Energy Efficiency
https://doi.org/10.1007/s12053-018-9679-8

ORIGINAL ARTICLE

The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation

Charlie Wilson · Hazel Pettifor · Emma Cassar · Laurie Kerr · Mark Wilson

Received: 3 November 2017 / Accepted: 26 April 2018

Abstract This paper investigates the potential for consumer-facing innovations to contribute emission reductions for limiting warming to 1.5 °C. First, we show that global integrated assessment models which characterise transformation pathways consistent with 1.5 °C mitigation are limited in their ability to analyse the emergence of novelty in energy end-use. Second, we introduce concepts of disruptive innovation which can be usefully applied to the challenge of 1.5 °C mitigation. Disruptive *low-carbon* innovations offer novel value propositions to consumers and can transform markets for energy-related goods and services while reducing emissions. Third, we identify 99 potentially disruptive low-carbon innovations relating to mobility, food, buildings and cities, and energy supply and distribution. Examples at the fringes of current markets include car clubs, mobility-as-a-service, prefabricated high-efficiency retrofits, internet of things, and urban farming. Each of these offers an alternative to mainstream consumer practices. Fourth, we assess the potential emission reductions from subsets of these disruptive low-carbon innovations using two methods: a survey eliciting experts' perceptions and a quantitative scaling-up of evidence from early-adopting niches to matched segments of the UK population. We conclude that disruptive low-carbon innovations which appeal to consumers can help efforts to limit warming to 1.5 °C.

Keywords Consumers · Mitigation · Energy end-use · Innovation

Abbreviations

DLCIs	Disruptive low-carbon innovations
IAM	Integrated assessment model (process-based, global)

Transformation pathways for 1.5 °C mitigation

The Paris Agreement on climate change stated an objective of 'Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C' (Article 2). The Paris Agreement was ratified and came into force in November 2016. To limit warming to 1.5 °C, global greenhouse gas emissions must reduce to net zero around mid-century, with residual emissions thereafter being more than offset by sinks or negative emission technologies (Rogelj et al. 2015). This requires a very rapid and pervasive transformation of the global energy system.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12053-018-9679-8) contains supplementary material, which is available to authorized users.

C. Wilson (✉) · H. Pettifor · E. Cassar · L. Kerr · M. Wilson
Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR1 7TJ, UK
e-mail: charlie.wilson@uea.ac.uk

C. Wilson
International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria

Transformation pathways to achieve the 2 °C target or the more stringent 1.5 °C ambition of the Paris Agreement are quantified in detail by global integrated assessment models. Process-based integrated assessment models (hereafter 'IAMs') represent in some detail the key biophysical and socioeconomic processes in economic, energy, agricultural, forestry and other systems, as well as the impact of resulting emissions on the climate system (Sathaye and Shukla 2013). Global IAMs are commonly run over the remaining 80+ years of the twenty-first century to quantify cumulative long-term emissions and resulting warming outcomes. Consequently, IAMs provide a unique analytical bridge between global mean temperature rise, cumulative emission budgets, and detailed representations of energy-system transformation. In this way, they enable technology, cost and policy assessments of transformation pathways consistent with the objectives of the Paris Agreement.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) synthesised evidence from 116 transformation pathways for limiting warming to 2 °C quantified by over 10 global IAMs (Clarke et al. 2014). Several 'robust' features of these pathways were consistently identified by the IAMs as integral to a 2 °C future: (1) The energy supply rapidly decarbonises, including large-scale deployment of biomass with carbon capture and storage (bioCCS) as a negative emission technology; (2) energy end-use rapidly and pervasively electrifies, and economies continue to become ever-more efficient; and (3) delaying concerted global action increases costs and increases the difficulty of meeting the 2 °C target.

Two global IAM studies published recently have generated transformation pathways consistent with the even more restrictive 1.5 °C emissions budget (Rogelj et al. 2015; Luderer et al. 2016). Additional insights on 1.5 °C mitigation beyond the robust findings on 2 °C mitigation can be summarised as: 'harder and faster'. Particular emphasis is placed on energy end-use: 'Demand-side emissions account for most of the additional mitigation efforts for reaching the 1.5°C limit relative to 2°C pathways ... [because] in 2°C scenarios, freely emitting fossil installations are already almost fully eliminated from the power system by mid-century' (p19–20, Luderer et al. 2016).

Reducing demand-side emissions combines four effects: (1) improving conversion efficiencies of end-use technologies, (2) reducing losses from passive systems (particularly heat loss in buildings), (iii) reducing activity levels (e.g. passenger-kilometres of mobility, m^2 of heated floorspace), and (4) changing the structure or mix of activities towards less energy-intensive alternatives (e.g. from driving private vehicles to cycling and walking).

Global IAMs privilege mitigation from technical efficiency improvements (Table 17.11 in Riahi et al. 2012; p29 in Luderer et al. 2016). Explicit representation of end-use technologies and their passive systems in IAMs is generally quite coarse—and necessarily so for parsimonious and tractable models trying to capture the entire global energy system. 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 (Wilson et al. 2012). Many end-use technologies are also consumer goods with a variety of attributes over which end-user preferences vary (Mundaca et al. 2010). Energy efficiency may be traded off against style, speed, safety, size and status. These 'behavioural' characteristics of end-use technology adoption pose problems for modellers needing reduced form and context-independent expressions of cause and effect. Consequently, changes in energy end-use in global IAMs tend to be captured at the aggregated sectoral level as a function of changing incomes and prices (Bauer et al. 2017).

As a result, IAMs are neither designed to explore nor are useful for exploring the emergence of *novelty* in energy end-use. A backward look to 1930 tells us that it is not science fiction to imagine that portfolios of mitigation options in 2100 may look very different from those available today. Yet, peering through an IAM lens into a distant 2100 world in which warming has been limited to 1.5 °C, we see short-distance mobility is still by car, buildings still need heating and cooling, and food is still grown extensively using land. Consequently, scenario modelling tells us more about the preoccupations, beliefs and uncertainties of the present than about the possibilities of the future (Kramer 2018).

Transformation pathways consistent with 1.5 to 2 °C mitigation rely heavily on the widespread diffusion of technologies which are currently available and already deployed in the market at scale (upper half of Fig. 1). These are ready substitutes for existing carbon-emitting or inefficient technologies: wind and solar power for unabated fossil power; electric and biofuel vehicles for the internal combustion engine; and energy-efficient buildings, appliances, lights and industrial processes for inefficient current practices. The striking anomaly is bioCCS, a pre-commercial mitigation option whose negative emissions are necessary to offset hard-to-decarbonise activity in industrial, agricultural and international freight sectors (UNEP 2017).

This emphasis on commonly-available substitutes omits a wide range of *novel* energy-using goods and services which *may* diffuse rapidly among consumers (lower half of Fig. 1). These consumer-facing innovations are a *potential* means of pushing the speed and magnitude of emission reductions beyond that shown in transformation pathways for 1.5 °C mitigation.

In this paper, we ask the following:

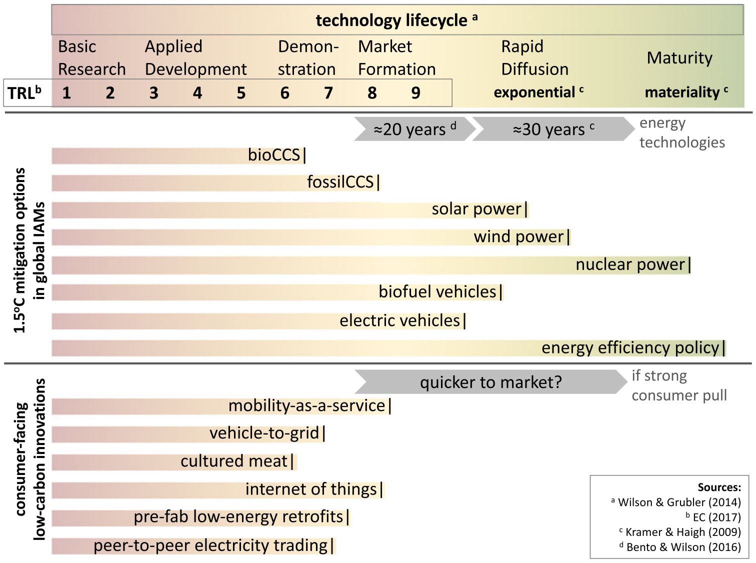
Q1. Which consumer-facing innovations may potentially reduce emissions to facilitate transformation pathways consistent with 1.5 °C mitigation?

Q2. What is the magnitude of potential emission reductions from the widespread adoption of low-carbon innovations by consumers?

We provide answers to these questions using a combination of methods, including expert workshops and bottom-up quantifications using observational data from early-adopting niches. Before presenting our methods and findings, we first explain our use of 'disruptive low-carbon innovation' (DLCI) as an analytical framework for identifying consumer-facing innovations with the potential to reduce emissions.

Analytical framework: disruptive low-carbon innovations (DLCIs)

'Disruptive innovation' provides a useful framing for how consumers can reshape the way firms and markets provide goods and services. The term originates in Clayton Christensen's 1997 book, 'The Innovator's Dilemma' (Christensen 1997). This has since been described as one of the top six most influential business books ever written (The Economist 2011). According to Christensen, disruptive innovations are remarkable for being uncompetitive on conventional attributes of price, reliability and performance valued by mainstream consumers. Rather, they offer potential adopters a wholly new set of attributes. If successful, they effectively create a new market with a new set of demands and preferences. In the process, they disrupt the business models of incumbent firms. Christensen uses the



Sources:
[a] Wilson & Grubler (2014)
[b] EC (2017)
[c] Kramer & Haigh (2009)
[d] Bento & Wilson (2016)

Fig. 1 Commercial maturity of mitigation options in global IAMs and disruptive low-carbon innovations. Coloured bands in upper half of figure show commercial maturity of mitigation options analysed in Global IAMs for 1.5 °C mitigation (Rogelj et al. 2015; Luderer et al. 2016). Coloured bands in lower half of figure show commercial maturity of potentially disruptive consumer-facing low-carbon innovations (see text for details). Left-to-right scale at top of figure overlays the technology readiness level (TRL) framework used to assess the commercial maturity of new technologies (EC 2017) onto a simple staged model of the technology lifecycle from basic research to diffusion (Wilson and Grubler 2014). The exponential and materiality stages describe initially rapid and subsequently linear market growth (Kramer and Haigh 2009). Timescales shown in grey arrows are based on empirical research (Bento and Wilson 2016) but are indicative only as they generalise across diverse samples of energy technologies microcomputer disrupting the mainframe computing industry in the late 1970s as a canonical example. Mainframe users valued processing speed, storage capacity, cost per MB, reliability. Microcomputers performed poorly on all these attributes. But, the novelty of the microcomputer's portability, versatility and low unit cost enfranchised a whole new market segment—individuals, households and small firms (Christensen 1997). The resulting transformative effect is history.[1]

There are many other elements of Christensen's disruptive innovation theory and its subsequent interpretation and application (Christensen 1997; Govindarajan and Kopalle 2006; Lambert 2014). In this article, we are interested specifically in the emphasis placed on novel attributes offering distinctive value propositions to consumers. These value propositions typically combine both technological and business model innovations, and encompass both low-end and high-end goods and services as well as both low-tech and high-tech sources of novelty (Table 1).[2]

Applying disruptive innovation concepts to 1.5 °C mitigation means also factoring in potential emission reductions resulting from widespread adoption. Disruptive *low-carbon* innovations (DLCIs) therefore combine an emphasis on private benefits for consumers (novel attributes and value) with social benefits or public goods (lower emissions) (Wilson 2018). This public-goods characteristic is an important distinction from usual applications of disruptive innovation. It points to the supporting role of public policy or other mechanisms for incentivising low-carbon innovation among private firms. It also shifts the object of disruption from incumbent firms and markets to the high-carbon practices and their associated service providers in mainstream markets (Table 1).

In sum, for the purposes of this article, disruptive low-carbon innovations (DLCIs) are defined as follows:

> *Technological and business model innovations which offer novel value propositions to consumers and which can reduce greenhouse gas emissions if adopted at scale.*

Method

We use three main methods to answer our two research questions. First, we comprehensively survey peer-reviewed and grey literature to identify potential DLCIs (Q1). Second, we elicit perceptions of low-carbon innovators and researchers during two expert workshops (Q1, Q2). Third, we identify early adopters of select DLCIs and 'scale-up' observed emission reductions to matched segments of the UK population. This provides first-order estimates of mitigation potentials (Q2).

Literature survey of potential DLCIs

We surveyed a wide range of literature on low-carbon innovation and energy-system transformation to identify potential DLCIs. Our survey encompassed modelling analysis of 1.5 to 2 °C mitigation, bottom-up sectoral analyses, innovation case-studies, news reports, blogs and magazine articles. We sought specific mentions of the terms 'disruptive', 'game-changing', 'breakthrough', 'radical' used in reference to energy, carbon, or climate change-related innovations.

Examples of literature we surveyed include the following:

- *Market surveys*: e.g. (McKinsey 2012, 2013; New Scientist 2016)
- *Innovation strategies*: e.g. (HMG 2013; King et al. 2015; WEF 2015; BEIS 2017a; Innovation 2017; King 2017b)

---

[1] Other examples of disruptive innovation according to Christensen include desktop photocopiers vs. giant Xerox copy machines; digital photography vs. film; mobile telephones vs. landline services; small off-road motorcycles (e.g. Honda) vs. large powerful bikes (e.g. Harley); transistors vs. vacuum tubes; discount retailing vs. department stores; drones vs. bombers; Wikipedia vs. Encyclopaedia Britannica; massive open online courses (MOOCs) vs. university degrees; and outpatient and in-home clinics vs. general hospitals. In each case, disruptive innovations enter the market as 'good enough' alternatives which offer something novel to an under-served market segment.

[2] Christensen defined disruptive innovations as low-end, low-tech goods and services attractive to users marginalised by mainstream goods and services. This has since been challenged by a 'Silicon Valley' argument that disruption can and does *also* come from above (Arbib and Seba 2017). High-end and typically high-tech products with more capabilities and functionality than mainstream alternatives appeal initially to a price-insensitive or technophile market niche (Seba 2014). But, exponentially declining costs and exponentially improving performance mean that these high-end products rapidly outcompete incumbents and move mainstream. It is important to note that including high-tech products blurs the distinction between Christensen's emphasis on *disruptive* innovations whose challenge is primarily one of finding markets and users, and the more familiar dichotomy in the innovation literature between *radical* and *incremental* innovations which describes the extent of technological advancement or breakthrough (Wilson and Grubler 2014).

Table 1 Characteristics of disruptive low-carbon innovations. ✓✓ = strongly emphasised; ✓ = emphasised; – = not emphasised. Source: adapted from Wilson (2018)

	Disruptive innovation	Disruptive *low-carbon* innovation (DLCIs)
Novel application of knowledge (i.e. innovation)	✓✓	✓✓
Initially attractive in a market niche then performance improves	✓✓	✓
Disrupts incumbent firms and markets	✓✓	✓
Combines technological and business model innovation to create value	✓✓	✓✓
Offers novel product or service attributes to consumers or end-users	✓	✓✓
Appeals to low-end market and price-sensitive users or non-users	✓✓[a]	✓
Simple, low-tech alternatives to over-performing mainstream goods	✓✓[a]	✓
Appeals to high-end market and price-insensitive technophile users	✓✓[b]	✓
Radical technological breakthroughs which improve exponentially	✓✓[b]	✓
Reduces greenhouse gas emissions if adopted at scale	–	✓✓
Disrupts high-carbon practices, and associated infrastructures and firms	–	✓✓
Requires supportive policy or regulatory environment	–	✓

[a] Christensen's original definition of disruptive innovation (Christensen 1997; Govindarajan and Kopalle 2006; Lambert 2014)

[b] Silicon Valley 'addition' to Christensen's concepts (Seba 2014; Arbib and Seba 2017)

- *Energy and climate scenarios and modelling*: e.g. (Johansson et al. 2012; Clarke et al. 2014; Rogelj et al. 2015; Luderer et al. 2016)
- *Research and policy studies*: e.g. (The Climate Group 2013; EC 2015; House of Commons 2016; Moore 2016; Sussams and Heaton 2017)
- *Strategy and advisory reports*: e.g. (Seba 2014; WBCSD 2016; Arbib and Seba 2017)
- *Sectoral studies*: e.g. (FAO 2013; Breakthrough Institute 2015; ITF 2015, 2016; King 2017a; Midttun and Piccini 2017)
- *Institutional websites, reports and blogs*: e.g. Rocky Mountain Institute (blog.rmi.org), Climate-KIC (www.climate-kic.org)
- *Peer-reviewed research studies*: e.g. (Tyfield and Jin 2010; Tyfield et al. 2010; Dixon et al. 2014; Ruan et al. 2014; Hang et al. 2015; Dotsika and Watkins 2017)

We used convenience and snowball sampling of diverse sources, rather than a systematic literature review based on pre-defined search terms applied to pre-identified databases. This was for two reasons. First, 'disruption' and disruptive innovation are slippery, inconsistently defined terms (Wilson 2018; Wilson and Tyfield 2018). Second, online content from commentators, think tanks and industry observers are important sources in this fast moving field. Given this methodological preference, we cannot and do not claim that the potential DLCIs identified are exhaustive. However, we did find evidence of sampling saturation as additional search effort tended to yield variants of already-identified innovations rather than new ones.

A final set of 99 potential DLCIs identified from the literature is provided in Table SI-1 (online Supporting Information), organised into four domains: mobility, food, buildings and cities, and energy supply and distribution.

We then screened this full set of DLCIs for those which clearly offer novel value propositions for consumers in line with our definition of DLCIs set out above (see also Table 1). We distinguished the following:

- Forty-two innovations which relate to end-use goods and services (downstream, consumer-facing)
- Forty-six innovations which relate to production, supply chains or markets (upstream, business-facing)
- Eleven meta-innovations which are cross-cutting, enabling or embodied in either downstream or upstream innovations.

These three groups are shown in full in Table SI-1. Our analysis and results focus only on the 42 potential

DLCIs which are clearly consumer-facing. The literature search and subsequent screening are therefore consistent with the four key elements of DLCIs as defined above: technological and business model innovations, novel value propositions, consumer-facing, and potential to reduce greenhouse gas emissions if adopted at scale.

Expert perceptions of potential DLCIs

We held two workshops in London in March 2017 to explore the potential contribution of disruptive innovation to reducing carbon emissions. The workshops were organised by Future Earth and the Tyndall Centre, with financial support from the UK Science & Innovation Network. The first workshop focused on innovations and markets, bringing together firms, investors, market intermediaries and policymakers. The second workshop focused on research needs and challenges, bringing together thinkers and researchers working on disruption, system transformation and innovation. A full report of the workshops including all key findings is available at silci.org and in Wilson (2017).

Low-carbon innovation experts participating in the workshops were sent a short pre-workshop survey to elicit their perceptions of DLCIs in terms of both disruptiveness and emission reductions. A total of 32 (of 40) participants from the innovator workshop and 24 (of 35) participants from the researcher workshop completed the survey (response rates of 80 and 63%, respectively). Average survey completion time was 4 min. This is a small sample size and provides illustrative results only.

The survey asked respondents to select their domain of greatest expertise: mobility, food, buildings and cities, energy supply and distribution. In their selected domain, respondents were asked to score a set of 10 low-carbon innovations on two 7-point scales: potential disruptiveness (+ 3 = very disruptive, − 3 = not disruptive at all) and potential emission reductions (+ 3 = large reduction in emissions, − 3 = large increase in emissions). The sets of 10 innovations in each of the four domains were based on the literature survey, mainly focusing on consumer-facing innovations but with some upstream supply-chain and production innovations included for comparison purposes.

Scaling-up emission reductions from early adopters

Potential DLCIs are by definition not yet mainstream. Empirical evidence of their impact on emissions is therefore limited. In the absence of measurable effects, either prospective modelling or case-study analysis is an alternative for quantifying impacts. We use the second approach, based on evidence of how DLCIs have impacted behaviour, energy use and emissions in early-adopting market niches.

We drew on the approach used by Dietz et al. (2009) who quantified ‘realistically achievable emission reductions’ from a range of household actions in the USA, based on a scaling-up of best practice from observed trials, programmes and initiatives. Our analogous methodology comprised four steps:

1. Identify an early-adopting or pioneer niche of a DLCI
2. Quantify annual reductions in greenhouse gas emissions as a result of adoption, based on evidence of observed changes in behaviour and/or energy end-use
3. Match early-adopting niche to corresponding segment of the UK population using relevant socio-demographic, geographic or contextual characteristics
4. Estimate potential annual reductions in UK greenhouse gas emissions if early-adopting niche was scaled up to the UK population

Steps (1) and (2) are based on actual (observed) change in real-world settings. Steps (3) and (4) are a hypothetical scaling-up exercise which asks: What would be the impact on emissions if all those in the UK population with similar characteristics to *actual* early adopters *also* adopted the DLCI?

The UK is a useful case-study country as long-term emission-reduction targets in line with 2 °C mitigation are enshrined in UK law through the Climate Change Act (BEIS 2017b). The incremental challenge for moving from a 2 °C to 1.5 °C mitigation pathway has not yet been formally defined by the UK government. However, modelling analysis confirms the basic intuition that much stronger mitigation efforts are needed than those currently prescribed by policy (Pye et al. 2017; UK CCC 2017).

Results

Potential disruptive low-carbon innovations (DLCIs)

The potential DLCIs identified in the literature survey were grouped and organised into a final set of 99 technological and/or business model innovations shown in full in Table SI-1 (online Supporting Information). They vary widely in their specificity, application, technological radicalness, cost and accessibility. But, several underlying themes are clear.

Everyday life is being digitalised (Røpke et al. 2010). Exponential cost reductions show few signs of saturating in small-scale, low unit cost, modular technologies from PV panels and batteries to chips and sensors (Farmer and Lafond 2016). Digital-enabling of peer-to-peer and other sharing-economy platforms are raising ‘usership’ as an alternative to single-purpose ownership (Frenken 2017). Traditionally centralised energy infrastructures and utility service providers are being eroded away at the edges (Fares and Webber 2017). Transportation and electricity systems are also converging as electrons and bits are entering the historical realm of hydrocarbons (Freeman et al. 2017). Passive energy consumers are diversifying into multifarious roles of producer, citizen, activist, designer, community member and advocate (Schot et al. 2016). These trends towards more digital, granular, use-based models of energy-service provision are opening up new value propositions for consumers with potential benefits for emission reductions.

Mobility

Table 2 shows the consumer-facing DLCIs identified as relating to mobility, grouped into four broad types: *alternative fuel or vehicle technologies* displacing the internal combustion engine (ICE), *alternative forms of auto-mobility* displacing private car ownership and use, *alternatives to auto-mobility* displacing car use, and *reduced demand for mobility*. All four strategies target private ownership and use of petrol or diesel-powered ICE vehicles. Most of the potential DLCIs in Table 2 are defined by some combination of business model and technological innovation.

Table 2 is not a comprehensive set of innovations for reducing mobility-related emissions. It summarises only those identified in the literature survey which are consistent with our definition of DLCIs in offering novel value propositions to consumers. Some consumer-facing innovations are excluded because either they are not novel or they compete on already-valued mainstream attributes including price, efficiency and reliability (e.g. fuel-efficient cars). There are also a whole host of non-consumer-facing strategies which rely more directly on regulation (e.g. fuel taxes), infrastructure (e.g. cycle highways) or planning (e.g. car-free communities). Some of these are captured in Table SI-1 (online Supporting Information).

The impact of potential DLCIs on energy end-use and so emissions depends on the emission profile of the incumbent good or service being displaced. Table 2 links each potential DLCI with the higher-carbon incumbent which currently dominates mainstream consumption. This is indicative only; what DLCIs actually displace will vary by context and adopter segment. As an example, alternative forms of auto-mobility may displace private car ownership and use, or may substitute for public transport and active modes (Sprei 2018). Displacement of incumbents is therefore set against a dynamic and variegated background of changing technologies, users and markets, which are themselves potentially shaped by disruptive innovation (McDowall 2018; Tyfield 2018).

Each potential DLCI identified varies in the novel attributes of potential appeal to consumers. Some are goods with high investment costs; others are use-based services. Some preserve individual or household-scale autonomy and independence; others tie users into relational networks. *Alternative forms of auto-mobility* such as car clubs clearly diverge from the incumbent model of private car ownership and use. So too do *alternatives to auto-mobility* such as mobility-as-a-service. These potential DLCIs offer novel value propositions based around service consumption (or usership), pay-per-use, choice variety, flexibility and freedom from maintenance and care responsibilities (Prettenhaler and Steininger 1999). In contrast *alternative vehicle technologies* sustain the incumbent model of auto-mobility but with lower emissions. Apart from being cleaner, the novel attributes for consumers are less clear. As an example, biofuel vehicles are a broadly like-for-like substitute for ICE vehicles in terms of their driving, maintenance and functional characteristics (Ribeiro et al. 2012). However, both biofuel, fuel cell and electric vehicles—while reinforcing prevailing norms on private car ownership and use—offer low or zero emission alternatives to ICEs, while also being consistent with green identity and associated status signalling (Axsen and Kurani 2013).

Food

Table 3 shows the consumer-facing DLCIs related to food identified by the literature search, together with the

Table 2 Consumer-facing innovations relating to mobility which can potentially reduce emissions. • = included in survey of experts; x = included in scaling-up methodology for estimating emission reductions (see text for details)

Potentially disruptive low-carbon innovation (DLCI)		Higher-carbon incumbent	Survey	Scaling-up
Alternative fuel or vehicle technologies	Electric vehicles (EVs)	ICE vehicles[a]	•	
	Autonomous vehicles		•	
	Fuel cell vehicles (H_2FCVs)		•	
	Biofuel or flex-fuel vehicles		•	
Alternative forms of auto-mobility	Car clubs (car-sharing)	Car ownership and use[b]	•	x
	Ride-sharing		•	
	Shared taxis or 'taxi-buses'[c]			
	Neighbourhood electric vehicles[d]			
Alternatives to auto-mobility	e-Bikes	Car ownership and use[b]	•	x
	Mobility-as-a-service (MaaS)[e]		•	x
Reduced demand for mobility	Telecommuting	Commuting by car	•	
	Interactive virtual reality, telepresence[f]			

[a] ICE = petrol or diesel-powered internal combustion engines

[b] Indicative only, displaced transport mode may by public transport or active modes (see text for discussion)

[c] *Shared taxis or 'taxi-buses'* (also real-time ride-sharing) are cars or minivans with multiple passengers on similar routes, booked on short notice via apps so wait times are short

[d] *Neighbourhood electric vehicles* (NEVs) are light-weight low-speed battery-driven vehicles allowed on roads (HBR 2015)

[e] *Mobility-as-a-service* (also inter-modality) refers to app-based scheduling, booking and payment systems for multiple transport modes (ride-sharing, bike-sharing, bus, tram, metro, train) through a single gateway or account (ITF 2016)

[f] *Interactive virtual reality* or *telepresence* can be used for immersive interaction by remote (as currently used in medical diagnosis or surgery) (Roby 2014)

mainstream higher-carbon practice they typically displace (which determines their potential impact on emissions). The DLCIs are grouped into four broad types: *alternative dietary preferences* reducing demand for livestock production; *urban food production* displacing large-scale, extensive rural food production and associated food miles; *producer-consumer relationships* displacing impersonal centralised retail (including supermarkets); and *reduced demand for food* by tackling food waste.

As with mobility, these DLCIs are identified in the literature as *potentially* contributing to emission reductions by displacing or substituting for energy-intensive food production, distribution and waste. Realistically achievable emission reductions in real-world contexts require careful empirical analysis and will vary across adopters and contexts. In the food domain, this implies lifecycle or system analysis to link changes in consumption with agricultural practices upstream (Springmann et al. 2016).

Some of the potential food-related DLCIs in Table 3 may not seem overly new. Examples include reduced meat in diet, community farms and own-food growing. They are included in Table 3 because of novel applications of digital technologies in business models which create, enable or incentivise new consumer practices. For example, 'Part-Time Carnivore' and 'The Climatarian Challenge' gamify low-carbon diets through apps which record, connect and challenge user practices.

Other potential DLCIs in Table 3 characterise less carbon-intensive forms of food production which are not evidently consumer-facing. Examples include vertical farming, rooftop greenhouses and food link schemes. They are included in Table 3 because they introduce, bring closer or strengthen direct links or relationships between producers and consumers. Again, this is often enabled by digital technologies. For example, online producer-consumer hubs such as 'Farmdrop' or 'Open Food Network UK' serve as digital marketplaces allowing consumers to buy directly from multiple producers subject to pre-specified dietary preferences, nutritional requirements, production techniques or location.

There are many other innovations and strategies for reducing emissions through alternative farming and

Table 3 Consumer-facing innovations relating to food which can potentially reduce emissions. • = included in survey of experts; x = included in scaling-up methodology for estimating emission reductions (see text for details)

Potentially disruptive low-carbon innovation (DLCI)		Higher-carbon incumbent	Survey	Scaling-up
Alternative dietary preferences	Reduced meat diet[a]	Livestock production	•	x
	Cultured meat[b]			
Urban food production	Community farms, own-food growing	Land- and/or resource-intensive food production and transportation	•	x
	Vertical farming[c]			
	Rooftop greenhouses[d]			x
Producer-consumer relationships	Food box deliveries[e]	Food transportation, food waste		
	Food links schemes[f]			
Reduced demand for food	Food redistribution or sharing[g]	Food waste		
	Food waste reduction[h]			x

[a] Includes any dietary preferences which reduce meat consumption, from meat-free Fridays to veganism or insect-based protein

[b] *Cultured meat* is animal meat that is grown using a bioreactor (Tuomisto and Teixeira de Mattos 2011)

[c] *Vertical farming* includes stacked modular food pods with self-contained hydroponic growing mediums

[d] *Rooftop greenhouses* can use waste heat (and CO_2) from buildings' heating and ventilation systems to boost productivity (Vogel 2008)

[e] *Food box deliveries* bring regular door-to-door selections of fresh produce, which may be tailored to specific recipes, reducing waste and transport requirements for food retail (Hertz and Halkier 2017)

[f] *Food links schemes* connect producers directly with consumers including through digital marketplaces to reduce waste, improve supply-chain transparency and support specific production methods

[g] *Food redistribution or sharing* schemes link local retailers (or consumers) with surplus food to charities (or consumers) needing food (Aschemann-Witzel et al. 2017)

[h] *Food waste reduction* includes schemes in self-service food outlets to reduce portion size (Perchard 2016)

land-use practices which are not included in Table 3 as they do not clearly offer novel value propositions to consumers (see column headed 'upstream' in Table SI-1). These alternative farming practices range from sustainable intensification, precision 'smart' agriculture and agroforestry to aquaculture and greenhouse hydroponic systems (FAO 2013).

As is often the case with disruptive innovations, many of the food-related DLCIs perform poorly on valued mainstream attributes such as year-round availability, standardisation, cheapness, and one-stop shop availability (at centralised retailers). However, they offer new sources of value across many different attributes, creating opportunities for consumers to express preferences for healthier, localised, personalised, interconnected food systems. In some cases, defined market niches are well established, and the DLCIs are less reliant on technological innovation than is the case for mobility.

Buildings

Table 4 shows the consumer-facing DLCIs related to buildings identified in the literature search. They are grouped into three broad types: *interconnectivity for optimised usage* of devices, appliances, homes; *improved thermal performance* through alternative heating technologies, improved building design and construction, or energy management; and *reduced demand for space and materials* through sharing of surplus or shareable capacity.

Many of these are in turn enabled by urban-scale innovations which either collect and analyse data to improve system integration and performance (under the rubric of 'smart cities') or which improve upon design, construction and planning practices (e.g. construction of Passivhaus or net zero energy buildings). These upstream innovations relating more to infrastructure and cities are included in Table SI-1 but are excluded here as they do not directly offer novel value propositions to consumers.

Of the potential DLCIs identified across four domains, those relating to buildings were the least clear in offering novel and appealing value propositions. Control and controllability are the main new attributes promised. By integrating digital interfaces and connectivity into smart appliances, heating, lighting and home energy management systems, building users have a wider range of potential control functionality (including automation, adaptive learning and user-defined routines). But, it remains unclear if this control functionality

Table 4 Consumer-facing innovations relating to buildings which can potentially reduce emissions. • = included in survey of experts; x = included in scaling-up methodology for estimating emission reductions (see text for details)

Potentially disruptive low-carbon innovation (DLCI)		Higher-carbon incumbent	Survey	Scaling-up
Interconnectivity for optimised usage	Smart appliances, internet of things (IoT)	Energy waste (from limited user control)	•	x
	LED lighting with smart controls		•	
	Smart homes			
Improved thermal performance	Home energy management systems (HEMS)	Energy waste (from limited user control and inefficient heating or building systems)	•	
	Smart heating controls			x
	Heat pumps		•	
	Pre-fab high-efficiency retrofits[a]			
Reduced demand for space and materials	Sharing space[b]	Under-used resources	•	
	Sharing products, tools, stuff[c,d]		•	

[a] *Pre-fab high-efficiency retrofits* refers to custom-fitted high-performance building shells combined with solar PV and heat pump units fabricated off-site and installed externally around properties within a week, an approach pioneered in the Netherlands as Energiesprong (Jacobs et al. 2015)

[b] *Sharing space* includes peer-to-peer networks such as AirBnB

[c] *Sharing products, tools, stuff* includes peer-to-peer networks such as Streetbank

[d] *3D printing* was also identified as a potential consumer-facing DLCI to reduce demand for materials (see Table SI-1), but was omitted here due to a lack of evidence on its emission-reducing potential (Gebler et al. 2014)

is appealing, useable, and emissions-reducing (Hargreaves and Wilson 2017). These same innovations also tend to reduce users' autonomy by increasing the dependence of building management and performance on external service providers and infrastructures.

Energy supply and distribution

Table 5 shows the consumer-facing DLCIs related to energy supply and distribution, together with the higher-carbon incumbent they may displace. This domain is explicitly about technological and business model innovations at the interface between end-use and supply.

The DLCIs are grouped into three broad types: *new service providers* or market entrants with novel service offerings for end users; *integrating consumers into grids* increases the demand-responsiveness of end-users to grid constraints (e.g. for avoiding costly or high-carbon peak generation); and *decentralised energy supply* includes both technologies (e.g. solar PV + storage) and organisational forms of service provision (e.g. community energy).

There are a host of other resources and technologies for decarbonising the energy supply (e.g. offshore wind, nuclear reactors) as well as enabling infrastructures (e.g. utility-scale grid storage for balancing intermittent renewables). As shown in Fig. 1, these upstream innovations are emphasised by global IAMs in transformation pathways consistent with 1.5 °C mitigation. Although included in the full list of DLCIs in Table SI-1, they are excluded here as they do not have clearly distinguishable consumer-facing attributes. This is particularly the case for alternative ways of generating or supplying electricity, as this is a homogeneous commodity for consumers.

Energy supply and distribution-related innovations cluster around value propositions which challenge centralised networks and utilities. These value propositions see electricity users in particular diversifying their roles away from passive consumption towards actively managing, producing, trading and organising (Schot et al. 2016). The changing roles of energy end-users are enabled by digitalisation to enable the integration and management of diverse small-scale energy resources and rapid cost reductions in household-scale technologies like solar PV and batteries.

Expert perceptions of potential disruptiveness and emission reductions

Tables 2, 3, 4 and 5 provide a general indication of the higher-carbon incumbent which potential DLCIs may displace. Most of these DLCIs are not yet or only

Table 5 Consumer-facing innovations relating to energy supply and distribution which can potentially reduce emissions. • = included in survey of experts; x = included in scaling-up methodology for estimating emission reductions (see text for details)

Potentially disruptive low-carbon innovation (DLCI)		Higher-carbon incumbent	Survey	Scaling-up
New service providers	Energy service companies (ESCOs)	Barriers to low-carbon capital investment	•	n/a
	Energy aggregators[a]			
	Third-party financing[b]			
Integrating consumers into grids	Demand response (DR)[c]	Demand unresponsive to needs of grid	•	
	Time-of-use pricing			
	Disaggregated feedback[d]			
	Electric vehicle-to-grid (V2G)		•	
Decentralised energy supply	Community energy	Centralised utility-supplied electricity or gas		
	Solar PV + storage		•	
	Peer-to-peer electricity trading[e]		•	
	Micro-wind turbines			
	Fuel cells for distributed generation + storage			

[a] Municipal or market intermediaries enable consumers to group together for collective bargaining or low-carbon capital investment programmes

[b] For domestic solar PV or energy-efficiency investments, including facade or roof leasing (Seba 2014)

[c] Utilities remotely curtail electricity-using appliances to reduce peak loads, subject to pre-agreed terms with consumers

[d] Real-time feedback on electricity loads disaggregated to specific appliances or activities (Stankovic et al. 2016)

[e] From solar PV + battery systems (Green and Newman 2017), or vehicle-to-grid applications (Freeman et al. 2017)

recently commercialised (lower half of Fig. 1). This section and the next section present expert perceptions and *what-if* estimations of emission-reduction potentials for subsets of the DLCIs identified in Tables 2, 3, 4 and 5.

Low-carbon innovators and researchers participating in two expert workshops were asked to score sets of low-carbon innovations along two dimensions: disruptiveness and emission reductions. Figure 2 plots the mean scores on potential disruptiveness (y-axis) and potential impact on emissions (x-axis) for innovations in each of the four domains. The innovations were drawn from the full set of those identified in the literature survey and include both consumer-facing DLCIs (closed circles) as well as select upstream innovations for comparison purposes (open circles).

The innovations are all clustered in the top right of the Fig. 2 plots as they were identified from the literature survey of potential DLCIs. In terms of potential disruptiveness *and* potential emission-reductions, the top three consumer-facing DLCIs in each domain are as follows:

- *Mobility*—mobility-as-a-service, electric vehicles (EVs), car clubs (car-sharing)
- *Buildings*—internet of things, home energy management systems (HEMS), LED lighting and controls
- *Energy supply and distribution*—solar PV + storage, demand response, vehicle-to-grid (V2G)

Food-related DLCIs are not included here, as only two consumer-facing DLCIs were scored in the food domain by a small number of respondents.

How low-carbon innovators and researchers scored the potential DLCIs is revealing. First, many innovations considered by experts to be highly disruptive are either dependent on technological advances (e.g. internet of things, smart grids, vertical farming) or do not appear to offer novel attributes valued by end users (e.g. artificially-lit greenhouse agriculture, large-scale grid storage). Potential DLCIs for buildings in particular are strongly technological (and weakest in terms of business model innovation). One interpretation is that changes in energy end-use are most strongly constrained in buildings and cities by long-lived existing infrastructures.

Second, various highly-scored potential DLCIs appear dependent on behavioural change, without a clear link to technological or business model innovation. This is most strongly the case for food (e.g. reduced food waste, reduced meat in diet). However, as noted earlier, digital technologies are opening up opportunities for new business models to facilitate innovation in this area.

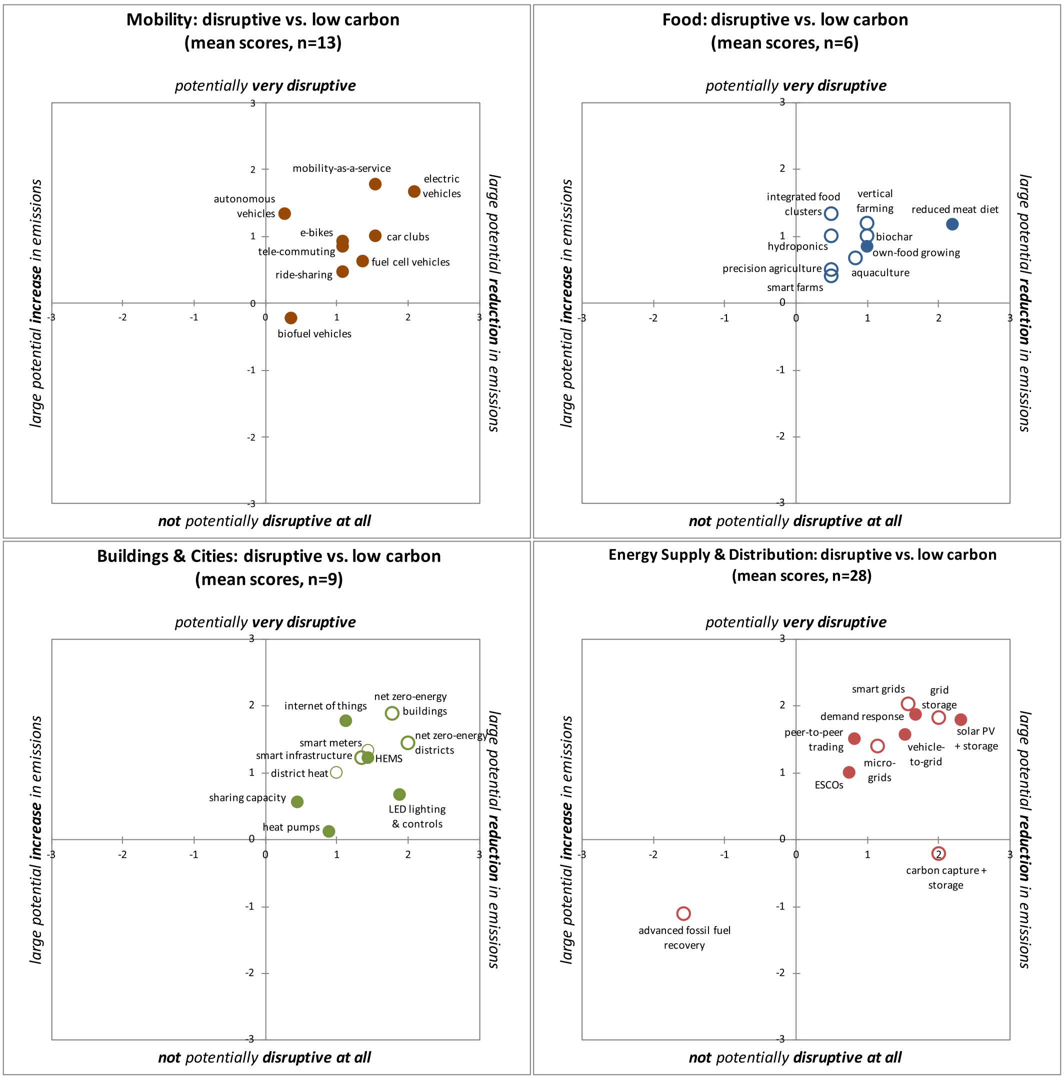


Fig. 2 Mean scores from a survey of experts on perceived disruptiveness and emission reduction potentials for low-carbon innovations. Closed circles denote consumer-facing innovations (see text for details). Open circles denote upstream innovations included for comparison purposes but not analysed further (see Table SI-1)

Third, potential emission reductions are contingent on the innovations being adopted at scale in the market, so should implicitly account for both the size of potential market demand and the incumbent good or service being displaced. The relative scorings of potential DLCIs in the Fig. 2 plots seem more influenced by proximity to market and current market size than longer-term transformative potentials. As an example, autonomous vehicles are scored much lower in potential emission impact than electric vehicles even though autonomous vehicle studies generally assume electrification (Arbib and Seba 2017). However, it is not possible to infer reliably the extent to which respondents were accounting for displaced goods or services when scoring particular DLCIs.

Quantification of emission-reduction potentials

Results from the expert survey are consistent with the literature in identifying emission-reduction potentials from DLCIs. Quantitative estimates of the magnitude of these emission reductions need to account for both market growth potential and the displacement of higher-carbon incumbents. We developed and applied a standardised methodology to quantify potential emission reductions from a sample of DLCIs using the UK as a case study. We relied to the extent possible on actual observations of energy or emission reductions among early adopters. We then scaled up this evidence base to the UK population based on matched sample characteristics.

Taking urban farming as an example, we identified a community farm in Sutton (an urban district in London) as an early adopter. A detailed lifecycle analysis quantified emission reductions from the farm's produce at 34 tCO_2e per hectare per year, accounting for both displaced high-input agriculture and avoided food miles (Kulak et al. 2013). Two hundred ninety-five urban districts in the UK have equivalent or lower population density to Sutton (ONS 2015) so could potentially site comparable community farms. Assuming similar types and quantities of annual produce, this yields potential emission reductions of 2.1 $MtCO_2e$ per year from scaling-up Sutton's precedent to the UK as a whole. Further details for this example are provided in online Supporting Information Table SI-2.

We implemented the scaling-up methodology on a sample of 11 potential DLCIs across the mobility, food and building domains. These DLCIs were selected, as behavioural, energy or emissions data were available from early-adopting niches. Table 6 summarises the results, with full documentation of assumptions, data and sources provided in Table SI-2.

Potential emission reductions from 11 DLCIs total ~ 2.5% of the UK's annual emissions from passenger vehicles, ~ 11% of the UK's annual emissions from agriculture and ~ 2% of annual emissions from homes.

These estimates for the UK from a select set of 11 DLCIs are a first-order (back of the envelope) indication of potential emission reductions based on observations of what *actually* happens to energy and food demand when consumers adopt DLCIs. The main assumption is that the DLCIs scale up from existing early-adopting niches to the UK as a whole, but only within the population segments matched to early adopters. This is a conservative assumption. There is strong evidence from diffusion research that later-adopting population segments are initially risk averse but become more attracted to innovations as they learn from the experience of early adopters (Rogers 2003). As a result, the characteristics of adopters diversify as the innovation becomes more widespread.

Tables 2, 3, 4 and 5 set out 31 additional DLCIs to the 11 analysed in Table 6. Further research is needed to quantify their contribution to 1.5 °C mitigation. However, there are prospective modelling studies which confirm significant potential emission reductions. Examples in each domain include the following:

- *Mobility*. The International Transport Forum (ITF) evaluated city-scale impacts of new forms of mobility using an agent-based simulation model of Lisbon, Portugal, based on real mobility and network data. They found that a combination of *shared taxis*

Table 6 Potential reductions in annual emissions if 11 DLCIs were to scale up from early-adopting niches to matched segments of the UK population. See Table SI-2 for assumptions, data and sources. UK emissions data by sector for 2015 include both direct and indirect (upstream) emissions from territorial or production-based emission inventories (BEIS 2017c)

Domain	Potential DLCI	Annual emission reductions from scaling-up evidence from early-adopting niches to matched UK population		
		As $MtCO_2e$	As % of UK territorial emissions in corresponding sector in 2015	
Mobility	Car clubs	0.8 to 0.9	0.8 to 0.9%	Of direct and indirect emissions from passenger and light duty vehicles (96.8 $MtCO_2e$)
	E-bikes	0.04 to 0.08	0.04 to 0.08%	
	E-bike sharing	0.09	0.09%	
	Mobility-as-a-service (MaaS)	1.4	1.4%	
Food	Cultured meat	0.02	0.03%	Of direct and indirect emissions from agriculture (51.1 $MtCO_2e$)
	Food waste reduction	2.6 to 3.6	5.2 to 7.1%	
	Urban farming	2.1	4.1%	
	Rooftop greenhouses	0.04 to 0.6	0.1 to 1.2%	
	Reduced meat diet	0.7	1.4%	
Buildings	Smart heating controls	1.4 to 2.6	1.2 to 2.3%	Of direct and indirect emissions from homes (112.1 $MtCO_2e$)
	Smart appliance (fridge)	0.1	0.1%	

and taxi-buses (30 min pre-book, flexible route) could use 3% of the existing car fleet to provide a flexible, cheap, available, comfortable alternative to private vehicle ownership and use, reducing CO_2 emissions by 34% and congestion to close to zero (ITF 2016). A separate study found that a fleet of *shared autonomous vehicles* comprising multiple passenger 'Taxibots' and single passenger 'Autovots' could use 10–20% of the existing vehicle fleet to provide a viable alternative to both private cars and buses, with commensurate benefits for freed-up road infrastructure (ITF 2015).

- *Food*. Lifecycle analysis of the environmental impacts of *cultured meat* grown in a bioreactor estimated 7–45% lower energy use and 78–96% lower greenhouse gas emissions (including methane) relative to conventionally produced meat in Europe (Tuomisto and Teixeira de Mattos 2011).
- *Buildings*. Shifting or curtailing energy use through *demand response* to utilities' price signals while accounting for household comfort found that *home energy management systems (HEMS)* could reduce electricity costs by 23% and peak demand by 30% with corresponding reductions in emissions (Beaudin and Zareipour 2015).

Discussion

Global IAMs are useful analytical tools linking transformation pathways to warming outcomes consistent with the 1.5 °C ambition of the Paris Agreement. However, IAMs have important limitations in their ability to analyse the emergence of novel consumer-facing goods and services. Bottom-up, sectoral, case study analysis provides complementary insights to top-down global modelling on the rapid and pervasive emission reductions needed for 1.5 °C mitigation.

Disruptive innovations are pulled into mainstream markets by the attractiveness and novelty of their value proposition for consumers. Disruptive *low-carbon* innovations (DLCIs) represent an underexplored dimension of 1.5 °C mitigation pathways which require ever-greater emphasis on demand-side emission reductions (Rogelj et al. 2015; Luderer et al. 2016).

This paper presents an initial analysis of consumer-facing DLCIs and their potential to reduce emissions. We asked (Q1): which consumer-facing innovations may potentially reduce emissions to facilitate transformation pathways consistent with 1.5 °C mitigation?

Tables 2, 3, 4 and 5 identify a wide range of consumer-facing DLCIs which can displace higher-carbon practices. Some of these DLCIs are built on business model innovations (e.g. car clubs, energy service companies); others rely on technological breakthroughs (e.g. cultured meat, autonomous vehicles). Many potential DLCIs combine traditional energy-using hardware with digital platforms or controls (e.g. peer-to-peer electricity trading from domestic PV with battery storage).

In general, the DLCIs identified are more distributed, accessible, small-scale, shareable, and extendable or replicable at low marginal cost relative to the incumbents they displace. In other words, DLCIs tend to offer user-scaled alternatives to large-scale, infrastructure-dependent, centrally provided goods and services. In a low-carbon context, this points towards a 'granular' distributed energy transformation involving end-users in multiple domains and services from heating and eating to moving and making.

The appeal of DLCIs to consumers is centred around novel attributes. The attractiveness of these attributes will help determine the speed of diffusion into niche and then mainstream markets. Consumer preferences are likely to vary strongly between adopter segments, whereas early adopters may be price-insensitive and attracted to new functionality, identity signalling or status distinctions, and more mainstream consumers are typically concerned with price, reliability and compatibility (Rogers 2003). Diffusion out of early-adopting niches is far from certain.

Yet, this diffusion is a determinant of the relevance of DLCIs for 1.5 °C mitigation. We asked (Q2): what is the magnitude of potential emission reductions from the widespread adoption of low-carbon innovations by consumers?

Actual emission reductions from DLCI adoption depend on what is being displaced. As by definition, DLCIs are not yet mainstream, and careful in situ studies of early-adopting niches are needed to quantify changes in behaviour, energy use and resulting emissions. These should account for both the socioeconomic and lifestyle characteristics of the adopters, contextual conditions shaping adoption (e.g. policies, infrastructures, incentives), as well as any observed rebound effects. As examples, car sharing may substitute for car ownership and use, or may complement it as a flexible 'second car' option; mobility-as-a-service (MaaS) may move people onto public transit by weaving seamless intermodal connections or may result in taxis substituting for active travel modes for the final legs of journeys (Sprei 2018).

In the absence of robust evidence from market behaviour, we drew on expert perceptions, innovation-specific quantifications, and literature review to characterise emission-reduction potentials. These potentials are contingent on DLCIs displacing carbon-intensive modes of energy-service provision ranging from private car ownership and use, large-scale food production and distribution, inefficient building design and performance, and centralised energy-supply networks.

As well as directly reducing emissions by displacing higher-carbon practices, DLCIs also have an indirect effect. Disruptive innovations are typically brought to market by new entrants who challenge mainstream service providers. The political economic power and vested interests of incumbent firms, particularly those with interests in fossil fuels, are considered a major source of stability or 'carbon lock-in' in current systems (Unruh 2000; Seto et al. 2016). Consumers attracted to DLCIs can undermine the business models on which this stability rests. This is already evident in the 'edge-of-the-grid' threats to conventional energy utilities from decentralised energy resources (Wainstein and Bumpus 2016). Incumbent firms may of course co-opt or adapt to disruptive threats. But, these defensive responses presage wider system transformation. This is an important area for further research. Whether it is appropriate or relevant to view this transformative potential through the lens of discrete innovations is open to debate. This debate is clearly evidenced by 10 contrasting perspectives on 'Disruptive Innovation and Energy Transformation' in a recent Special Issue (Geels 2018; Wilson and Tyfield 2018).

Conclusion

Limiting warming to 1.5 °C requires concerted innovation throughout the global system of producing, distributing and using energy (Grubler and Wilson 2014). Consumers and consumption are commonly framed as part of the problem. Consumption is energy (and material) intensive and expands in lockstep with income (Sorrell 2015). Consumers are addicted and profligate (Costanza et al. 2017). Yet, consumption also has transformative potential. Disruptive innovation is a lens through which to examine this transformative potential of novel goods and services. Disruptive low-carbon innovations (DLCIs) combine business models and technologies to create appealing value propositions for consumers. This can engage consumers in efforts to reduce emissions. DLCIs are therefore an important lens through which to examine 1.5 °C mitigation. They focus attention on consumers as possible agents of transformative change both directly by displacing carbon-intensive goods and services, and indirectly by dislodging incumbent firms.

Acknowledgements This research was supported by ERC Starting Grant no. 678799 for the SILCI project (Social Influence and Disruptive Low Carbon Innovation). Additional support was provided from the UK Department of Business, Energy and Industrial Strategy (BEIS) as part of the project 'Implications of global warming of 1.5°C and 2°C project'. The workshops were funded by the UK Science & Innovation Network and co-organised with Future Earth.

References

Arbib, J., & Seba, T. (2017). *Rethinking transportation 2020–2030: The disruption of Transortation and the collapse of the internal-combustion vehicle and oil industries. RethinkX Sector Disruption Reports*. California: RethinkX.

Aschemann-Witzel, J., Jensen, J. H., Jensen, M. H., & Kulikovskaja, V. (2017). Consumer behaviour towards price-reduced suboptimal foods in the supermarket and the relation to food waste in households. *Appetite, 116*, 246–258.

Axsen, J., & Kurani, K. S. (2013). Hybrid, plug-in hybrid, or electric—what do car buyers want? *Energy Policy, 61*, 532–543.

Bauer, N., K. Calvin, J. Emmerling, O. Fricko, S. Fujimori, J. Hilaire, J. Eom, V. Krey, E. Kriegler, I. Mouratiadou, H. Sytze de Boer, M. van den Berg, S. Carrara, V. Daioglou, L. Drouet, J. E. Edmonds, D. Gernaat, P. Havlik, N. Johnson, D. Klein, P. Kyle, G. Marangoni, T. Masui, R. C. Pietzcker, M. Strubegger, M. Wise, K. Riahi and D. P. van Vuuren (2017). Shared socio-economic pathways of the energy sector—quantifying the narratives. *Global Environmental Change, 42*, 316–330.

Beaudin, M., & Zareipour, H. (2015). Home energy management systems: a review of modelling and complexity. *Renewable and Sustainable Energy Reviews, 45*, 318–335.

BEIS. (2017a). *Building our industrial strategy*. London: Department for Business, Energy and Industrial Strategy (BEIS).

BEIS. (2017b). *The clean growth strategy: Leading the way to a low carbon future*. London: Department for Business, Energy and Industrial Strategy (BEIS).

BEIS. (2017c). *Final UK greenhouse gas emissions national statistics* (pp. 1990–2015). London: Department for Business Energy and Industrial Strategy (BEIS).

Bento, N., & Wilson, C. (2016). Measuring the duration of formative phases for energy technologies. *Environmental Innovation and Societal Transitions, 21*, 95–112.

Breakthrough Institute. (2015). *Nature unbound: Decoupling for conservation*. Washington DC: Breakthrough Institute.

Christensen, C. M. (1997). *The innovator's dilemma*. New York: HarperBusiness.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P. R., Tavoni, M., Zwaan, B. v. d., & Vuuren, D. P. v. (2014). *Chapter 6: Assessing transformation pathways. Working group III contribution to the IPCC 5th assessment report, climate change 2014: Mitigation of Climate Change*. Cambridge: Cambridge University Press.

Costanza, R., Atkins, P. W. B., Bolton, M., Cork, S., Grigg, N. J., Kasser, T., & Kubiszewski, I. (2017). Overcoming societal addictions: what can we learn from individual therapies? *Ecological Economics, 131*, 543–550.

Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C., & Vandenbergh, M. P. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences, 106*(44), 18452–18456.

Dixon, T., Eames, M., Britnell, J., Watson, G. B., & Hunt, M. (2014). Urban retrofitting: identifying disruptive and sustaining technologies using performative and foresight techniques. *Technological Forecasting and Social Change, 89*(0), 131–144.

Dotsika, F., & Watkins, A. (2017). Identifying potentially disruptive trends by means of keyword network analysis. *Technological Forecasting and Social Change, 119*, 114–127.

EC. (2015). *Communication from the Commission C(2015) 6317 final. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation*. Brussels: European Commission (EC).

EC. (2017). *European Commission Decision C(2017)2468 of 24 April 2017: HORIZON 2020 WORK P ROGRAMME 2016–2017. General Annexes*. Brussels: European Commission (EC).

FAO. (2013). *Climate-Smart Agriculture*. Rome: Food and Agriculture Organisation of the United Nations (FAO).

Fares, R. L., & Webber, M. E. (2017). The impacts of storing solar energy in the home to reduce reliance on the utility. *Nature Energy, 2*, 17001.

Farmer, J. D., & Lafond, F. (2016). How predictable is technological progress? *Research Policy, 45*(3), 647–665.

Freeman, G. M., Drennen, T. E., & White, A. D. (2017). Can parked cars and carbon taxes create a profit? The economics of vehicle-to-grid energy storage for peak reduction. *Energy Policy, 106*, 183–190.

Frenken, K. (2017). Political economies and environmental futures for the sharing economy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 375*(2095), 20160367.

Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy, 74*, 158–167.

Geels, F. W. (2018). Disruption and low-carbon system transformation: progress and new challenges in socio-technical transitions research and the multi-level perspective. *Energy Research & Social Science, 37*, 224–231.

Govindarajan, V., & Kopalle, P. K. (2006). The usefulness of measuring disruptiveness of innovations ex post in making ex ante predictions. *Journal of Product Innovation Management, 23*(1), 12–18.

Green, J., & Newman, P. (2017). Citizen utilities: the emerging power paradigm. *Energy Policy, 105*, 283–293.

Grubler, A., & Wilson, C. (2014). *Energy technology innovation: Learning from historical successes and failures*. Cambridge: Cambridge University Press.

Hang, C. C., Garnsey, E., & Ruan, Y. (2015). Opportunities for disruption. *Technovation, 39–40*, 83–93.

Hargreaves, T., & Wilson, C. (2017). Control of Smart Home Technologies. In T. Hargreaves & C. Wilson (Eds.), *Smart homes and their users* (pp. 91–105). London: Springer International Publishing.

HBR. (2015). Tesla's not as disruptive as you might think. *Harvard Business Review, 2015*, 22–23.

Hertz, F. D., & Halkier, B. (2017). Meal box schemes a convenient way to avoid convenience food? Uses and understandings of meal box schemes among Danish consumers. *Appetite, 114*, 232–239.

HMG. (2013). *8 great technologies*. London: HM Government.

House of Commons. (2016). *The energy revolution and future challenges for UK energy and climate change policy: Third report of session 2016–17*. London: Energy and Climate Change Committee, House of Commons.

Innovation, M. (2017). *Clean Energy R&D Focus Areas*. Paris: Mission Innovation.

ITF. (2015). *Urban mobility system upgrade: How shared self-driving cars could change city traffic*. Paris: France International Transport Forum (ITF).

ITF. (2016). *Shared mobility: Innovation for Liveable cities*. Paris: France International Transport Forum (ITF).

Jacobs, P., Leidelmeijer, K., Borsboom, W., van Vliet, M., & de Jong, P. (2015). *Energiesprong: Transition Zero*. The Netherlands: Energiesprong.

Johansson, T. B., Nakicenovic, N., Patwardhan, A., & Gomez-Echeverri, L. (2012). *Global energy assessment: Towards a sustainable future*. Cambridge: Cambridge University Press.

King, A. (2017a). Technology: the future of agriculture. *Nature, 544*(7651), S21–S23.

King, D. (2017b). Global clean energy in 2017. *Science, 355*(6321), 111.

King, D., Browne, J., Layard, R., O'Donnell, G., Rees, M., Stern, N., & Turner, A. (2015). *A global Apollo Programme to combat climate change*. London: Centre for Economic Performance, London School of Economics (LSE).

Kramer, G. J. (2018). Energy scenarios—Exploring disruption and innovation. *Energy Research & Social Science, 37*, 247–250.

Kramer, G. J., & Haigh, M. (2009). No quick switch to low-carbon energy. *Nature, 462*, 568–569.

Kulak, M., Graves, A., & Chatterton, J. (2013). Reducing greenhouse gas emissions with urban agriculture: a life cycle assessment perspective. *Landscape and Urban Planning, 111*, 68–78.

Lambert, C. (2014). Disruptive Genius. *Harvard Magazine, 2014*, 38–43.

Luderer, G., Kriegler, E., Delsa, L., Edelenbosch, O. Y., Emmerling, J., Krey, V., McCollum, D. L., Pachauri, S., Riahi, K., Saveyn, B., Tavoni, M., Vrontisi, Z., van Vuuren, D. P., Arent, D., Arvesen, A., Fujimori, S., Iyer, G., Keppo, I., Kermeli, K., Mima, S., Broin, E. Ó., Pietzcker, R. C., Sano, F., Scholz, Y., van Ruijven, B., & Wilson, C. (2016). *Deep decarbonisation towards 1.5 °C – 2 °C stabilisation: Policy findings from the ADVANCE project*. Potsdam: Potsdam Institute for Climate Impact Research (PIK).

McDowall, W. (2018). Disruptive innovation and energy transitions: is Christensen's theory helpful? *Energy Research & Social Science, 37*, 243–246.

McKinsey (2012). *Energy = innovation: 10 disruptive technologies*. McKinsey on Sustainability & Resource Productivity, McKinsey Global Institute. *1*: 10–15.

McKinsey (2013). *Disruptive technologies: Advances that will transform life, business, and the global economy*. San Francisco, CA: McKinsey Global Institute.

Midttun, A., & Piccini, P. B. (2017). Facing the climate and digital challenge: European energy industry from boom to crisis and transformation. *Energy Policy, 108*, 330–343.

Moore, S. (2016). *The disrupted decade: 4 disruptions that will shake things up for energy consumers*. London: Citizens Advice.

Mundaca, L., Neij, L., Worrell, E., & McNeil, M. (2010). Evaluating energy efficiency policies with energy-economy models. *Annual Review of Environment and Resources, 35*(1), 305–344.

New Scientist. (2016). *Gamechangers: Energy*. London: New Scientist.

ONS. (2015). *Population density tables*. London: Office of National Statistics (ONS).

Perchard, E. (2016). *New app hoping to revolutionise restaurants' treatment of surplus food that is too good to go. . Resource Magazine* (pp. 1–9). Bristol: Resource Media Ltd.

Prettenhaler, F., & Steininger, K. (1999). From ownership to service use lifestyle: the potential of car sharing. *Ecological Economics, 28*(3), 443–453.

Pye, S., Li, F. G. N., Price, J., & Fais, B. (2017). Achieving net-zero emissions through the reframing of UK national targets in the post-Paris agreement era. *Nature Energy, 2*, 17024.

Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., McCollum, D., Pachauri, S., Rao, S., van Ruijven, B., van Vuuren, D. P., & Wilson, C. (2012). *Energy pathways for sustainable development. The global energy assessment*. Cambridge: Cambridge University Press.

Ribeiro, S. K., Figueroa, M. J., Creutzig, F., Dubeux, C., Hupe, J., & Kobayashi, S. (2012). *Energy end-use: Transport. Global energy assessment*. Cambridge: Cambridge University Press.

Roby, H. (2014). Understanding the development of business travel policies: reducing business travel, motivations and barriers. *Transportation Research Part A: Policy and Practice, 69*, 20–35.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5oC. *Nature Climate Change, 5*(6), 519–527.

Rogers, E. M. (2003). *Diffusion of innovations*. New York: Free Press.

Røpke, I., Haunstrup Christensen, T., & Ole Jensen, J. (2010). Information and communication technologies—a new round of household electrification. *Energy Policy, 38*(4), 1764–1773.

Ruan, Y., Hang, C. C., & Wang, Y. M. (2014). Government's role in disruptive innovation and industry emergence: the case of the electric bike in China. *Technovation, 34*(12), 785–796.

Sathaye, J., & Shukla, P. R. (2013). Methods and models for costing carbon mitigation. *Annual Review of Environment and Resources, 38*(1), 137–168.

Schot, J., Kanger, L., & Verbong, G. (2016). The roles of users in shaping transitions to new energy systems. *Nature Energy, 1*, 16054.

Seba, T. (2014). *Clean disruption of energy and transportation*. Clean Planet Ventures: Silicon Valley.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. *Annual Review of Environment and Resources, 41*(1), 425–452.

Sorrell, S. (2015). Reducing energy demand: a review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews, 47*(0), 74–82.

Sprei, F. (2018). Disrupting mobility. *Energy Research & Social Science, 37*, 238–242.

Springmann, M., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences, 113*(15), 4146–4151.

Stankovic, L., Stankovic, V., Liao, J., & Wilson, C. (2016). Measuring the energy intensity of domestic activities from smart meter data. *Applied Energy, 183*, 1565–1580.

Sussams, L., & Heaton, J. (2017). *Expect the unexpected: The disruptive power of low-carbon technology*. London: Carbon Tracker.

The Climate Group. (2013). *Unlocking low carbon innovation*. London: The Climate Group.

The Economist. (2011). *Business books: Aiming high*. London: The Economist.

Tuomisto, H. L., & Teixeira de Mattos, M. J. (2011). Environmental impacts of cultured meat production. *Environmental Science & Technology, 45*(14), 6117–6123.

Tyfield, D. (2018). Innovating innovation—disruptive innovation in China and the low-carbon transition of capitalism. *Energy Research & Social Science, 37*, 266–274.

Tyfield, D., & Jin, J. (2010). Low-carbon disruptive innovation in China. *Journal of Knowledge-based Innovation in China, 2*(3), 269–282.

Tyfield, D., Jin, J., & Rooker, T. (2010). *Game-changing China: Lessons from China about disruptive low carbon innovation*. London: National Endowment for Science, Technology and the Arts (NESTA).

UK CCC. (2017). *Meeting carbon budgets: Closing the policy gap*. London: UK Committee on Climate Change.

UNEP. (2017). *The emissions gap report 2017*. Nairobi: United Nations Environment Programme (UNEP).

Unruh, G. (2000). Understanding carbon lock-in. *Energy Policy, 28*, 817–830.

Vogel, G. (2008). *Upending the traditional farm*. *Science, 319*, (5864), 752–753. https://doi.org/10.1126/science.319.5864.752.

Wainstein, M. E., & Bumpus, A. G. (2016). Business models as drivers of the low carbon power system transition: a multi-level perspective. *Journal of Cleaner Production, 126*, 572–585.

WBCSD. (2016). *Low carbon technology partnerships: From ambition to implementation*. World Business Council on Sustainable Development: Geneva.

WEF. (2015). *Top ten urban innovations*. Geneva: Global Agenda Council on the Future of Cities, World Economic Forum (WEF).

Wilson, C. (2017). *Disruptive low carbon innovation workshops: Synthesis report*. Norwich: Tyndall Centre for Climate Change & Future Earth.

Wilson, C. (2018). Disruptive low-carbon innovations. *Energy Research & Social Science, 37*, 216–223.

Wilson, C., & Grubler, A. (2014). *The energy technology innovation system. Energy technology innovation: Learning from historical successes and failures. A. Grubler and C. Wilson* (pp. 11–29). Cambridge: Cambridge University Press.

Wilson, C., & Tyfield, D. (2018). Critical perspectives on disruptive innovation and energy transformation. *Energy Research & Social Science, 37*, 211–215.

Wilson, C., Grubler, A., Gallagher, K. S., & Nemet, G. F. (2012). Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change, 2*(11), 780–788.