking 330,000 cars off the UK roads (Paterson-Jones and Watson 2014). Building energy management systems (BEMS) include tools which shift and curtail energy demand to improve the energy consumption and production profile of a building in response to prices and end-user needs for comfort. Beaudin and Zareipour (2015) found that a BEMS installed in a domestic property could reduce electricity costs by 23.1% and reduce residential peak demand by 29.6%, with corresponding benefits for GHG emissions.

Conclusions

This is a preliminary analysis of *d*LCIs and their potential to reduce GHG emissions. According to both experts and innovation-specific quantifications, *d*LCIs offer substantial emission-reduction potentials. The rankings in Figure 4 provide a further indication of their potential disruptiveness to the incumbent carbon-intensive modes of goods and service provision: private car ownership and use; centralised large-scale food production and retail; non-responsive inefficient building design and performance. Subsets of *d*LCIs in each of three domains perform well on two criteria: they are disruptive (in offering novel attributes from those valued by mainstream users); and if adopted at scale they offer significant potential reductions in GHG emissions.

For mobility, this subset of *d*LCIs comprises mobility-as-a-service, electric vehicles (EVs), car sharing (potentially with autonomous vehicle fleets). These are predominantly characterised by a move towards mobility becoming a pay-per-use service using modes which are clean at the point of use.

For food, this subset of *d*LCIs comprises reduced meat in diet, vertical farming, own-food growing. These are predominantly characterised by a move towards more urban and localised food production, and changing dietary preferences (with strong health benefits).

For buildings & cities, this subset of *d*LCIs comprises net zero energy buildings, building energy management systems, LED lighting. These are predominantly characterised by technological innovation in building design and operating to provide more responsive and efficient living environments.

These *d*LCIs are the potential kernel of an end user-led transformation in the dominant forms of mobility, food production & consumption, and building & city design.

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