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Title

Potential climate benefits of digital consumer innovations

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Abstract

Digitalisation has opened up a wealth of new goods and services with strong consumer appeal alongside potential emission-reduction benefits. Examples range from shared, on-demand electric mobility and peer-to-peer trading of electricity, food and cars, to grid-responsive smart appliances and heating systems. In this review we identify an illustrative sample of 33 digital consumer innovations which challenge emissions-intensive mainstream consumption practices in mobility, food, homes and energy domains. Across these domains, digital innovations offer consumers a range of potentially appealing attributes from control, choice, and convenience, to independence, interconnectedness, and integration with systems. We then compile quantitative estimates of change in activity, energy or emissions as a result of consumers adopting digital innovations. This novel synthesis of the evidence base shows clear but variable potential emission-reduction benefits of digital consumer innovations. However a small number of studies show emission increases from specific innovations as a result of induced demand or substitution effects which need careful management by public policy. We also consider how concurrent adoption of digital consumer innovations across mobility, food, homes and energy domains can cause broader disruptive impacts on regulatory frameworks, norms and infrastructures. We conclude our review by arguing for the importance of public policy in steering the digitalisation of consumer goods and services towards low-carbon outcomes.

Keywords

consumers, digital innovations, climate change, mobility, food, homes, energy

Key terms and acronyms

avoid-shift-improve

a typology for distinguishing consumption-based options for reducing emissions according to whether they 'avoid' consumption, 'shift' to less emissions-intensive forms of consumption, or 'improve' the emissions-intensity of consumption

digital consumer innovations

digital or digitally-enabled goods and services offering novel value propositions to consumers in mobility, food, homes and energy domains

ICTs

information and communication technologies for creating, sharing, exchanging, storing and transmitting information, with a particular emphasis in this review on digital and internet-connected ICTs such as smart phones, tablets, computers, and related applications

mainstream, incumbent

consumption practices, firms, service providers, regulatory frameworks and infrastructures with well-established positions which dominate how a particular good or service is provided or consumed

innovation attributes

specific characteristics, features or functionalities of a new good or service

value proposition

attributes which provide clear and demonstrable benefits for consumers as a result of buying, using or otherwise experiencing a good or service

Summary Points

- A wide range of consumer innovations enabled by digitalisation offer novel value propositions which challenge mainstream consumption practices, and can potentially reduce greenhouse emissions if widely adopted.
- Common themes in the consumer appeal and impact of digital innovations across mobility, food, homes and energy domains include: making use of surplus, using not owning, controlling service provision, customising choice, and integrating into systems.
- There are clear and consistent potential emission-reduction benefits from the adoption and use of digital consumer innovations, although the evidence case is stronger for innovations studied at scale in real-world contexts.
- Challenges to consumption practices from innovations clustering and interacting at the consumer level can lead to disruption at larger scales. As an example, mobility innovations such as shared, electric, autonomous vehicles offer novel attributes to consumers but can also impact urban form, social exclusion and working practices as well as the automotive industry.
- Digital consumer innovations have important consequences for rules and structures including data rights and consumer protection, and the balancing act faced by regulators in maintaining stability while enabling low-carbon transformation.
- Public policy has a critical role to play in managing induced demand effects, enabling market access, learning from urban-scale experiments, and developing digital capabilities to anticipate and steer change dynamics towards societal goals.

Future Issues

- Identify interdependencies between alternatives to mainstream consumption practices in mobility, food, homes and energy domains.

- Carry out more empirical research in real-world settings to estimate the direct, indirect, and induced impacts on emissions from consumer adoption of digital .innovations.
- Map out potential second-order impacts of digital consumer innovations on firms, infrastructures, and regulatory frameworks.
- Build the competences and capacities for policymakers and regulators to steer digital consumer innovations to deliver on societal goals.

Conflicts of interest

The authors have no conflicts of interest.

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Table of Contents

1 Digital consumer innovations.

1.1 *Consumer activity and climate change*

Consumers account for the substantial majority of greenhouse gas emissions. If emissions from manufacturing, distribution and production systems 'upstream' are attributed to the consumer goods and services which they supply 'downstream', over three quarters of all emissions can be attributed to consumption (1-3). Consumption activity related to mobility, food, homes, and energy makes up the principal domains of daily life as well as the principal opportunities for emission reductions (1, 4). We use the term 'domain' to describe types of consumption activity (e.g., mobility, food) as distinct from the economic 'sector' which provides for that activity (e.g., transportation, agriculture) (5). The energy domain describes activity at the interface between energy-supply infrastructure and energy use in homes, recognising the emerging opportunities for households to generate, store, trade, and supply energy as well as consume it (6, 7).

Mainstream consumption practices are often wasteful, emissions-intensive, and shaped by consumers' private interests without regard to the carbon intensity or effective functioning of production systems. Mainstream consumption practices include: owning and driving single occupancy vehicles (mobility); provisioning for meat-based diets at large out-of-town retailers (food); passively using or manually controlling domestic appliances and devices whenever needed (homes, energy).

A large body of research dating back to the 1970s has identified, analysed, and quantified opportunities to reduce energy demand with associated emission-reduction benefits (8-11). Changing behaviour and routines, maintaining equipment and appliances, and investing in energy-efficiency improvements and technologies can all yield large savings under current policy, market, and infrastructural conditions (12). Demand-side options for reducing emissions are increasingly recognised in syntheses and assessments (5, 13, 14). A recent EU study estimated 25-30% emission reductions from a portfolio of 90 actions termed 'green demand-side initiatives' including both behavioural changes and efficiency investments (4). However, the type of action contributing the most emission reductions was changing consumption patterns through the purchase of alternative goods and services.

There are numerous opportunities for consumers to buy, subscribe, adopt, access, install or otherwise use lower-carbon goods and services as alternatives to mainstream consumption practices. These opportunities are the emphasis of this review.

1.2 *Digitalisation of consumer goods and services*

Digitalisation has opened up a wealth of new possibilities across all domains of consumption (15). The most dramatic changes to-date have been in the consumption of media and how information spreads through social networks. Information about available resources (supply) and people's needs as part of daily life (demand) flow through digital networks in real time at low or zero marginal cost (16). Real-time information flows also allow for surplus resources to be identified, shared, transacted or exchanged through digital platforms (17, 18). Sharing-economy business models now cover cars, rides, taxis, food, meals, tools, consumer goods, and even electricity (19). Across different domains of consumption, digitalisation is inextricably linked to smartphones and other information and communication technologies (ICTs) which act as interfaces to cloud-based services (20). As one futurist has put it: we may no longer need to own stuff if we can access it online whenever we need it (21). In this and other ways, digital innovations are having far-reaching consequences on the way we live (16, 22).

In the mobility domain, mobility-as-a-service apps synthesise data from a wide range of transport providers so that users can combine different modes to meet specific trip needs (23). Identifying users' mobility needs in real-time enables car-, ride- and taxi-sharing services to make use of surplus capacity otherwise sitting idle (24). In the food domain, online food hubs, food-sharing and redistribution apps match users' food preferences with available food grown locally or surplus from supermarkets or restaurants (25). Other services and apps deliver, gamify, or suggest recipes to encourage dietary change or reduced waste (26). In the homes domain, internet-enabled 'smart' technologies provide new control functionality with possibilities for algorithms to manage heating, lighting or appliances to reduce bills or support the electricity and gas networks during times of peak demand (27-29). The number of digitally networked devices is growing exponentially (30). In the energy domain where supply networks meet final demand, algorithms and control software enable distributed generation through rooftop solar systems or electric vehicles to be extended into electricity storage, trading, and provision of services back to the grid (6, 31).

These are but some of the new goods and services available to consumers as a result of digitalisation. As we show in this review, all could have potential emission-reduction benefits if adopted at scale. But few are primarily and purposefully designed to reduce greenhouse gas emissions. Indeed their mass market uptake depends on their consumer appeal on core attributes such as affordability and reliability as well as a range of novel attributes such as control, flexibility, and connectedness (32).

1.3 <u>Aim and scope of this review</u>

In this review we survey digital consumer innovations in mobility, food, homes and energy domains, and analyse their consumer appeal and potential emission-reduction benefits. Our emphasis is on generalisable insights across different domains, not on providing a systematic review of innovations within any given domain (Table 1).

Our motivating question is: *Are there new and appealing value propositions for consumers, enabled by digitalisation, which could potentially help reduce emissions?* By value proposition, we mean the attributes of a good or service which provide clear and demonstrable benefits to consumers. Novel value propositions which are alternatives to mainstream consumption practices may provide a 'radical functionality' which enables users to do or accomplish something that they could not do before (33).

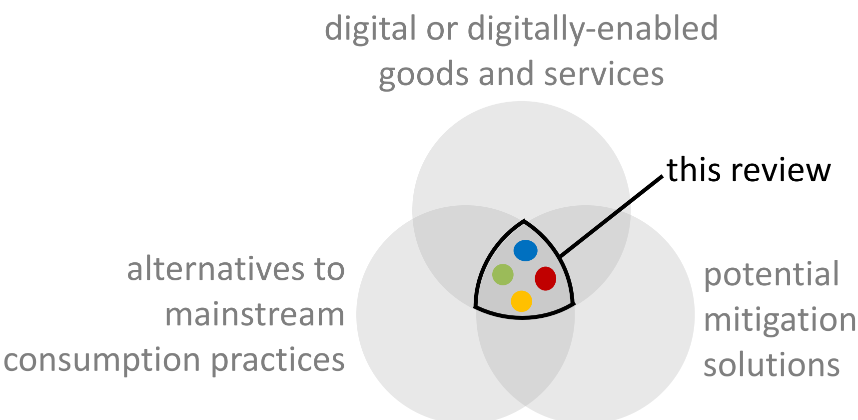
We are specifically interested in digital or digitally-enabled innovations that offer a distinctive set of features, performance metrics, and attributes of potential appeal to consumers (34, 35). Novelty stimulates early adoption, and broad consumer appeal is necessary for subsequent widespread diffusion (32, 36). Within this wide scope, we are interested only in those innovations with evidenced benefits for emission reductions. By definition, therefore, all the digital consumer innovations we consider are potentially 'low-carbon' even though this is not central to their value proposition. A premise of our review is that being low-carbon is insufficient to drive widespread uptake beyond motivated and resourced niche consumer segments.

Table 1 sets out more clearly the scope and aim of our review to help manage readers' expectations about what we do, and what we do not try to do given the breadth and range of the topic. From the outset, we recognise that our review is partial in examining from only one angle the complex relationship between consumers and climate change. Our narrow aim is to explore the *potential* for consumers and consumption practices in an ever-more digital age to contribute to climate change mitigation.

We use a directed review of peer-reviewed and grey literature to identify digital consumer innovations with potential emission-reduction benefits in mobility, food, homes and energy domains (Section 2). We characterise the novel value propositions or consumer appeal of these innovations and draw out thematic similarities across domains (Section 3). We also synthesise quantitative estimates of changes to consumption activity, energy or emissions associated with these innovations and explore reasons for variation (Section 4). We then broaden out our analysis to consider the wider impacts of alternative consumption practices on mainstream markets and incumbent regulatory frameworks, emphasising again the thematic similarities across consumption domains (Section 5). Finally, we reflect on some of the limitations of our review, and conclude with implications for climate change policy and practice (Section 6).

TABLE 1. SCOPE OF THIS REVIEW.

In this review, we *do*:	**In this review, we *do not*:**
- focus on potentially low-carbon digital innovations available to consumers as an alternative to mainstream consumption practices - conduct a directed and selective literature review of 215 studies (summarised in Supplementary Information, and with full annotated bibliographies available from the authors on request) - identify 33 illustrative examples of digital consumer innovations with evidenced emission-reduction benefits in mobility, food, homes and energy domains - comparatively analyse the value propositions of these innovations across domains to draw out common elements in the consumer appeal of potentially low-carbon digital innovations - estimate the potential emission-reduction benefits of these innovations within and across consumption domains to explore reasons for variation - assess the wider challenge to mainstream consumption practices, markets, regulatory frameworks and infrastructures from digital consumer innovations	- consider behavioural change and efficiency investment options available to individuals and households for reducing emissions - conduct a systematic literature review of all digital innovations or all low-carbon innovations - identify an exhaustive set of digital innovations available to consumers including those with evidenced adverse impacts on emissions - analyse the business models or services offered by specific firms like Uber or Amazon - focus in depth on consumer appeal or emission-reduction benefits within a specific consumption domain



2 Identifying digital consumer innovations with potential emission-reduction benefits

We review literature on consumer innovations with potential emission-reduction benefits in mobility, food, homes, and energy domains. Our review is extensive and wide ranging, but is neither systematic nor exhaustive. We seek to identify a set of goods and services illustrative of the changing possibilities available to consumers as a result of digitalisation from among a much larger set of low-carbon innovations (see Supplementary Information, SI-1). Table 2 summarises our search criteria.

We follow precedent in using 'literature-based discovery methods' to survey scientific articles, industry reports and media as a common means for identifying innovations which challenge mainstream practices (20, 37). Patent databases provide an alternative resource for tracking technology development including for climate change mitigation (38, 39). However, patents tend to be better measures of inventive activity than of consumer adoption (e.g., if patented innovations are not commercialised) (40). Some business model innovations creating novel value propositions may also not be patentable. Publications, patents and other indicators such as sales figures and firm valuations have also been used in combination to identify consumer innovations with clear potentials such as mobile phones, GPS, and digital photography, but insights tend to be conclusive only *ex post* (41). As a result, we confine our search to publications.

TABLE 2. OUR LITERATURE SEARCH CRITERIA.

our literature search identified:	our search criteria implied:
(i) novel goods and services available to consumers …	<~10 years since market introduction and/or <~15% market share corresponding to Rogers' early adopters (36).
(ii) which are digital or digitally-enabled, and …	internet-enabled services accessed or controlled by consumers through smartphones or other ICTs (e.g., car-sharing, meal kits), as well innovations using digitalisation to support system integration (e.g., electric vehicle-to-grid), match demand with surplus resources (e.g., food sharing apps), or otherwise enhance functionality and performance (e.g., electric vehicles, heat pumps).
(iii) which offer an alternative to mainstream consumption practices in mobility, food, homes, and energy domains …	exclusion of a wide range of goods and services offering more efficient variants of existing practices (e.g., energy-efficient appliances, fuel-efficient vehicles, loft insulation).
(iv) with clear evidence of potential emission-reduction benefits	exclusion of goods, services, and business models with ambiguous or adverse impacts on emissions (e.g., on-demand ride-hailing, e-commerce and rapid home delivery, see Box 1).

Using the search criteria shown in Table 2 we identify a set of 33 digital consumer innovations such as bike-sharing (mobility), 11^{th} hour apps (food), smart heating (homes), and electric vehicle-to-grid (energy). Figure 1 represents all the innovations except for those in the food domain which are shown separately for space reasons in Supplementary Information (SI-2). The app symbolism used for each innovation points to digitalisation as a general enabler. Figure 1 shows how energy, materials and other resources (far right of Figure 1) are converted into useful goods and services for consumers (far left of Figure 1) through complex provisioning systems and supply chains. All the innovations are shown on the left of Figure 1 as they are at or near the point of consumption.

FIGURE 1. DIGITAL CONSUMER INNOVATIONS INFLUENCE HOW ENERGY AND RESOURCES ARE CONVERTED INTO USEFUL SERVICES. NOTES: ENERGY, BIOMASS, AND MATERIAL RESOURCES (RIGHT) ARE CONVERTED THROUGH A SERIES OF STAGES INTO FINAL ENERGY AND RESOURCES AVAILABLE TO CONSUMERS (MIDDLE) AND THEN INTO USEFUL SERVICES IN THE HOME AND ON THE MOVE (LEFT). THE OUTLINE OF THE HOME DEMARCATES RESOURCE CONSUMPTION IN A PRIVATE CONTEXT FROM SHARED AND PUBLIC CONTEXTS, PARTICULARLY FOR TRANSPORT. MOBILITY INNOVATIONS (BLUE, T1-T13), HOMES INNOVATIONS (RED, H1-H8), AND ENERGY INNOVATIONS (YELLOW, E1-E7) ARE DESCRIBED IN THE MAIN TEXT.

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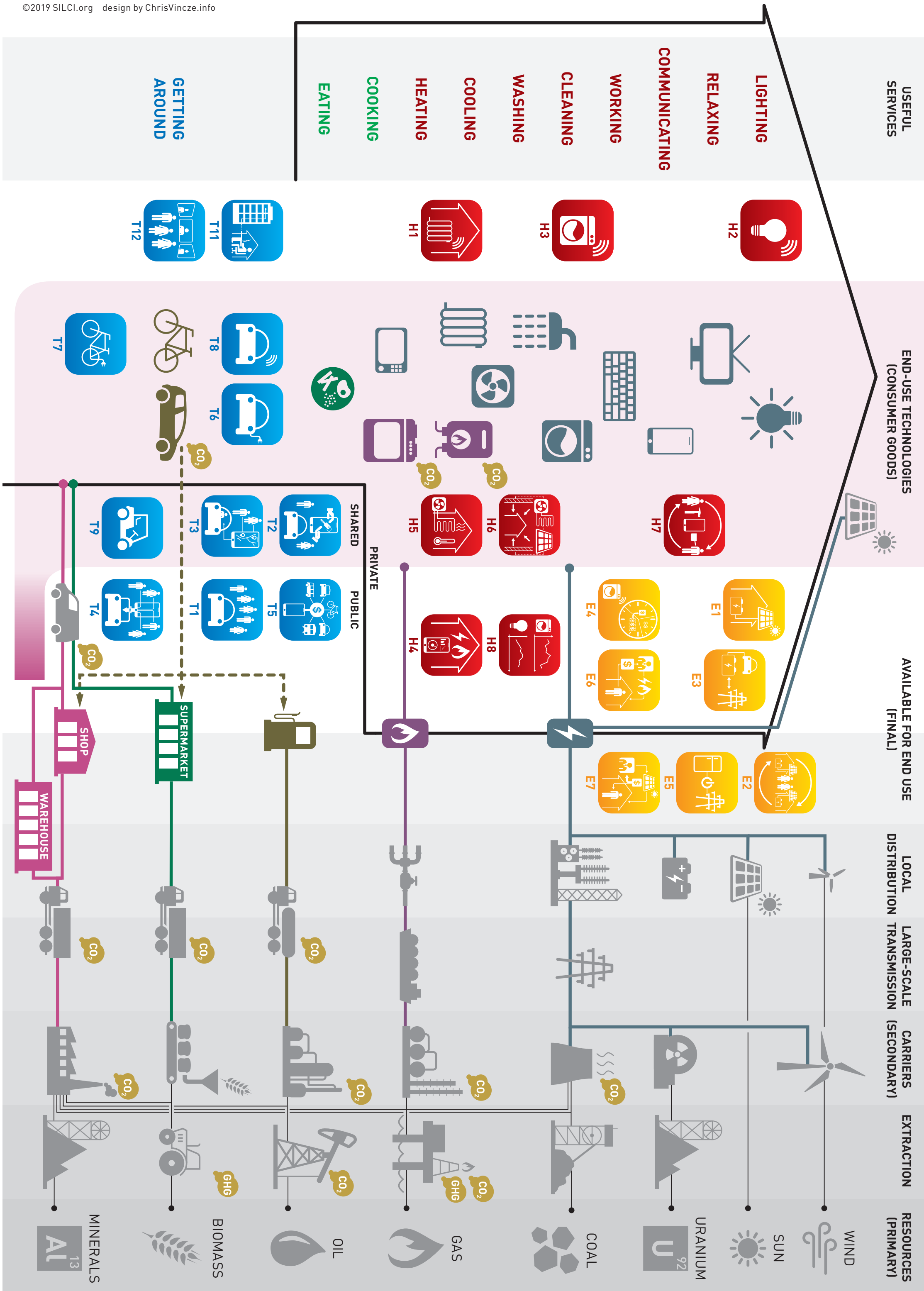


BOX 1. WHY DON'T WE INCLUDE UBER (ON-DEMAND RIDE-HAILING) AND AMAZON (E-COMMERCE WITH RAPID HOME DELIVERY) AS DIGITAL CONSUMER INNOVATIONS IN OUR REVIEW?

Uber and Amazon are poster children of disruptive innovators shaking up incumbent practices in mobility and retail domains respectively (42, 43). Yet we do not include on-demand ride-hailing nor e-commerce with rapid home delivery in our review of digital consumer innovations - why?

There are three reasons. First, we aim to provide examples of novel goods and services not an exhaustive account. Second, despite the evident disruptive impacts of ride-hailing and e-commerce on established businesses and market, from a consumer perspective they improve on already valued attributes (affordability, convenience) as much as they provide novel value propositions as an alternative to mainstream consumption practices. Third, and most importantly for our review, neither innovation offers clear potential emission-reduction benefits.

A recent US study found on-demand ride-hailing services lead to a small decrease in vehicle ownership but nonsignificant impacts on vehicle-miles travelled and fuel consumption (44). However, ride-hailing can also: (i) substitute for trips made by active or public transport modes (45); (ii) induce trips which otherwise would not have been taken (46); (iii) increase congestion including as a result of vehicle relocation between trips (47). All these effects directly or indirectly increase not reduce emissions. In contrast, studies of *shared* ride-hailing services clearly show how increasing occupancy rates of vehicles can have dramatic benefits for congestion and emissions, so we do include these in our review (24).

The increase in speed, flexibility and product range of e-commerce is changing consumers' purchasing behaviour and expectations (48). Consequently the impact on emissions of Amazon's business model combining vast product ranges with rapid home delivery is likely dominated by hard-to-estimate induced demand effects. As we note in our review of meal kits (home delivery of recipe boxes), home delivery can save emissions from avoided trips by individual consumers driving to retail outlets. However, Amazon's same-day and one-day delivery premium services for small packages potentially increase delivery trips and reduce capacity factors of delivery vans (48). Current testing of drone-based delivery as a substitute for road freight offers potential emission-reduction benefits under certain conditions, principally that delivery distances are kept short which implies a network of small urban and suburban distribution centres (49, 50). However, this is not yet a commercial reality.

For each innovation identified, we use convenience sampling of peer-reviewed and grey literature to identify 3-6 relevant studies either of the innovation's consumer appeal, or of its potential emission-reduction benefits, or both. Where possible, we prioritise studies with quantitative estimates of emission impacts using robust study designs. We use the full set of studies to analyse value propositions (Section 3), and a subset of studies with quantitative impact estimates to analyse potential emission-reduction benefits (Section 4). We record relevant information on both topics in annotated bibliographies (available from the authors on request) to enable comparative analysis across innovations and domains. Table 3 summarises the sample sizes of innovations and studies in our review.

TABLE 3. NUMBER OF INNOVATION IDENTIFIED AND NUMBER OF STUDIES REVIEWED.

consumption domain	# of digital consumer innovations	# of studies reviewed and annotated	subset # of studies with quantitative impact estimates
mobility	12	74	49
food	6	30	15
homes	8	83	30
energy	7	28	-

Table 4 defines and gives commercially-available examples of the 33 innovations in our sample, along with an illustrative source reference (see Supplementary Information, SI-3, for full bibliographies per innovation).

For each innovation we use the 'avoid-shift-improve' typology to characterise how the innovation may potentially reduce emissions. Avoid-shift-improve originates in transport studies but is becoming more widely used to distinguish demand-side or consumption-based options for reducing emissions (51). 'Avoid' means consuming less of a good or service (e.g., fewer passenger-kilometres travelled). 'Shift' means consuming more resource-efficient forms of a good or service (e.g., travelling more by train and less by car). 'Improve' means upgrading the resource-efficiency of an existing good or service (e.g., buying a more fuel-efficient vehicle) (51).

TABLE 4. EXAMPLES OF DIGITAL CONSUMER INNOVATIONS WITH POTENTIAL EMISSION-REDUCTION BENEFITS IN MOBILITY, FOOD, HOMES AND ENERGY DOMAINS. NOTES: THE 'EXAMPLE' COLUMN DRAWS MAINLY ON CURRENT US & UK MARKETS. THE '-Δ EMISSIONS' COLUMN USES THE AVOID-SHIFT-IMPROVE FRAMEWORK TO IDENTIFY THE MECHANISM BY WHICH INNOVATION ADOPTION LEADS TO POTENTIAL EMISSION REDUCTIONS, WITH '-Δ EMISSIONS' SIGNIFYING NEGATIVE CHANGE IN EMISSIONS (I.E., EMISSION REDUCTIONS). THE 'REF' COLUMN GIVES ONE EXAMPLE CITATION, WITH FULL BIBLIOGRAPHIES PROVIDED IN SUPPLEMENTARY INFORMATION (SI-3).

	innovation	definition	example	-Δ emissions	ref
MOBILITY					
T1	car sharing (car clubs in UK)	a membership-based service offering short-term rental of vehicles	ZipCar	shift	(52)
T2	peer-to-peer (P2P) carsharing	networks of car owners making their vehicles available to others for short-term rental	Turo	shift	(53)
T3	ridesharing (liftsharing in UK)	networks connecting passengers and drivers for shared car journeys or commutes (can be payment based or for free)	Liftshare	shift (improve)	(54)
T4	shared ride-hailing or taxis	cars or minivans with multiple passengers on similar routes, booked on short notice via apps	Uber Pool	shift (improve)	(24)
T5	mobility-as-a-service	app-based scheduling, booking and payment platform for multiple transport modes	Whim	shift	(23)
T6	electric vehicles	vehicles with electric motor propulsion and a battery that is recharged from external sources of electricity	Nissan Leaf	improve	(55)
T7	e-bikes	bicycles with an electric motor and battery for assisting with pedalling up to limited speeds	Gocycle G3	shift	(56)
T8	fully autonomous vehicles	vehicles that can be driven autonomously without active engagement from the driver	Waymo	improve (shift)	(57)
T9	neighbourhood electric vehicles (NEVs)	light-weight low-speed battery-driven vehicles allowed on roads	Hongdi	shift	(58)
T10 [i]	bike-sharing	fleets of bicycles available for short-term rental from fixed points (docked) or free-floating (dockless)	Ofo	shift	(59)
T11	telecommuting	remote working enabled by information and communication technology (ICT)	Slack	avoid	(60)
T12	video-conferencing & virtual meetings	virtual interactions between people in different physical locations, enabled by ICTs	Cisco TelePresence	avoid	(61)
FOOD					
F1	digital hubs for local food	buy food for delivery directly from multiple local producers	Open Food Network	shift	(25)
F2	meal kits (or meal boxes)	home deliveries of fresh produce pre-portioned for cooking specific recipes	Hello Fresh	avoid (shift) [ii]	(62)
F3	11th hour apps	food outlets advertise surplus fresh food at reduced prices	Too Good to Go	shift (avoid)	(63)
F4	foodpairing apps	design vegetarian recipes using surplus ingredients	Plant Jammer	avoid (shift)	- [iii]

F5	food sharing	enable retailers or individuals to share surplus food with local charities and residents	Olio	avoid	(26)
F6	food gamification apps (for dietary change or waste reduction)	elements of gameplay used to support efforts to reduce food waste or meat consumption	Quit Meat	shift (avoid)	(64)
HOMES					
H1	smart heating systems	monitoring, automation, adaptive learning, and control (via app) of heating	Nest	improve (shift) [iv]	(65)
H2	smart lighting	customisation and control (via app) of lighting	Philips Hue	improve (shift) [iv]	(66)
H3	smart home appliances	automation and control (via app or by utilities) of white goods and other large appliances	Samsung Smart Fridge	improve (shift) [iv]	(67)
H4	home energy management systems	monitoring, control and management system for multiple home functions including heating, cooling, lighting, appliances and solar photovoltaics (PV)	Greenwave Systems (Energy Management)	improve (shift) [iv]	(68)
H5	heat pumps	heating (or cooling) technologies which extract available heat from the air or ground to thermally condition homes	Mitsubishi Ecodan	improve	(69)
H6	pre-fabricated whole home retrofits	custom-fitted high-performance building shells combined with solar PV and heat pump units fabricated off-site and retrofitted externally	Energiesprong	improve	(70)
H7	peer-to-peer (P2P) exchange of goods	networks of individuals for exchanging products, tools and other material goods	Streetbank	shift	(71)
H8	disaggregated real-time energy feedback	activity or appliance-level electricity or gas consumption data available to households	Neurio	improve (shift) [iv]	(72)
ENERGY					
E1	domestic electricity generation with storage	electricity generated domestically stored in a battery system to maximise own-consumption	Tesla Powerwall	shift	(73)
E2	peer-to-peer (P2P) electricity trading	networks of households for trading surplus electricity generated domestically	Brooklyn Microgrid	shift	(74)
E3	electric vehicle-to-grid	allowing bidirectional flows between the grid and batteries of electric vehicles when plugged in to recharge	DriveElectric V2G	shift	(75)
E4	time-of-use pricing	electricity or gas tariff reflecting marginal cost of supply with high prices during peak periods	Agile Octopus	improve (shift) [iv]	(76)
E5	demand response	remote control of domestic appliances by utilities to help reduce peak demand	Geo Hybrid Home	shift (avoid)	(77)
E6	energy service companies (ESCOs)	third-party service providers who manage domestic energy use subject to performance contracts	Sealed HomeAdvance	improve (shift) [iv]	(78)
E7	third-party financing	third-party finance providers who install efficiency or renewables in homes on a pay-as-you-save basis	SunPower Corp	improve (shift) [iv]	(79)

Notes: [i] not shown in Figure 1; [ii] avoid food waste from pre-portioned ingredients; [iii] plantjammer.com; [iv] these innovations offer novel service characteristics ('shift') but are mainly designed to provide a similar service for less energy input ('improve').

3 Novel value propositions of digital consumer innovations with potential emission-reduction benefits

All the digital consumer innovations identified in Table 4 offer potential emission-reduction benefits (see next section). But this is rarely their main design criterion nor the basis of their consumer appeal. In this section, we consider the value propositions of digital consumer innovations within each domain, and then focus on drawing out common themes across domains.

3.1 Mobility

Most of the 12 mobility innovations labelled T1-T12 in Table 4 are either shared [T1-T5, T10], electric [T6-7, T9], or autonomous [T8] forms of mobility (80). Potential emission reductions come from disrupting mainstream consumption practices of owning and driving internal combustion engine vehicles with low occupancy rates. Two innovations, telecommuting and virtual meetings [T11-T12], are distinct in providing a virtual substitute which 'avoids' the need for physical mobility related to work, social, health, educational or other activities.

The value propositions which make the mobility innovations in Table 4 attractive to consumers are varied. Shared mobility offers 'usership' instead of ownership [T1-T5, T10]. Having access to, rather than owning a vehicle incurs lower fixed costs including those associated with vehicle depreciation, insurance, parking permits, and taxes (81). Paying per use or per trip increases the transparency and distribution of costs (82, 83). However, the overall cost advantage of shared mobility over private vehicle use depends on usage patterns. Service-based and shared mobility options provide flexibility and choice over a wider range of vehicle models (84), and so customisable or 'fit-for-purpose' solutions for particular travel needs (85). Users of services also value different attributes from buyers and owners of goods: car markets may become more homogeneous as shared modes mean model obsolescence and in-car features become less important for consumers (86).

Despite air pollution and CO_2 benefits, electric vehicles [T6] are the closest like-for-like substitute for current mainstream consumption practices based on car use. Private mobility reinforces core attributes of autonomy and independence (87). Neighbourhood electric vehicles [T9] similar to golf carts are more novel than electric vehicles [T6] in terms of their value propositions as they enfranchise young and old otherwise unable to drive or afford regular cars (58). This is borne out in China where there are over two million 'low-speed' electric vehicles used by older generations who never got their driving licences when young (88).

Virtual mobility [T11-T12] offers clear financial as well as time benefits. Reducing work-related time and geographic constraints positively impacts quality of life by improving flexibility and reducing commuting-related stress (89). Vehicle automation [T8] can also reduce driving stress and free up travel time for other activities including productive work (90). Active modes [T7, T10] have appealing health and wellbeing attributes (91). All the alternatives to car ownership are more socially inclusive, widening accessibility to mobility services (90).

3.2 Food

The 6 food innovations labelled F1-F6 in Table 4 help share or use surplus food [F3-F6], and shift consumers to less emission-intensive diets [F4, F6] or food retail [F1-F2]. Potential emission reductions come from disrupting mainstream consumption practices which are meat-based and wasteful. In the UK over half of people eat meat every day and over 7m tonnes of the total 12m annual tonnes of food waste occurs in homes rather than in the supply chain (92, 93).

The appealing attributes for consumers of food innovations vary. Value propositions offer novel combinations of choice [F1, F3], convenience [F2-F3], better quality food [F1], and healthier diets [F4, F6] (62, 94, 95). Several of the food innovations help build social connections as an integral part of their appeal to consumers [F1, F5-F6] (26, 64). Alternative food networks [F1, F5] appeal because of the alternative they offer to lengthy, anonymised supply chains from conventional farming through food processing and distribution to supermarkets (96-98). Some innovations combine traditional attributes such as saving money with opportunities for new culinary experiences [F3-F5] (63). As new ways of buying, sourcing, cooking, or eating food, these innovations sit alongside long-established behavioural change strategies to avoid food waste, change dietary preferences, and reduce food miles to improve public health and environmental outcomes (95, 99).

3.3 Homes and energy

The 8 homes innovations labelled H1-H8 in Table 4, and the 7 energy innovations labelled E1-E7, are closely related but with different emphases: homes innovations change how useful services like heating are consumed with domestic settings; and energy innovations change how energy is supplied to, generated by, or managed by households. This distinction is captured in Figure 1 which shows the homes innovations (red) closer to useful services whereas energy innovations (yellow) sit at the interface between homes and energy-supply networks.

Five homes innovations [H1-4, H8] fall under the 'smart technology' rubric for controlling and managing thermal comfort, lighting and appliances. These closely relate to two energy innovations: time-of-use pricing [E4] as a variable tariff structure offered to consumers which enables home energy management systems [H4] to better manage costs; and demand response [E5] which allows utilities or network operators to remotely curtail smart appliances to reduce consumption during critical periods of peak demand [H3]. Three other energy innovations [E1-3] broaden out the role of domestic energy consumers to include generation, trading, and the provision of services back to the grid (7). Two homes innovations are examples of alternatives to fossil-based heating and cooling [heat pumps, H5] and alternatives to owning products with low utilisation rates [peer-to-peer exchange of goods, H7]. The final homes innovation is an alternative to piecewise energy-efficiency improvements [pre-fabricated whole home retrofits, H6] (100). This links to two energy innovations for outsourcing and professionalising energy management [E6] and renovation finance [E7]. Although these outsourcing business models are established in the commercial sector (101), digitally-enabled streams of real-time, granular information on energy performance reduce transaction costs of application in the residential sector (102).

Potential emission reductions from this diverse set of homes and energy innovations come from challenging inefficient or carbon-intensive forms of consumption associated with manual controls and on-demand 'immediate' use of energy whenever needed and without regard to optimal energy system performance.

Consumer value propositions for the cluster of smart energy management technologies [H1-H4] are based on controllability and accessibility (including by remote) (27-29), and opportunities for adaptive automation of tasks or routines to reduce energy costs by shifting consumption out of peak periods or reducing standby consumption (103). Connectivity through networks of data [H1-H4] or people [H7] raises expectations among consumers for a greater breadth of services that a device, appliance or system should provide (104). Homes and energy innovations open up new possibilities for consumers to generate, store and trade their own electricity [E1-E2] and even provide services to grid operators needing to continually balance supply and demand during peak periods [H3-H4, E4-E5] (31, 105).

Some of the other homes innovations have highly distinctive value propositions. Pre-fabricated retrofits [H6] combine high specifications from offsite fabrication in controlled conditions with hassle-free installations as the work is largely external (70). Peer-to-peer exchange of goods [H7] has novel social attributes relating to building community relationships and interconnectedness, in addition to affordability (106).

3.4 Variation in consumer appeal between innovations and domains

All the digital consumer innovations identified in Table 4 challenge emissions-intensive mainstream consumption practices but there is wide variation in their value propositions. Some innovations are costless [food sharing, F5], others are still prohibitively costly [pre-fabricated retrofits, H6]. Some innovations are personal [smart heating, H1], others are interpersonal or collective [shared ride-hailing, T4]. Some are primarily hardware [heat pumps, H5], others are mainly software [food-pairing apps, F4]. Some are based on new possibilities [vehicle-to-grid, E3], others are new versions of old practices [ridesharing, T3].

There are also clear differences between the four domains of consumption activity. Mobility plays out in a public and visible sphere, whereas homes are private, and energy innovations intermediating between supply networks and consumption in the home are largely invisible. Food consumption choices are largely unregulated, energy retail is highly regulated. Mobility innovations are strongly dependent on network density particularly in cities, homes innovations are not.

Although being ‘low-carbon’ is not a core attribute supporting consumer uptake, our search criteria mean that all the innovations in Table 4 potentially contribute emission reductions. Drawing on the avoid-shift-improve framework, there are further differences in emphasis in how the innovations potentially contribute to reducing emissions. The food domain sees the greatest proportion of 'avoid' strategies given the problem of overconsumption and waste in mainstream food practices (107). Innovations in the homes domain are almost all 'improve' strategies to manage or reduce energy demand without changing the basic form of useful services like heating and lighting. Mobility innovations are dominated by 'shift' strategies for switching out of private cars to public and shared modes with very different service attributes but much lower emissions intensity.

The avoid-shift-improve framework also usefully highlights different emission-reduction strategies within a domain. For example, mobility innovations can ‘avoid’ consumption of passenger-kilometres [telecommuting, T11], can ‘shift’ to lower emission forms of mobility [mobility-as-a-service, T5], or can ‘improve’ the emissions-intensity of mainstream forms of mobility [T6, electric vehicles].

3.5 Common themes in consumer appeal across innovations and domains

Despite these differences, there are also some common themes among innovations and novel value propositions across consumption domains, each of which is clearly associated with digitalisation as an enabling ‘meta-innovation’ applicable across domains (20, 22, 37). These common themes are: making use of surplus, integrating into systems, controlling service provision, customising choice, using not owning, blurring boundaries of consumption, and contributing collective benefits.

First, information about available resources (supply) and consumers' needs (demand) can flow through digital networks in real time at low or zero marginal cost (16). This affords consumers opportunities to connect, share and exchange available or surplus resources with other consumers on digital platforms which range from transactional big business to community-based networks (17, 108). Peer-to-peer innovations using sharing-economy business models enable the exchanging or sharing of cars [T2], rides [T3], taxis [T4], food [F5], goods [H7] and even electricity [E2].

Second, digitalisation brings connectedness, with consumers playing more integrated roles within transport, food, and energy provisioning systems. Consumption becomes less atomised, autonomous and independent. Through their consumption practices, consumers can help balance supply and demand, reduce waste including through redistributing surplus food [F3, F5], make idle assets available to other users or system operators [T2, H3, E3], and alleviate pressures on supply infrastructure [E4-E5].

Third, ubiquitous internet connectivity affords consumers greater control over how services are provided. This can be control *by* active users (e.g., through apps or websites) or control *for* users through algorithms, automation, and adaptive learning (109). The appeal of active and passive roles varies by innovation. As examples, consumers may prefer *not* to fully cede control to home energy management systems [H4] or smart appliances [H3] providing demand response services to the grid [E5], whereas consumers *may* prefer to allow algorithms to manage the storage and trade of own-generated electricity [E1-3].

Fourth, innovations based on real-time information about consumers' needs enable services to be customised or enriched in terms of functionality (20). Mass customisation affords consumers versatility and flexibility of choice in how services are matched to specific demands. Mobility-as-a-service [T5] offers different combinations of modes for different trips. Digital food hubs [F1] combine the locality and personality of a farmers' market with the breadth of choice of a supermarket or online shop.

Fifth, a shift in consumption practices from ownership to 'usership' affords convenience and ready accessibility (82, 110). Shifting to a consumer culture based on accessing services rather than owning goods is one of the essential characteristics of innovations which challenge mainstream consumption practices (33). Business models enabling this shift are increasingly evident across consumption domains, particularly mobility, but also in homes. Service-based mobility innovations [T1-T5] free drivers from owning, insuring, maintaining, and parking privately-owned vehicles which typically sit idle more than 95% of the time. Energy service companies [E6] or finance providers [E7] can take on responsibility for mundane efficiency improvements and investments on behalf of households (111).

Sixth, increasing connectedness alongside the shift from owning to using is blurring the boundaries between private, shared, public and collective forms of consumption. Peer-to-peer platforms [F5, H7] connect private users into relational networks, placing private goods in shared or public domains. The virtual mobility innovations [T11-T12] redefine the geography of work while many of the homes and energy innovations redefine consumers as producers, traders and service providers (7).

Seventh, although 'low-carbon' is not strongly emphasised in the consumer appeal of innovations shown in Table 1, collective benefits around health, community and society as well as environment clearly align with diverse public policy goals. Food innovations provide the clearest example. Digital food hubs introduce notions of accountability for environmental standards, animal welfare and farmer livelihoods into consumers’ shopping preferences (96, 98). Apps and platforms for redistributing food surpluses pressure large retailers to address social exclusion (26, 112). Changing dietary norms through an emphasis on the health and environmental benefits of reducing meat consumption can alleviate pressure on health care systems (64). Whether in food or other domains, business models which can capture 'social business cases' help challenge emissions-intensive consumption cultures (113, 114).

Taken together, these seven common elements in the consumer appeal of digitally-enabled goods and services *across* different domains of consumption form a compelling value proposition to stimulate adoption of multiple innovations within specific consumer groups.

4 Direct and indirect impacts on emissions of digital consumer innovations

4.1 Synthesis of quantitative estimates of change

If digital consumer innovations prove sufficiently appealing in challenging mainstream consumption practices, what would be the impact on emissions? We extract quantitative estimates of change in an outcome variable relevant to emissions from all the studies in our directed review which reported useable data (Table 3). We leave each variable with its original metric but expressed as a percent change relative to a baseline or reference point typically defined by the absence of the innovation. This percent change measure (or '%Δ' in shorthand) was either reported directly or could be estimated from other data in the studies reviewed.

We use variable quantities or metrics of three main types:

- %Δ activity: percent change in the amount of activity or useful service consumed (e.g., passenger-kilometres travelled);
- %Δ energy: percent change in the amount of energy or resources needed to provide a useful service (e.g., natural gas consumption for heating);
- %Δ carbon: percent change in the amount of greenhouse gas emissions either in absolute terms (e.g., tCO_2e from energy consumption in homes) or in relative terms (e.g., gCO_2 per kilometre travelled by car). Note that some metrics use CO_2 and others use CO_2-equivalent greenhouse gases; see Supplementary Information, SI-4, for details).

The activity and energy metrics are one or more step removed from emissions (Figure 1). However, reductions in any of the metrics are directionally consistent with reductions in emissions. For example, fewer passenger-kilometres travelled in a single occupancy vehicle (%Δ activity) reduces fuel use for mobility (%Δ energy) which directly reduces tailpipe CO_2 emissions (%Δ carbon).

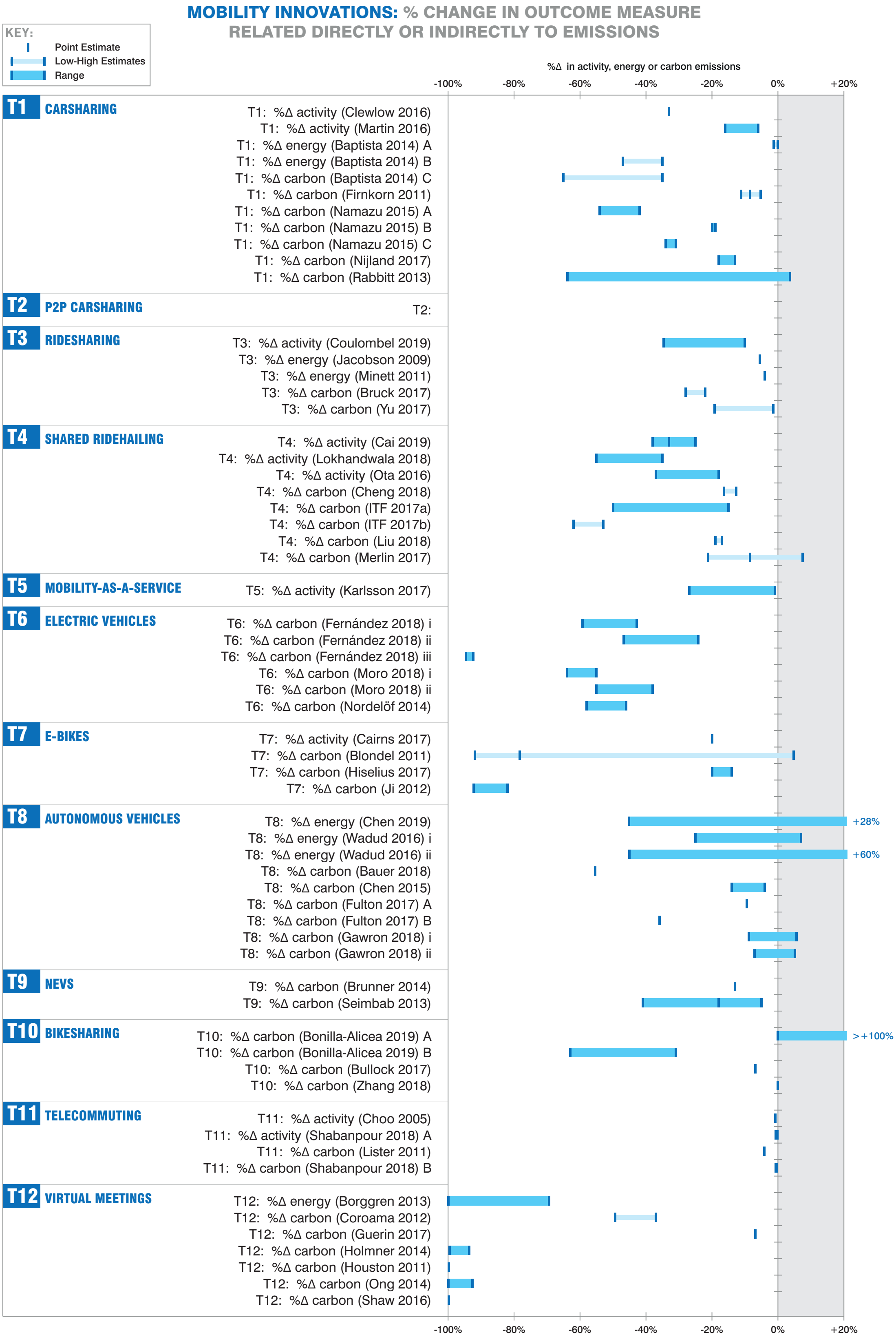
Having measures of different types isolates the effect of innovation adoption on changing consumption practices. In contrast, converting all measures into emission reductions would require context-dependent assumptions about the emissions intensity of energy, materials and food production systems. However, a disadvantage of having measures of different types is that the estimates are not directly comparable, nor can they be used to quantify overall emission-reduction potentials. We discuss this further below.

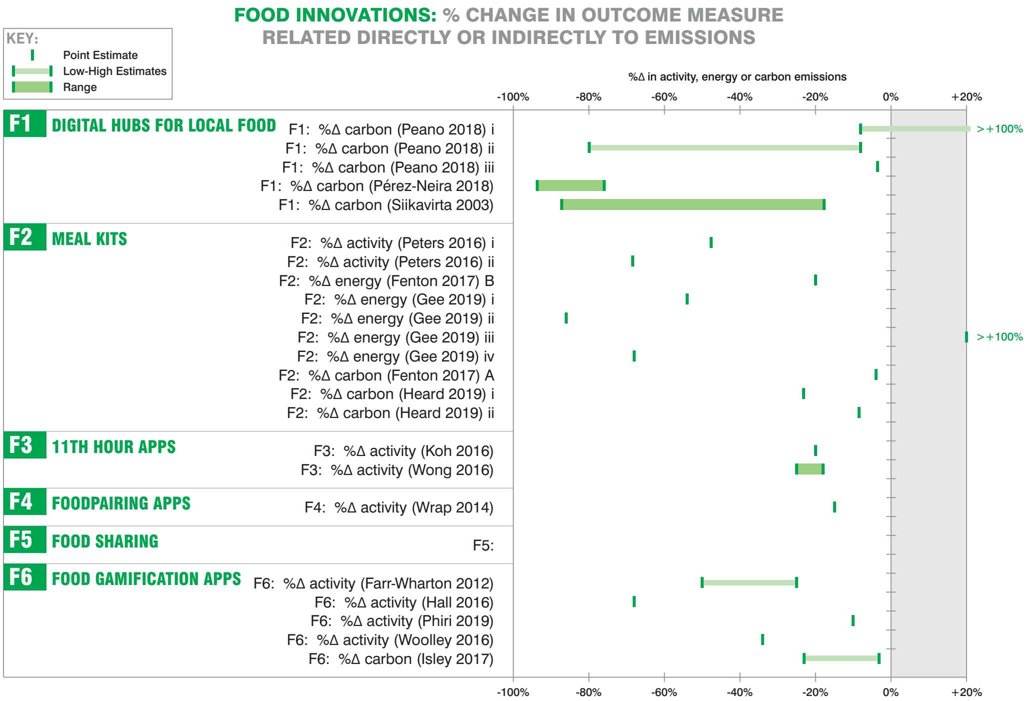
Figure 2 summarises the results for the 12 mobility innovations, 6 food innovations, and 8 homes innovations in our sample (see Supplementary Information, SI-4, for full details). We do not show results for the energy innovations as impacts tended to be indirect (upstream) through changes in system functioning and so are difficult to isolate and attribute to the adoption and use of an innovation. As an example, time-of-use pricing [E4] may shift demand from peak to off-peak periods, but the impact on emissions is dependent on the carbon intensity of electricity generation at different times of the day.

Each row in Figure 2 shows percent change (%Δ) in a consumption-related measure, grouped by innovation, and ordered within each innovation from %Δ activity to %Δ energy then %Δ carbon.

Some studies provided more than one measure if an innovation was trialled or implemented in more than one way, or if the impact was measured in more than one way. These are denoted in the row labels by suffixes A, B, C or i, ii, iii (see Supplementary Information, SI-4, for details).

FIGURE 2. PERCENT CHANGE (%Δ) IN CONSUMPTION-RELATED MEASURES FROM THE ADOPTION AND USE OF DIGITAL CONSUMER INNOVATIONS IN MOBILITY, FOOD AND HOMES DOMAINS. NOTES: MEASURES ARE GROUPED BY INNOVATION, AND ORDERED WITHIN EACH INNOVATION AS %Δ ACTIVITY, %Δ ENERGY, %Δ CARBON EMISSIONS. MEASURES INCLUDE POINT ESTIMATES, LOW-HIGH ESTIMATES, RANGES, AND SYNTHESES. LABELS FOR EACH MEASURE IDENTIFY THE STUDY FIRST AUTHOR (SEE SUPPLEMENTARY INFORMATION, SI-2, FOR FULL BIBLIOGRAPHY).




FOOD INNOVATIONS: % CHANGE IN OUTCOME MEASURE RELATED DIRECTLY OR INDIRECTLY TO EMISSIONS
KEY:
Point Estimate
Low-High Estimates
Range
%Δ in activity, energy or carbon emissions
-100% -80% -60% -40% -20% 0% +20%
F1 DIGITAL HUBS FOR LOCAL FOOD
F1: %Δ carbon (Peano 2018) i
F1: %Δ carbon (Peano 2018) ii
F1: %Δ carbon (Peano 2018) iii
F1: %Δ carbon (Pérez-Neira 2018)
F1: %Δ carbon (Siikavirta 2003)
>+100%
F2 MEAL KITS
F2: %Δ activity (Peters 2016) i
F2: %Δ activity (Peters 2016) ii
F2: %Δ energy (Fenton 2017) B
F2: %Δ energy (Gee 2019) i
F2: %Δ energy (Gee 2019) ii
F2: %Δ energy (Gee 2019) iii
F2: %Δ energy (Gee 2019) iv
F2: %Δ carbon (Fenton 2017) A
F2: %Δ carbon (Heard 2019) i
F2: %Δ carbon (Heard 2019) ii
>+100%
F3 11TH HOUR APPS
F3: %Δ activity (Koh 2016)
F3: %Δ activity (Wong 2016)
F4 FOODPAIRING APPS
F4: %Δ activity (Wrap 2014)
F5 FOOD SHARING
F5:
F6 FOOD GAMIFICATION APPS
F6: %Δ activity (Farr-Wharton 2012)
F6: %Δ activity (Hall 2016)
F6: %Δ activity (Phiri 2019)
F6: %Δ activity (Woolley 2016)
F6: %Δ carbon (Isley 2017)
-100% -80% -60% -40% -20% 0% +20%


HOMES INNOVATIONS: % CHANGE IN OUTCOME MEASURE RELATED DIRECTLY OR INDIRECTLY TO EMISSIONS
KEY:
Point Estimate
Low-High Estimates
Range
Synthesis
%Δ in activity, energy or carbon emissions
-100% -80% -60% -40% -20% 0% +20%
H1 SMART HEATING
H1: %Δ energy (Khajenasiri 2017) A
H1: %Δ energy (Khajenasiri 2017) B
H1: %Δ energy (Park 2017)
H1: %Δ energy (Ringel 2019) i
H1: %Δ energy (Ringel 2019) ii
H2 SMART LIGHTING
H2: %Δ energy (Byun 2013)
H2: %Δ energy (Chew 2017) i
H2: %Δ energy (Chew 2017) ii
H2: %Δ energy (Chew 2017) iii
H2: %Δ energy (Laidi 2019)
H3 SMART HOME APPLIANCES
H3:
H4 HEMS
H4: %Δ energy (Adika 2014)
H4: %Δ energy (AlFaris 2017)
H4: %Δ energy (Beaudin 2015) i
H4: %Δ energy (Beaudin 2015) ii
H4: %Δ energy (Bozchalui 2012) i
H4: %Δ energy (Bozchalui 2012) ii
H4: %Δ energy (Ilic 2002)
H4: %Δ energy (Jin 2017) A
H4: %Δ energy (Jin 2017) B
H4: %Δ energy (Li 2011)
H4: %Δ energy (Louis 2014)
H4: %Δ energy (Nilsson 2018) A
H4: %Δ energy (Nilsson 2018) B
H4: %Δ energy (Paatero 2006)
H5 HEAT PUMPS
H5: %Δ energy (Sivasakthivel 2014) A
H5: %Δ energy (Sivasakthivel 2014) B
H5: %Δ energy (Yuan 2019) i
H5: %Δ energy (Yuan 2019) ii
H5: %Δ carbon (Jenkins 2009)
H6 PRE-FAB RETROFITS
H6: %Δ energy (Beattie 2017)
H6: %Δ energy (Energiesprong 2015)
H7 P2P EXCHANGE OF GOODS
H7: %Δ activity (Fremstad 2017)
H8 DISAGGREGATED FEEDBACK
H8: %Δ energy (Chakravarty 2013)
H8: %Δ energy (Ehrhardt-Martinez 2010) i
H8: %Δ energy (Ehrhardt-Martinez 2010) ii
H8: %Δ energy (Ehrhardt-Martinez 2010) iii
H8: %Δ energy (McCalley 2002) i
H8: %Δ energy (McCalley 2002) ii
H8: %Δ energy (Sokoloski 2015)
H8: %Δ energy (Spagnolli 2011)
H8: %Δ energy (Tifenbeck 2019)
H8: %Δ energy (Ueno 2006)
-100% -80% -60% -40% -20% 0% +20%

4.2 *The evidence for potential emission reductions from digital consumer innovations*

The synthesis of %Δ estimates shown in Figure 2 draws on a wide range of studies with varying assumptions, methodologies, sample sizes, time horizons, and study locations. Studies reported point estimates, low and high values, ranges with or without means, and data syntheses. Methodologies included field trials, natural experiments, simulation models, accounting or simple estimation models, demonstration projects, and testing in labs and other controlled conditions. Some studies estimated technical potentials under what-if scenarios; other studies observed actual changes. Sample sizes varied from a single home or individual to hundreds of thousands participating tacitly in natural experiments. Data collection or observational timescales varied from a week to over a decade. Study locations spanned all the inhabited continents but with the majority in Europe and North America. As a result of this variation in study designs and estimation methodologies, both the internal validity (robustness) and external validity (generalisability) of the quantitative estimates in Figure 2 vary widely.

The %Δ estimates in Figure 2 also vary in the type of quantities or measures, their specificity, and how directly they relate to emissions. Some studies measured change in a defined activity at a specific time and place whereas other studies generalised changes over longer time periods and more varied contexts. As noted above, studies reporting changes in activity were several steps removed from measuring impacts on emissions. Impacts on emissions from reported changes in activity are therefore subject to many assumptions and intervening conditions.

These variations in both study designs and types of measure synthesised in Figure 2 mean that descriptive statistics across the full sample are not meaningful. We therefore limit our interpretation to some general observations.

First, and notwithstanding the many caveats with the sampling and studies reviewed, Figure 2 clearly shows that changes in consumption practices from adopting and using digital consumer innovations can directly or indirectly help reduce emissions. That almost all studies show outcomes consistent with emission reductions is not surprising as this was a search criterion for the innovations (Table 2). Nevertheless, the consistency of potential reductions in activity, energy consumption or greenhouse emissions is quite striking.

Second, a handful of studies report positive %Δ estimates for certain innovations, with four innovations potentially exceeding +20% changes: autonomous vehicles [T8], bike-sharing [T10], digital hubs for local food [F1], meal kits [F2]. These adverse impacts are due to substitution effects or induced demand effects. Substitution effects describe the reference point or baseline form of good or service for which the innovation is a substitute. If docked or free-floating bike-sharing schemes substitute for private bicycles, then the additional energy used by the digital booking, payment, and unlocking infrastructure means adverse indirect impacts on emissions (see row “T10: %Δ carbon (Bonilla-Alicea 2019) A”) (115). Induced demand effects describe changes in consumer behaviour as a result of adopting an innovation. For example, consumption of a good or service can increase if the good or service becomes more appealing or affordable (103). If autonomous vehicles decrease the effective cost of car use while freeing up productive time for users, then the increase in passenger-kilometres travelled by cars mean adverse indirect impacts on emissions (see row “T8: %Δ energy (Wadud 2016) i” (90). These two counter-examples to the general trend of negative %Δ estimates shown in Figure 2 point to the importance of real-world contexts and careful empirical study designs.

Third, the magnitude of %Δ in consumption-related measures varies widely, both within and between innovations. No single innovation dominates others in terms of change potential. Only two innovations show broad convergence between multiple data points: telecommuting [T11] in the range 0 to -10%; and disaggregated energy feedback [H8] in the range -5 to -25%. Otherwise within-innovation variation is large emphasising the many differences and contingencies in both study design and outcome measures. Several innovations almost span the full range of possibility from positive to -100% change: home energy management systems [H4], digital food hubs [F1], e-bikes [T7]. These wide ranges are linked to differences in assumptions about what's being avoided, substituted for, or improved by the innovation.

Fourth, the evidence base is clearly weaker for some innovations, particularly those characterised either by novelty and so very low market share (e.g. mobility-as-a-service [T5]), or by novel value propositions which are not commonly associated with emission reductions (e.g., peer-to-peer exchange of goods [H7]). For some innovations we were unable to find any robust quantifications (e.g., smart home appliances [H3]) despite arguments and evidence in the literature for potential emission-reduction benefits {Hittinger, 2019 #5118}. Outcome measures of 'avoid' strategies tend to be the hardest to quantify as the reference point needed to estimate %Δ is counterfactual. These include the virtual mobility innovations [T11, T12] and the food waste innovations [F4, F5, F6] for which the evidence base is either weak or particularly dependent on assumed system boundaries of what consumption practices are being avoided.

Fifth, those studies reporting changes in emissions generally made static assumptions about the emissions-intensity of production systems, particularly for electricity. This improves the transparency and interpretability of the %Δ estimates, but fails to capture the strong interactions between demand-led change (left of Figure 1) and upstream production systems (right of Figure 1). Scenario analysis of consumer preferences, innovation adoption rates, and wider market conditions and supply chains using system modelling tools is one approach for testing the full scope of change potential (116).

Overall, the synthesis presented in Figure 2 establishes a clear evidence base for potential emission reductions from innovation adoption, while also calling for more empirical research to strengthen the evidence, reduce variability, and identify perverse substitution or induced demand effects which can be managed through business model design and public policy.

5 Second-order effects of digital consumer innovations on markets, regulatory frameworks and infrastructures.

In Section 3 of this review we have drawn out common elements in the value propositions of digital consumer innovations across mobility, food, homes and energy domains. In Section 4 we have characterised the potential impact of innovation adoption on emissions whether directly or indirectly. Here we explore the broader consequences of digital consumer innovations on larger-scale rules and structures, on digital competences and data protection, on the balancing act for regulators to maintain stability while enabling low-carbon transformation, and on the critical importance of public policy for steering change dynamics to deliver societal benefits.

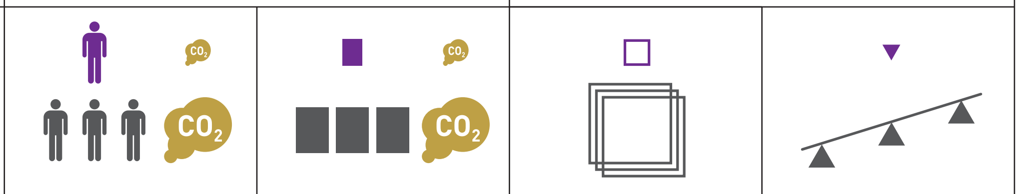
5.1 Interactions between innovations giving rise to second-order disruption

Interdependencies between consumer innovations diffusing concurrently can lead to more widespread or disruptive impacts (41). Interdependencies take many different forms: between novel value propositions offering similarly distinctive attributes of appeal (32); between risk-taking opinion leaders adopting innovations in different market segments (117); or between firms, markets, and consumption norms being challenged by innovation adoption.

In this way, challenges to consumption practices from innovations clustering and interacting at the consumer level can lead to 'second-order disruptions' defined as "*substantially changing societal norms and institutions*" (20). Mobility innovations provide the clearest example. Shared, electric and autonomous mobility innovations each offer distinct types of appeal to consumers, but have a much stronger disruptive effect in combination (80). Shared and usage-based mobility challenge deeply embedded norms of private car ownership (118). Automation further confronts norms and perceptions of driving and control (90). Shared and autonomous vehicles can provide for current urban mobility needs with dramatically fewer vehicles at higher occupancy rates (119). This improves overall transport system efficiency, reduces congestion to close to zero, and allows for a massive repurposing of urban road infrastructure for public benefit (24, 120). If vehicles are also electrified, urban air pollution and the adverse health impacts of private transport in cities are dramatically reduced. Virtual mobility innovations which erode workplace norms including the temporal coordination of daily travel needs offer health, safety, and emissions benefits (121).

Whether in mobility or other domains, second-order disruptions can destabilise regulatory frameworks, challenge embedded consumption cultures, and drive change in physical infrastructures locked-in to emissions-intensive pathways (122). These first-order and second-order impacts are illustrated in Figure 3 which paints a highly stylistic picture of 'successful' disruption. First-order disruptions to consumption practices do not deterministically lead to second-order disruptions to regulatory frameworks, norms and infrastructures. These wider impacts typically involve multi-level dynamics with a diverse cast of actors beyond consumers and firms (123). Systemic change occurs when innovations align with political arguments, social debates, strategic games being played by incumbent actors, and other broader institutional processes (124). In contrast, Figure 3 takes an innovation-centric 'point source' dynamic of change which reduces this complexity to virtuous feedback cycles initiated by novel value propositions for consumers.

FIGURE 3. FIRST-ORDER AND SECOND-ORDER 'DISRUPTIONS' FROM WIDESPREAD ADOPTION OF DIGITAL CONSUMER INNOVATIONS. NOTES: UPPER PART OF FIGURE SHOWS NEW (MAGENTA) AND MAINSTREAM OR INCUMBENT (GREY) CONSUMERS, FIRMS, REGULATORY FRAMEWORKS, INFRASTRUCTURES AND NORMS. CLOUDS (BROWN) REPRESENT DIRECT & INDIRECT GREENHOUSE GAS EMISSIONS FROM CONSUMPTION. LOWER PART OF FIGURE GIVES EXAMPLES OF DISRUPTIVE IMPACTS IN MOBILITY, FOOD, HOMES AND ENERGY DOMAINS.



	First-order disruption		Second-order disruption	
Novel value propositions Mainstream goods & services	Consumption practices	Firms and markets	Regulatory frameworks	Norms and infrastructure
Mobility	Owning and driving petrol or diesel vehicles with low occupancy	Automakers, dealers	Revenue-raising taxation	Parking, transit and ownership norms
Food	Doing big (meaty) food shops	Supermarkets and centralized suppliers	Food safety	Land use, high streets and shopping norms
Homes	Manually controlling devices whenever needed	Small renovation firms, non-digital competences	Data, privacy and consumer protection	Wireless and phone networks, boundaries of home
Energy	Using grid-supplied energy whenever needed	Centralized utilities	Grid access and market participation	Distribution networks and energy use norms

How digital consumer innovations impact firms, markets, and regulations is also context-specific. The lower part of Figure 3 gives examples in each of the four consumption domains. Mobility innovations challenging mainstream consumption practices centred around private vehicle use can impact urban infrastructure, public transport network operation, and status and identity norms associated with vehicle ownership (125). Disruptive impacts of electric vehicles are through interactions between transport and electricity networks (126) and the undermining of treasury reliance on fuel tax revenue (127). Food innovations challenging mainstream consumption practices of bulk food provisioning from supermarkets can impact centralised, concentrated retail and supply chain infrastructure as well as dietary norms. Homes and energy innovations offering alternatives to mainstream consumption practices of on-demand, inefficient, whenever-needed use of energy can impact the roles played by consumers in provisioning systems as well as the norms and boundaries of data generation, sharing and use. (We include further insights In Supplementary Information, SI-5, from a systematic review of literature on disruptive consumer innovations for climate change).

5.2 Data, digital competences and consumer protection

Digital innovations connect consumers to information, energy and social networks, offering new roles, sources of value, opportunities for control, but also risks and constraints. The collection and use of real-time mobility, food purchasing, electricity and gas data raises questions about privacy, trust, and security as the data used by providers to deliver services is linkable to intimate details of daily life (128). Shared, usage-based innovations change the relationship between consumer and service provider from one-off transaction to repeated interaction. This further emphasises the importance of sustaining trust.

Consumer protection concerns have already been felt in several markets with mandated smart meter programmes, and are frequently cited as a barrier to more pervasive uptake of internet-enabled devices, platforms and applications (129). Standards, codes of conduct, or regulatory oversight are needed to establish appropriate legal and ethical principles in these new markets (130), and state clearly where liability and responsibilities lie (67).

Pervasive digitalisation also means firms need strong digital competences as well as expertise in managing complex, secure IT systems (131). As an example, smart heating, lighting and appliances are not discrete products but a multi-layered technology and data infrastructure through which consumer and provider continually exchange data (130, 132). Tesla's "iPad on wheels" electric vehicles and Google's investment in self-driving cars provide other examples of how digital, data and software expertise are transforming incumbent markets (133). Data-driven companies are entering the traditionally quite stable car manufacturing industry on multiple fronts, from service providers (Uber, ZipCar) to technology companies (Apple, Google) to manufacturers (Tesla, BYD) (85). Cars' operating systems are moving towards the continual cycles of patching, updating and improvement familiar to smartphone users, ushering in a whole new range of data and security risks.

5.3 Regulatory balancing and policy steering

Regulatory frameworks are designed in part to maintain reliable, affordable and safe service provision for consumers. In a climate change context, alignment between regulatory frameworks and the firms providing for emissions-intensive consumption practices represents a form of 'institutional lock-in' slowing or resisting change (122). Second-order disruptions initiated by novel consumer value propositions can help escape this lock-in by demonstrating the value in rewriting or renewing rules governing access to transport infrastructure, energy retail markets, and consumer data. Indeed pressure on regulators to allow for new opportunities while guarding against new threats is a good indication of second-order disruption underway (41, 134).

Decentralised energy supply, storage and demand-response innovations create new opportunities for households to provide balancing or flexibility services 'from the edge of the grid' (6, 135). But this challenges the alignment between market access regulations and the business models of incumbent energy companies (31). Food-sharing through community fridges or from surplus food stocks creates private benefit but also a range of social benefits, from social capital to waste reduction. But this challenges incumbent regulations for ensuring food safety and traceability, and clear liability in case of low standards (136, 137). Shared ride-hailing creates versatile, scalable, hybridised modes of private-shared transport for efficient intra-urban mobility (24). But this challenges incumbent provision of fixed route, fixed schedule public transit.

How regulators respond in enabling and managing the market access of digital consumer innovations is therefore critical. Energy regulators in several countries have created 'sandboxes' for trialling new value propositions on a time-limited basis without impacts spilling out into national markets (138). These test beds allow certain rules to be suspended or relaxed so regulators can learn about potentially disruptive impacts. Municipal authorities have been using regulatory oversight and market access (e.g., operating licenses, use of parking infrastructure, road charging) to extract sustainability commitments by new mobility service providers (139). This is a period of experimentation and learning as to what works. In different cities around the world, shared vehicle fleet operators have been variously: (i) banned from competing with high-volume transit routes; (ii) allowed to serve as feeders from suburban residential areas into public transit hubs to address the 'last mile' problem; (iii) formally integrated into public transport networks; (iv) required to provide data on users to help optimise use of urban infrastructure and build the social case for their businesses (140, 141).

Comparing and learning from these different approaches builds the necessary regulatory and policy capacity to steer digital consumer innovations towards societal goals (16, 142). There are many examples in our four consumption domains of innovative policy approaches to test, learn about, stimulate, and steer digital innovations. In the food domain, for example, rules in France prohibit retailers from disposing food surplus (144). This encourages greater use of 11th hour apps, business-to-business food sharing platforms and, indirectly, peer-to-peer food sharing (26). In the homes and energy domains, public policy sets efficiency standards and adoption incentives to stimulate consumer demand for innovations which benefit energy-system management. In the mobility domain, limiting or increasing the cost of vehicle use in urban areas encourages active, shared or public modes with strong health and pollution benefits. Infrastructure provision at a local scale is particularly important, including high occupancy vehicle lanes or parking zones for shared vehicles (145), electric vehicle charging points (146), appropriate docking stations for bike sharing (147), and an integrated, co-located multi-modal transport system for mobility-as-a-service (148).

More generally, policymakers need to build substantive expertise to anticipate and respond to digital innovations, to signal intentions clearly to innovators and investors, and to consistently enforce rules (143).

6 Conclusions

There are large potential benefits for climate change mitigation from changing consumption practices (4, 5, 13). But consumers tend to be framed as part of the problem, resistant to change, and not active pursuers of low-carbon novelty nor willing participants in emission-reduction efforts (143). In this review we have identified many different examples of novel consumer goods and services enabled by digitalisation which challenge mainstream consumption practices in mobility, food, homes and energy domains. Many of the innovations in our sample offer new approaches to longstanding mitigation challenges such as how to stimulate modal shift to public transport or how to reduce wastage of food and energy. Digital consumer innovations sit alongside the numerous other opportunities for individuals and households to reduce their emissions including through behavioural changes and efficiency improvements to homes, devices and vehicles (11). More broadly, our emphasis on consumers meant we did not include the large number of low-carbon innovations applicable upstream in supply chains and production systems (Figure 1).

Important limitations also caution against a naive optimism for the contribution of digital consumer innovations to the challenge of climate change and invite further empirical research. Consumers' choices are constrained by innovation availability, socioeconomic conditions, and access to supporting infrastructure. Innovations may fail to gain market footholds or appeal only to niche consumer segments. Conversely, more appealing, accessible and affordable digital innovations may induce greater consumption, such that increases in activity offset decreases in emissions per unit of activity. Incumbents may successfully resist, slow or adapt to novel threats. Policymakers and regulators may prioritise stability and continuity by dampening digital innovations' access to consumers, particularly in mobility and energy domains which are more regulated.

In conclusion: through our narrow and partial lens on climate mitigation solutions, we found that digitally-enabled challenges to mainstream consumption practices across different domains are characterised in general terms by more exchange, control, choice, services, and system integration. In our quantitative synthesis of the evidence base, we demonstrated the clear emission-reduction benefits should these elements prove appealing to consumers in stimulating adoption (Figure 2). We also sketched wider 'second-order' impacts of shifting consumption on norms, infrastructures, and in particular, regulatory frameworks. Public policy has a critical role to play in ensuring that these second-order disruption dynamics contribute to greenhouse gas emission reductions.

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