Disruptive Low Carbon Innovations

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Abstract

Mitigating climate change requires disruptive low carbon innovations to challenge prevailing technologies or practices and lead to step change reductions in emissions when adopted at scale. Disruptive innovations are distinctive in offering novel product or service attributes to end users. Many potentially disruptive low carbon innovations exist today, but in small numbers. As examples, car clubs, car sharing, and reuse networks challenge mainstream consumer attributes of ownership, autonomy and status.

This paper investigates the potential for disruptive innovations to transform the market for energy-related goods and services. First, we consider the key concepts of disruption innovation, and propose a set of characteristics that define disruptive low carbon innovations. Second, we review sectoral and economy-wide studies of low carbon innovation, and use our set of characteristics as screening criteria to identify potentially disruptive innovations. We focus particularly on innovations relating to mobility. Third, we draw on innovation case studies to identify the novel attributes offered by these disruptive low carbon innovations. We assign rankings to these attributes and map how they compare across different innovations. We find that attributes common to different innovations include offering greater variety of choice, having a relational aspect, and being pay-per-use. Fourth, we use data from a small survey of innovation experts to evaluate a set of mobility-related innovations by their potential disruptiveness and their potential emissions impact. We find six mobility-related innovations that score highly on both criteria: mobility-as-a-service, car clubs, ride-sharing, e-bikes, telecommuting, 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
EV & NEV = electric vehicle & neighbourhood electric vehicle
GHG = greenhouse gas
ICE = internal combustion engine
ICT = information and communication technology

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). The attributes valued by end users of the energy innovations which enabled these transformations in energy service provision included versatility, reliability, availability, transportability, functionality, and cleanliness (at the point of use).

Low carbon energy services consumed directly by end users include renewably-fuelled heating, electrically-powered auto-mobility, or vegetarian sustenance. However the distinguishing feature of such services is that they are less energy or carbon intensive than alternatives. Rather than improving functionality for end users, they provide the same basic service but with different production characteristics (lower emissions). Low carbon innovations from solar PV and offshore wind, to smart grids and large-scale storage, to electric vehicles and energy efficient homes are emphasised in modelling studies, mitigation scenarios, national climate plans (UK_CCC 2010), and R&D initiatives (King 2017). Yet most of these technological innovations similarly offer few novel attributes to end users. Low carbon innovations lack widespread appeal or the pull of strong consumer demand. User communities - whether individuals, households, local groups, neighbourhoods - are insufficiently strong to act as a coordinating agent for escaping carbon lock-in (Lockwood 2013). End users are a missing constituency in energy system transformation as low carbon innovations do not offer substantially novel or differentiated attributes beyond those already valued in mainstream markets.

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.

Sustaining vs. disruptive innovations

An important distinction is therefore 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.

The distinction between sustaining and disruptive innovations (about attributes and users) contrasts with the widely-used typology distinguishing radical and incremental innovations (about technological improvements). Whereas *incremental* innovations improve cost or performance attributes without altering basic technological designs, *radical* innovations have design architectures or fundamental technological concepts that are novel. As examples, perovskite offers a novel material concept for solar PV panels (radical) whereas improved etching techniques for silicon wafers improves module efficiency (incremental). But neither innovation is disruptive as - for the end user - solar PV continues to improve in cost and performance. In contrast, a business model innovation creating value from decentralised PV and battery storage with ICT-enabled peer-to-peer electricity trading is potentially disruptive as it offers end users new attributes of autonomy and independence (from grids and from utilities) and an active trading role in electricity markets (in lieu of passivity).

Characteristics of disruptive innovations

Disruptive innovation theory is principally concerned with firm strategy and performance, and the distinctions between disruptive and incumbent firms. Key elements of disruption are:

- incumbent firms ignore disruptive innovations and their niche users because of low returns and/or lack of necessary internal processes, values or competencies;
- disruptive firms support experimentation, failure and learning with innovations and their users;
- disruptive firms identify business models which create value for new users, and so open up new market segments;
- innovations create asymmetric motivation as incumbent firms are motivated to move up into higher-end, more profitable segments rather than counter the strategy of disruptive firms.

However, this paper is interested specifically in the potential attractiveness of disruptive innovations for end users. In this respect, key characteristics of disruptive innovations are:

- disruptive innovations underperform on attributes valued by mainstream users, but offer novel attributes or functionality;
- disruptive innovations tend to be simpler, cheaper (and more reliable) than mainstream alternatives which have become over-specified in meeting users' needs;

- disruptive innovations appeal initially to low-end, price-sensitive users or non-users;
- disruptive innovations develop in initial market niches until their performance on mainstream attributes improves or mainstream users' preferences shift towards the novel attributes or functionality.

Examples of disruptive innovations

Examples of disruptive innovations that performed poorly on attributes valued by mainstream users but offered novel functionality to end users include (Christensen 1997, Govindarajan and Kopalle 2006, Lambert 2014):

(1) small off-road motorcycles (e.g., Honda) vs. large, powerful bikes (e.g., Harley);

(2) transistors vs. vacuum tubes;

(3) discount retailing vs. department stores;

(4) drones vs. fighters and bombers;

(5) digital photography vs. film;

(6) mobile telephones vs. landline service;

(7) desktop photocopiers vs. giant Xerox copy machines;

(8) Wikipedia vs. Encyclopaedia Britannica.

Applying disruptive innovation theory to social change

The disruptive innovation literature is principally concerned with business strategy and management, not on the potential for disruptive innovations to affect system outcomes - like GHG emissions. Disruptive innovation theory has not been applied to climate change mitigation. Web of Science search found only 2 hits for the terms 'disruptive innovation' and 'low carbon': a peer-reviewed article applying disruptive innovation theory to food security (Tyfield 2011); and a conference paper considering the potential for disruptive innovations in China's economic development (Wang and Chen 2008). However, there is precedent for applying disruptive innovation theory outside business studies and firm management.

Christensen has co-authored two books that examine disruptive threats to higher education (Christensen et al. 2008) and healthcare (Christensen et al. 2009). In both cases, the emphasis is on innovations "*for providing public services to people and in contexts which are marginalised by mainstream service providers*" (Christensen et al. 2006). Examples include: massive open online courses (MOOCs) vs. university degrees; online classes in noncore subjects to high school students alongside taught classes at school; nurse practitioners vs. medical doctors; walk-in clinics in pharmacies using software-based protocols to diagnose and treat common health problems; outpatient and in-home clinics vs. general hospitals. In each case, the innovations are lower cost, simpler, 'good enough', and serve an under-served need or market segment (Christensen et al. 2006). A critique of these public service-oriented applications of disruptive innovation theory is that they fail to account for the quality of the interaction (between patient and doctor, between pupil and teacher) which is critical in non-market contexts (Lepore 2014).

Disruptive low carbon innovations

The aim of this research 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.

Building on Christensen's canonical definition of disruptive innovation, the identification of disruptive *low carbon* innovations needs to take into account: (1) the need for widespread adoption of an innovation to result in emission reductions; (2) critiques and modifications of disruptive innovation theory since its original publication; (3) the disruptive potential of ICTs, big data and machine learning converging into traditional energy infrastructure and energy-using consumer goods.

Low carbon outcomes

Innovation studies are generally concerned with the generation and adoption of novelty, rather than their systemic consequence. However, Jordan and Huitema (2014) include 'effects' alongside 'invention' and 'diffusion' in their analysis of climate policy innovations, arguing that what is actually achieved by the introduction of new policies defines their innovativeness.

The first and most obvious adaptation to the characteristics of disruptive innovations listed above is that disruptive *low carbon* innovations must have the potential to substantially reduce greenhouse gas emissions if adopted at scale. This is a marked shift in emphasis from the consequence of disruptive innovations on specific firms to the consequence of how the adoption and use of disruptive innovations affects energy use and emissions. This depends not just on the energy-using characteristic of the innovation, but also on what it displaces or substitutes for.

Low-tech vs. high-tech: is Tesla disruptive?

The second main adaptation to the characteristics of disruptive innovations defined originally by Christensen reflects ongoing arguments in the field about high-end and/or high-tech sources of disruption (Seba 2014). According to Christensen, performance over-supply occurs as a result of incumbents' innovative efforts to continually improve their goods and services along the attributes valued by mainstream users. The rate of technological progress outstrips users' rising expectations and needs, opening up the lower end of the market to cheaper, simpler alternatives. Disruptive innovation creates the possibility so "*normal people can do what only the rich and very skilled could do before*" (Lambert 2014). This dynamic is clearly evident at the high end of many energy-using consumer goods including cars and mobile computing. Product over-specification opens up space for disruptive technologies which meet minimal requirements for functionality, but are more reliable, simple, cheap, convenient or otherwise offer novel attributes.

This is one prescriptive characteristic of Christensen's conceptualisation of disruption which has proved controversial. Is an *iPhone* or a *Tesla Model S* disruptive? Tesla in particular has sparked column inches of disagreement. Elon Musk is the poster child of disruption in the energy and automotive industries. Yet Tesla's initial defining electric vehicle, Model S, appeals to the very top-end of the market, retailing at over $70,000 in the luxury or sports car niche, and as over-performing as conventional ICE vehicles on attributes such as speed, acceleration, features and size (Christensen 2014). Through this lens, Tesla is a classic *sustaining* innovation, offering incrementally better performance at higher price, and competing on a like-for-like basis with the dominant selling (high-end) vehicles in the market (HBR 2015).

According to Christensen, electric vehicles (EVs) for mobility are potentially disruptive ... but in the form of golf carts not the Tesla Model S (Christensen 2014). These so-called 'neighbourhood electric vehicles (NEVs)' offer personal mobility to teenagers in suburbia or the elderly in retirement communities who would otherwise be travelling by transit, the cars of their carers (parents, relatives, friends), or not at all (Lambert 2014). In a suburban of Atlanta, Georgia, city planners have built extensive parking and recharging infrastructure for electric golf carts which teenagers are permitted to drive unsupervised (Horn 2014). These NEVs fail against all the attributes of vehicles valued by mainstream users. However, they enfranchise non-users with a service (personal mobility) from which they have been excluded by mainstream technologies (cars), while providing novel attributes: "*[An NEV] won't go fast or ride on the freeway. It costs about $5,000. It's really not a car, it's a mobile sound system*" (Lambert 2014).

Others reject the restrictiveness of Christensen's definition of disruptive innovation. For them, Tesla is clearly a disruptive threat to conventional ICE vehicles through the extent of its integration with advanced ICTs ("an iPad on wheels"). Not only does this allow for continuous software-based upgrades to its operating capabilities, but also provides new capabilities for both autonomous driving and grid services such as load balancing when recharging (Seba 2014). To generalise this argument, disruption can and does come from above, i.e., 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. But they disrupt mainstream rivals as 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). It's worth noting, however, this form of high-end disruption blurs the distinction between the *disruptive - sustaining* typology used by Christensen to distinguish innovations in terms of their attractiveness to end users, and the *radical - incremental* dichotomy that characterises the extent of technological advancement or breakthrough (Nemet 2009).

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 (NEVs), bike-share schemes, and even car-free or live-work communities (see below for details). However there are also many examples of high-tech challenges to established goods, services and practices. These tend to (but not always) 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 alternative forms of shelter and warmth from smart homes and the internet of things, to net zero-energy buildings and standardised pre-fabricated retrofits (Energiesprong) (CAT 2017).

To ensure we capture these potentials for rapid emission reduction, we relax the criterion that disruptive low carbon innovations have to provide simpler, cheaper alternatives, even though this certainly may be the case.

Non-users, and the bottom of the pyramid

The case of the NEV outlined above is a good example of novel attributes appealing to non-users: "*NEVs could eventually be what PCs were to minicomputers or what desktop copiers were to giant Xerox machines. Starting at the bottom still makes strategic sense*" (HBR 2015). This appeal to the bottom potentially enfranchises users marginalised from mainstream markets. This particular market segment is known as the 'bottom of the pyramid' (Hart and Christensen 2002, Prahalad 2004).

The phenomenal recent growth in e-bike sales in China is another bottom-of-the-pyramid application of disruptive innovation (Ruan et al. 2014, Tyfield et al. 2014). E-bikes are a simple configuration of existing technologies: bicycle, electric motor, controller and battery. E-bikes perform poorly against attributes valued by mainstream motorcycle users (speed, load, mileage). However e-bikes are much cheaper, easier to use, and reliable. These features appealed initially to 'non-users' (of motorcycles), particularly children, women, and the elderly whose daily transport needs exceeded the potential of the manual (non-electric) bicycle. As e-bike manufacturing in the mid-1990s was initially low quality and small-scale, serving only a specific market niche, it did not provoke a competitive response from the motorbike industry. But by 2005, e-bike sales in China exceeded those of gasoline-powered motorbikes. In 2010, almost 30 million e-bikes were sold, with China accounting for over 90% of the international market (Ruan et al. 2014). E-bikes illustrate a route to pollution control and emission reduction while developing the capabilities of previously marginalised consumers (Ruan et al. 2014).

However, for disruptive *low carbon* innovations, there's a clear tension between low carbon outcomes (emission reduction) and the enfranchisement of 'non-users'. To the extent that previous forms of non-consumption were low or zero-emission (e.g., households without cars who walked, cycled, or used public transport), the provision of disruptive new goods and services for mobility will not help reduce emissions, even if the innovations themselves are efficient or low carbon. In a development context, moving up the energy ladder from traditional (non-commercial biomass) to modern energy resources (grid electricity, solar homes, LPG, clean cookstoves) is typically net beneficial for emissions, particularly if forest or land clearance is avoided (Johansson et al. 2012). Further up the ladder, particularly in developing country cities, the acquisition of new energy services - cars for mobility, AC for space conditioning, meat for nutrition - is likely to be net negative for emissions even if strongly beneficial for material wellbeing and development. The emergence of e-bikes and now low-cost low-speed electric vehicles in China is reinforcing the car as the number one consumer aspiration for Chinese people who can express individual freedom and identity through their consumption practices but not their politics (Tyfield et al. 2014).

This limits the extent to which disruptive innovation theory can be applied directly onto GHG emission reductions as it relies on disruptions creating new growth markets among the under-consuming, and that 'business models' pursue these disruptions to profit and grow. Consequently, we relax the criterion that disruptive low carbon innovations have to serve low-end users or non-users, even though this certainly may be the case.

Characteristics of disruptive low carbon innovations

Table 1 summarises the characteristics of disruptive low carbon innovations based on Christensen's canonical definition but adapted as explained above to correspond with the particular emphasis here on climate change mitigation. In sum, we use the term 'disruptive low carbon innovations' (*d*LCIs) to mean low carbon innovations that offer novel attributes or functionality not currently valued by mainstream users and that can significantly reduce GHG emissions if adopted by mainstream users, typically by displacing or substituting for more carbon intensive goods and services. *d*LCIs may be simpler and cheaper than over-performing mainstream alternatives, but may also be high-tech, highly-specified alternatives on exponential improvement curves. Consequently, *d*LCIs may appeal initially to low-end, price-sensitive users or non-users, but may also appeal to high-end, price-insensitive early adopters attracted by technological novelty. We are particularly interested in the main user-facing characteristic of *d*LCIs which is that they offer novel attributes not currently valued by mainstream users.

Table 1. Characteristics of disruptive low carbon innovations (✔ = required; ✖ = not necessarily required).

	any low carbon innovation	Christensen: disruptive innovation	disruptive low carbon innovations (*d*LCIs)
novel application of knowledge	✔	✔	✔
initially attractive in a market niche then performance improves	✔	✔	✔
reduces greenhouse gas emissions if adopted at scale	✔	✖	✔
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	✖	✔	✖
simpler, low-tech alternatives to over-performing mainstream products	✖	✔	✖

Previous studies of disruptive low carbon innovations

Several recent studies which scan the horizon for potentially disruptive innovations are relevant to energy and/or GHGs. Tyfield and Jin (2010) is the only study to our knowledge which has specifically examined disruptive *low carbon* innovations. They focus on China, and identify seven potentially disruptive technologies (and their sponsoring firms) with a combined emission reduction potential of 0.3 $GtCO_2$ per year: e-bikes (by Luyuan); solar thermal water tanks (by Himin Group); anaerobic biogas digesters and slurry for organic agriculture (by GEI Lijang Snow Mountain Biogas Project); biomass pellets from agricultural residues (by Shengchang Biomass); low-tech AC and solar desalination (by ISAW); hydrogen fuel cells for generators, specialised vehicles, hand-held power sources (by Pearl Hydrogen); high-efficiency water purification for industrial processes (by ZNHK Sin-entech).

Other market surveys tend to focus either on low-cost manufactures, particularly from China, or on new 'game-changing' technologies in the energy sector but which offer few novel attributes to users.

Hang et al. (2015) identify four disruptive innovations through case studies of their sponsoring firms: e-bikes in China (by Luyuan); wind turbines in India (by Suzlon); water purifier in India (by Tata Swach); low power microchip in Europe (by ARM). Tyfield (2011) identifies low-cost disruptive innovations from Chinese manufacturers which are transforming global competition: harbour cranes (by ZPMC, 52% of the world market); medical X-ray equipment (by Zhongxing Medical, 10% of the price of established rivals and with 50% of the Chinese market); supercomputers (by Dawning, the second fastest in the world but at about one-third of the price per megaflop and with half the energy demand of the fastest); container ships (by CIMC, 55% of global market share and six times the size of its nearest rival). Tyfield et al. (2010) identify further examples in which Chinese businesses are global leaders in relatively high-technology sectors by socially re-defining established technologies at 'good enough' levels of functionality and low prices that appeal to new user segments: cars (by Chery, BYD); electrical goods (by Haier); pianos (by Pearl River); consumer electronics (by TCL).

In all these cases, the emphasis is on low-cost alternatives to mainstream goods. However, it is difficult to distinguish the novelty of performance attributes of these innovations, in addition to their low cost base. As such, their characteristics as disruptive low carbon innovations (*d*LCIs) are unclear.

With a clearer focus on disruptiveness rather than low-cost, low-end technological substitutes, McKinsey (2012) identify ten disruptive innovations which are or will affect energy productivity, focusing on the US: 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 retrofit. 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).

Scoping survey of disruptive low carbon innovations

We sampled recent literature on technological change linked to low carbon energy. We reviewed both sectoral and economy-wide reports (including modelling and scenario studies), as well as innovation-specific studies (see above for references). Literature reviewed included 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. As noted in the introduction, we were particularly interested in the novel attributes offered to end users by each innovation. We examined mobility, shelter and warmth (housing), and a range of consumer goods and related practices.

Examples of *d*LCIs relating to mobility include car clubs, car sharing and car-free communities that perform poorly on valued mainstream attributes associated with car ownership. Rather they offer novel attributes to end users including service use, collaboration, inter-dependent exchange, and no maintenance or care obligations. Car clubs such as Zipcar and Car2Go offer a pool of vehicles to members for use over short periods of time on an as-needs basis (Shaheen et al. 2010). Car sharing (or lift sharing) is the shared use of a private vehicle for a specific journey, particularly commuting (Deloach and Tiemann 2010). Car-free communities integrate car free mobility into the design of urban neighbourhoods with strong public transport links and walking and cycling infrastructure (Ornetzeder et al. 2008).

Examples of *d*LCIs relating to shelter and warmth (housing) include smart homes, net zero energy homes, and networked PV-storage systems that perform poorly on valued mainstream attributes such as low upfront cost, convenience, passive end-user roles, and dependence on centralised networks or utilities. Rather, they offer novel alternative attributes to end users including control, automation, active user and producer roles, and autonomy. Smart homes comprise sensors, monitors, interfaces, control hubs, and devices that are networked wirelessly, and allow households to control, automate and optimise the domestic environment (Cook 2012). Net zero energy homes combine advanced whole-system efficiencies (e.g., to Passivhaus standards) with onsite renewable generation (Sartori et al. 2012). Networked PV-storage systems with peer-to-peer trading (within communities or on the distribution grid) extend the potential for low energy homes to reduce or eliminate reliance on centralised service provision.

Examples of *d*LCIs relating to consumer goods include reuse networks (e.g., Freecycle) and service economies that perform poorly (if at all) on valued mainstream attributes of ownership, newness, and brand status. Rather, they offer novel alternative attributes to end users including use value, reciprocity, and collaboration. They are also potentially low carbon (Foden 2012). One study of a reuse network in the US (Craigslist) found the increased incentives for people to exchange rather than discard used goods reduced daily per capita solid waste generation by around 50kg a year (Fremstad 2017).

It is important to emphasise that these are broad-brushed examples of how the novel attributes of *d*LCIs for different energy services 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

We present more detailed results for mobility-related *d*LCIs, characterising the novel attributes for each innovation. Table 2 shows a set of 10 potential *d*LCIs (denoted by *) identified in the literature and linked to an 'incumbent' form of mobility for which they offer a substitute (which in turn determines their potential impact on GHG emissions). For comparison purposes, Table 2 also includes an additional 2 technological innovations (denoted by +) and a set of 4 commonly-cited strategies for reducing the need for, or consumption of, auto-mobility (denoted by o). These include structural approaches (e.g., designing and building car-free communities) as well as modal shifts (to public transport or active modes).

Table 2. Mobility-related innovations and strategies (* denotes innovations included in survey of innovation experts - see below; + denotes additional technological innovations; o 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)	internal combustion engines (ICE) vehicles
	*	autonomous (self-driving) vehicles	conventional ICEs
	*	fuel efficient ICEs	conventional ICEs
	*	hydrogen fuel cell vehicles	conventional ICEs
	*	advanced biofuels	conventional ICEs
alternative form of auto-mobility	*	car clubs, car sharing	car ownership & use
	*	mobility-as-a-service [1]	car ownership & use
	*	ride-sharing	car ownership & use
alternative to auto-mobility	*	e-bikes	bikes, motorbikes
	+	neighbourhood EVs	walking, public transport
	o	modal shift to public transport	car use
	o	active modes (walking, cycling)	car use, public transport
reduced demand for auto-mobility	*	telecommuting, video- or teleconferencing	commuting
	+	interactive virtual reality [2]	commuting, teleconferencing
	o	disappearing traffic [3]	road infrastructure
	o	car-free communities	car-dependent suburbs

Table notes: [1] mobility-as-a-service ('Maas') refers to app-based scheduling, booking and payment systems for multiple transport modes (ride-sharing, bus, train) through a single gateway or account; [2] virtual reality can be used for immersive remote communication including, e.g., medical diagnosis or surgery; [3] disappearing traffic refers to the removal of road infrastructure and restoration of car-free urban environments (e.g., express freeways in Seoul, South Korea).

Attributes of mobility-related d*LCIs*

Figure 1 provides an initial mapping of the novel attributes offered to end users by these different mobility-related innovations and strategies. These attributes are illustrative only, and are based on the attributes, functionality, service features or performance characteristics cited in the literature reviewed. The novelty of these attributes in all cases is *relative to* the incumbents assumed to be displaced (see Table 2). So, for example, although an EV may offer its owner and user 'control' and 'autonomy', this is not distinct from a conventional ICE vehicle so these attributes are not novel.

novel attributes (relative to displaced incumbent) ->	**pay per use**	**service-based**	**multiple uses**	**choice variety**	**rela-tional**	**control**	**auto-nomy**	**active (doing)**	**identity signal**	**clean at point of use**	**healthy**	**time saving**
electric vehicles (EVs)			(+)[1]					(+)[2]	(+)	+		
autonomous (self-driving) vehicles			+[3]			-			(+)	(+)		+[3]
fuel efficient ICEs										(+)		
hydrogen fuel cell vehicles									(+)	(+)		
advanced biofuels									(+)	(+)		
car clubs, car sharing	+	+	(+)[4]	+[4]	+	(-)[5]			(+)			+/-[6]
mobility-as-a-service		+		+	(+)		(+)	(+)				
ride-sharing	+	+		+	+	(-)[7]	(-)	(+)				+/-[6]
e-bikes								(+)		+	(+)	(+)
neighbourhood EVs			(+)			(+)	+		(+)	+		(+)
modal shift to public transport	+	+	(+)		(+)	(-)[8]	(-)[8]					(-)[8]
active modes (walking, cycling)		+	(+)[9]	(+)[10]		(+)	+	+	(+)	+	+	+/-[10]
telecommuting, videoconferencing	(+)	(+)	(+)	(+)	(+)	+	(+)		(+)	+		+
interactive virtual reality	(+)	(+)	(+)		+	(+)			(+)	+		+
disappearing traffic			(+)[11]		(+)[11]			(+)		+	+	
car-free communities			+[11]		+	(+)			+	+		(+)

Figure 1. Novel attributes of mobility-related innovations and strategies <u>relative to</u> displaced incumbents (shown in Table 2). *Key: + = strong positive association between novel attribute and innovation; (+) = weak positive association; blank = no association; +/- = contingent association; (-) = weak negative association; - = strong negative association. Notes: [1] grid services, [2] home charging, [3] while driving, [4] different vehicle types, [5] if vehicles unavailable, [6] booking & access time though no maintenance time, [7] if rides unavailable, [8] dependence on schedules & access, [9] exercise, [10] depends on distance, [11] restoration of public (car-free) space.*

Novel attributes that are shared by several different *d*LCIs in Figure 1 include:

- *multiple uses*: versatility and diversity of applications from a single innovation (<u>rather than</u> having a single purpose or function);

- *choice variety*: opportunities to trial alternatives (rather than being locked-in to a specific model or option based on ownership);
- *relational*: connections with other end users through networks, relationships, or shared commitments (rather than individual autonomy);
- *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);
- *active (doing)*: 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);
- *clean at point of use*: low emission or low polluting means of mobility, low waste impact or foregone demand for mobility (rather than being inefficient, profligate or otherwise dirty at the point of use).

Rankings of mobility-related d*LCIs*

Figure 2 (left panel) ranks the mobility-related innovations from Table 2 against two of the criteria for disruptiveness: novelty of attributes offered to end users (y-axis) and technological complexity (x-axis). Rankings are subjective, based on the strength of evidence in available literature. The four additional structural approaches for reducing demand for auto-mobility are also ranked for comparison purposes. Innovations in the top half of the plot shows potential *d*LCIs as these offer novel attributes to end users. These include:

- *alternative fuel or vehicle technology*: electric vehicles (EVs), autonomous vehicles;
- *alternative form of auto-mobility*: mobility-as-a-service (MaaS), car clubs, ride-sharing;
- *alternative to auto-mobility*: e-bikes, neighbourhood electric vehicles (NEVs)
- *reduced demand for auto-mobility*: telecommuting, interactive virtual reality.

Of these nine potential *d*LCIs, three are high tech (top right of figure) and so do not conform with the canonical definition of disruptive innovation by Christensen (see Table 1).

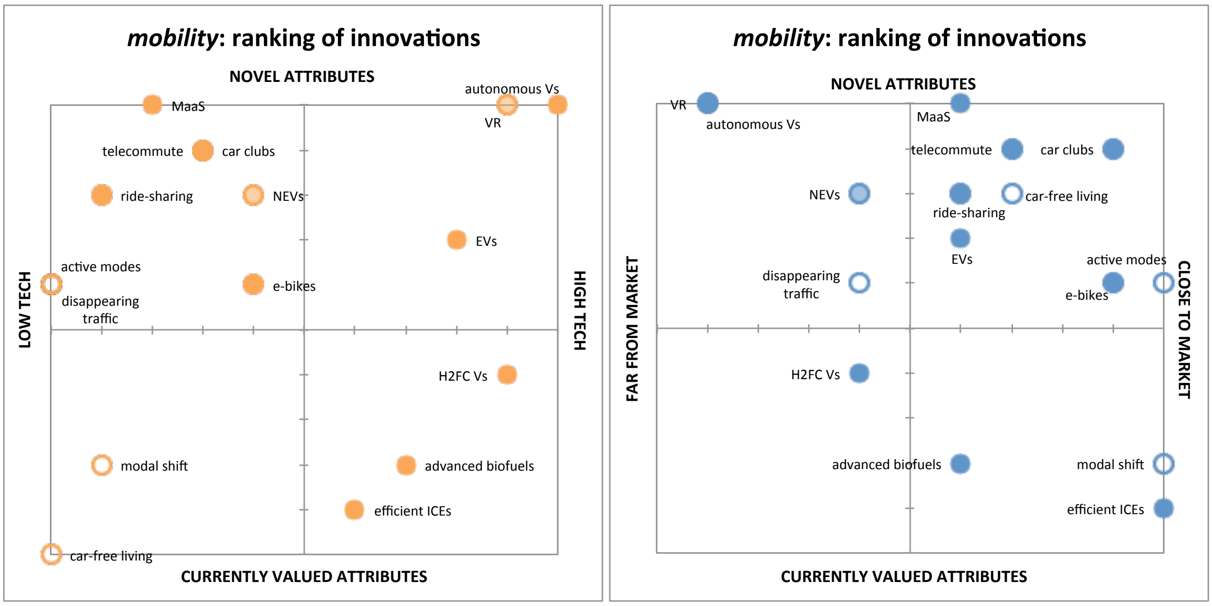

Figure 2. Novel attributes vs. technological complexity (left panel) and proximity to market (right panel) of mobility-related disruptive low carbon innovations. *Notes: Rankings are based on subjective interpretations of available literature (see text). Data points show: 12 potentially disruptive low carbon innovations (filled circles & shaded circles) and 4 mobility-related strategies for comparison purposes (open circles).*

For the same set of innovations and strategies, Figure 2 (right panel) ranks the novelty of attributes (y-axis) against proximity to market as a first order indication of the timescale to widespread commercialisation (x-axis) and so the potential for emission reduction. *d*LCIs in the top left of the figure are potentially disruptive, but are considered to be further from market. This may be because of incompatible social norms or institutional context (e.g., NEVs), required technological breakthroughs (e.g., autonomous vehicles, virtual reality), or required regulatory and institutional changes.

Overall, Figure 2 points towards six potential *d*LCIs with near-term potential for emission reductions (top right of figure): five are low tech (mobility-as-service, car clubs, ride-sharing, e-bikes, telecommuting) and one is high tech (EVs). These are predominantly characterised by a move towards mobility becoming a pay-per-use service.

Innovation expert scoring of mobility-related d*LCIs*

Innovation stakeholders and researchers with expertise in the field of mobility and transportation were asked to score a set of 10 mobility-related innovations (marked by * in Table 2) using an online survey. The survey was implemented prior to a series of two workshops on disruptive low carbon innovation held in London on 7-8 March 2017. A total of 13 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 3 plots the respondents' mean scores on potential disruptiveness (y-axis) and potential impact on GHG emissions (x-axis). Both 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 mobility being substituted, and the resulting effect on energy use or emissions. As in Figure 2, the innovations in the top half of the plot are more strongly consistent with the key characteristic of *d*LCIs in offering novel attributes to end users. Those innovations in the top right of the plot also offer potentially large emission reductions if widely commercialised.

All six of the potential *d*LCIs identified in Figure 2 are similarly scored by experts as being both potentially disruptive and potentially emissions-reducing. These are: mobility-as-a-service, car-sharing (or car clubs), ride-sharing, e-bikes, telecommuting, and electric vehicles (EVs). Experts also include autonomous vehicles and hydrogen fuel cell (H2FC) vehicles as potential *d*LCIs, even though their proximity to mass commercialisation seems more distant.

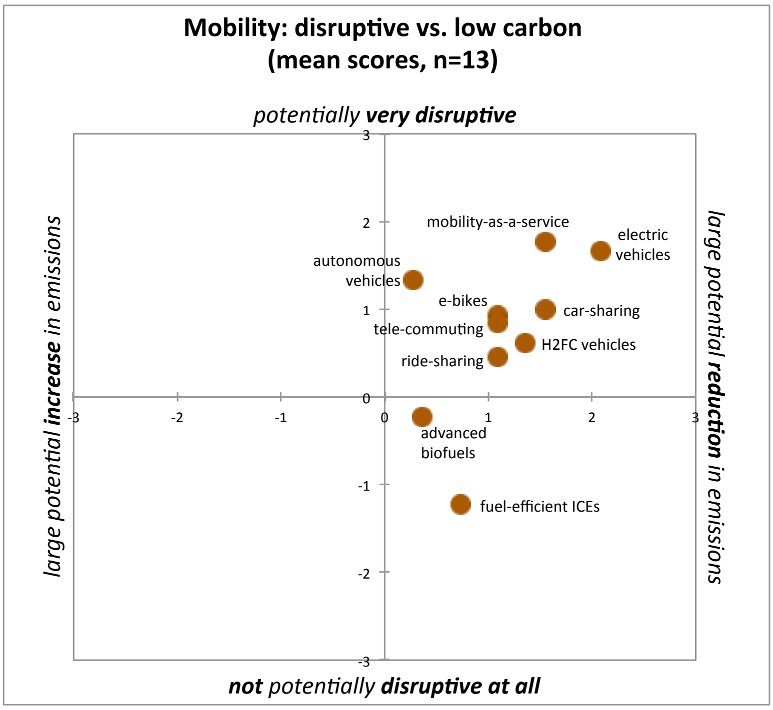

Figure 3. Potential disruptiveness and potential emission reductions of 10 mobility-related innovations. *Notes: mean scores from a survey of 13 experts working on mobility-related low carbon innovation.*

Conclusions & next steps

This is a preliminary analysis of *d*LCIs and their potential to reduce GHG emissions. The rankings of mobility-related innovations in Figures 2 and 3 provide an initial indication of their potential disruptiveness to private car ownership and use as the prevailing form of carbon-intensive mobility. From this initial analysis, a subset of six innovations perform well on three criteria: they are disruptive (in offering novel attributes from those valued by mainstream users); they are close to market (or already commercialised); and if adopted at scale they offer significant potential reductions in GHG emissions. This set of *d*LCIs comprises: mobility-as-a-service, car clubs, ride-sharing, e-bikes, telecommuting, and EVs. These are predominantly characterised by a move towards mobility becoming a pay-per-use service.

These *d*LCIs are the potential kernel of an end user-led transformation in the dominant forms of transportation. However, this depends on (1) the extent to which different *d*LCIs share novel attributes (do different disruptive low carbon innovations share a common appeal?), and (2) the extent to which early adopters of different *d*LCIs are members of similar social networks (do social influence processes spread the experiences of early adopters and so help widespread diffusion). These are the next steps for this research.

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