[online Supporting Information]

*Title*

**The potential contribution of disruptive low-carbon innovations to 1.5oC climate mitigation**

## Journal

Energy Efficiency (Special Issue on Demand-Side Measures for 1.5oC Mitigation)

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**Supporting Information SI-1.
Potentially disruptive low-carbon innovations identified in literature survey.**

Table SI-1 shows the full results of the literature survey of potentially disruptive low-carbon innovations (DLCIs), organised by domain (rows) and by type (columns). Domains are: mobility, food & land, buildings & cities, energy supply & distribution. Types are: consumer-facing (downstream); business-facing (upstream); enabling or cross-cutting. All the potential DLCIs listed in Table SI-1 were identified from literature surveyed, but vary widely in describing anything from a commercially-available product to a generic strategy or approach. As the literature search was not systematic, Table SI-1 is only indicative of the possible types and sources of disruption to incumbent goods and services which may also help reduce emissions if adopted at scale.

Table SI-1. Survey of potentially disruptive low-carbon innovations in four domains of end-use service. Notes: All consumer-facing innovations in the first two columns are considered further in the main text; innovations shown in *italics* are also scored by low-carbon innovation experts (see Figure 2 in main text).

|  |  |  |
| --- | --- | --- |
| **END-USE** | ***novel product or service available to end users (consumer-facing, downstream)*** | ***novel production, infrastructure or market(business-facing, upstream)*** |
| **primarily a service or business model innovation** | **primarily a technological or product innovation** | **primarily a production or supply chain innovation** | **primarily a market, infrastructure, or organisational innovation** | **enabling, underpinning or cross-cutting 'meta'-innovations** |
| **mobility** | - *car-sharing*- *ride-sharing*- *mobility-as-a-service (MaaS)*- shared taxis (taxi-buses)- neighbourhood electric vehicles (NEVs)- *telecommuting* | - *autonomous vehicles*- *electric vehicles (EVs)*- *e-bikes*- *fuel cell vehicles (H2FCVs)*- *biofuel or flex-fuel vehicles*- interactive virtual reality, telepresence | - goods delivery: airships, drones,bots | - smart infrastructure for active modes (e.g. bike highways)- car-free communities- disappearing traffic | - digital infrastructure, mobile internet, cloud computing- big data,data analytics, machine learning, artificial intelligence (AI)- distributed sensors, imaging & data collection- algorithms, optimisation + distributed control- automation, robotics- block chain (decentralised transactions)- sharing economy- distributed expertise + democratisation of innovation- advanced materials (inc. phase change, plastic electronics, micro-composites, biomaterials)- thermoelectrics (heat to electricity)- synthetic biology & advanced biotech |
| **food & land** | - *reduced meat diet*- *community farms,* *own-food growing*- food box deliveries- food links schemes (inc. farm shops, farmers' markets)- food redistribution or sharing- food waste reduction | - *vertical farming (inc. modular pods)*- rooftop greenhouses- cultured meat | - *hydroponic growing systems*- aquaponic (fish-plant) systems- *aquaculture*- *vertical farming**- greenhouses with LED lighting*- supply-chain waste reduction- feed & manure management- synthetic rubber & fibres | - *smart farms*- *precision agriculture*- *integrated food clusters*- *biochar*- sustainable intensification |
| **buildings & cities** | - pre-fab high-efficiency retrofits | - *smart appliances, internet of things (IoT)*- *LED lighting with smart controls*- *home energy management systems (HEMS)*- smart heating controls- smart homes- *heat pumps* | - new insulation materials- building-integrated energy production- *net zero-energy buildings (nZEB)*- pre-fab low-energy new builds- thermal storage | - *smart meters*- *smart urban infrastructure*- *district heat*- *zero energy districts*- flexible-use buildings |
| - *sharing space**- sharing products, tools, stuff* |  | - distributed manufacturing (inc. 3d printing) | - circular economy- sharing & rental networks |
| **energy supply & distribution** | - *demand response (DR)*- *energy service companies (ESCOs)*- time-of-use pricing- disaggregated feedback (appliance or activity-level)- *peer-to-peer electricity trading*- energy aggregators (for procurement or switching)- community energy- third-party financing- *vehicle-to-grid (V2G)* | - *solar PV + storage*- micro-wind turbines- fuel cells for distributed generation + storage | - load-flexible bioenergy- *carbon capture & storage (CCS)*- CO2 utilisation- *advanced fossil fuel recovery*- offshore wind- small modular nuclear reactors- advanced (algal) biofuels | - distributed energy systems- *micro-grids*- *smart grids (inc. new power electronics)*- *large scale grid storage*- power-to-gas or H2- high voltage DC grids- H2 gas network- wireless charging- tri-generation (power, heating, cooling) |

\* each potential DLCI is shown only once, even though it may apply in multiple domains (e.g., vehicle-to-grid: mobility *and* energy supply; smart meters: buildings *and* energy supply)

**Supporting Information SI-2.
Quantifying UK emission reduction potentials from select DLCIs based on evidence from early-adopting niches.**

Table SI-2 summarises the key assumptions and findings from early-adopting niches of nine select disruptive low-carbon innovations (DLCIs), and the assumptions made to scale up these results to a matched sample of the UK population. Subsequent sections set out the methodology, data, assumptions and sources for each DLCI in full detail.

TABLE SI-2. Summary of potential emission reductions from scaling up evidence from early-adopting niches.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **potentially disruptive low-carbon innovation** | **displaced good or service** | **current market share (% of population who have already adopted)** | **early adopter sample** | **matched UK population (based on sample characteristics)** | **GHG emission savings per year from early adopters within current niche (tCO2e)** | **GHG emission savings per year from scaling up early-adopting niche to matched UK population (tCO2e)** | **% reduction in UK GHG emissions (tCO2e) in corresponding sector (transport, buildings, agriculture etc.)** |
| **car clubs** | urban car use | 11% of car owners in inner London | car owners in inner London (n=78,120) (Carplus 2016) | 32m car owners living in cities in the UK | reduction of 33% of annual v-kms driven for savings of 0.02 MtCO2e | 0.77 to 0.90 MtCO2e | 0.8 to 0.9% reduction in GHG emissions from UK passenger vehicles (96.8 MtCO2e in 2015) |
| **e-bikes** | commuting 2 days per week in car | virtually zero | daily car commuters working in large organisations in Brighton (n=80) | over 197,000 daily car commuters working in large and medium sized organisations in UK | replacement of 40% of daily car commuting trips with e-bikes for savings of 1.64 tCO2e  | 0.04 to 0.08 MtCO2e  | 0.04 to 0.08% reduction in GHG emissions from UK passenger vehicles |
| **e-bike sharing** | local bus and private car | 0.04% of students and 0.11% of employees | students in UK university (n=1,709) | 2.3m students studying in UK higher education establishments  | 21% of students replaced at least 1 public transport trip with e-bike share by 21% of students for savings of 0.14 tCO2e | 0.09 MtCO2e | 0.09% reduction in GHG emissions from UK passenger vehicles |
| employees across three local government institutions (n=80) | 197,000 employees working in large and medium sized organisations in UK likely to also use their own cars for local business trips | employees made on average 11.18 business trips each by e-bike for savings of 0.03 tCO2e |
| **mobility-as-a- service (Maas)** | reduced car journeys | virtually zero | 16 to 60 year old urban residents of Gothenburg, Sweden (n=195) | 26.4m people between the ages of 16 and 60 living in cities in the UK |  n/a | 1.35 MtCO2e (across all modes)  | 1.4% reduction in GHG emissions from UK passenger vehicles |
| **cultured meat** | beef or veal consump-tion | zero | meat eaters aged 18+ who stated their positive preferences towards purchasing (n=580) | 46.7m meat eaters in UK | n/a | 0.02 MtCO2e | 0.03% reduction in GHG emissions from UK agricultural sector (51.1 MtCO2e in 2015) |
| **food waste reduction** | food production, transport-ation & packaging | virtually zero | students in a US university (n=296), hotels in Norway (n=7) | 6 billion meals served in UK food service outlets (in 2015) | reduction of 15% of food waste in sample cafeteria (low estimate) for savings of 28.9 tCO2e | 2.6 to 3.6 MtCO2e | 5.2 to 7.1% reduction in GHG emissions from UK agriculture sector  |
| **urban farming** | large-scale, intensive production & distrib-ution of equivalent food sold at local retailers | virtually zero | community garden in Sutton, London | 295 urban districts with population density of 1000 to 10,000 p/km2 | 34t CO2e per hectare per year  | 2.1 MtCO2e | 4.1% reduction in GHG emissions from UK agricultural sector |
| **rooftop greenhouses** | food production, transport-ation | virtually zero | retail parks in the Netherlands, Canada, USA and Switzerland (n=4) | 1,614 retail parks in the UK with 1,740 ha of rooftop space | reduction of 84 - 729 tCO2e per year (based on tomato production) | 0.04 – 0.59 MtCO2e | 0.07 to 1.15% reduction in GHG emissions from UK agricultural sector |
| **reduced meat diet** | food production, transport- ation & packaging | virtually zero | staff canteens in Switzerland (n=300) | 2.8 billion meals served in large UK catered or staff canteens (in 2015) | reduction of 9% emissions in participating canteens for savings of 1121.8 tCO2e | 0.74 MtCO2e | 1.4% reduction in GHG emissions from UK agricultural sector |
| **smart heating controls** | un-intelligent heating controllers  | 0.007% | homeowners living in medium or large sized properties (n=138) | 11.8m medium or large properties who use gas central heating in the UK | reduction of 5% of annual gas used for heating for savings of 0.02 tCO2e | 1.36 – 2.64 MtCO2e | 1.2 to 2.3% reduction in GHG emissions from UK residential sector (112.1 MtCO2e per year) |
| **smart fridge (as example of smart appliance)** | conven-tional fridges | virtually zero | housing association properties (n=280) | 1.9m housing association properties in the UK | reduction of 1.01 tCO2e over the lifetime of a fridge (average of 15 years) | 0.13 MtCO2e | 0.1% reduction in emissions from UK residential sector in 2015 |

# Car clubs (or car-sharing)

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is car club membership which provides access to shared vehicle fleets on a pay-per-use basis (Cornell 2011).

## Early adopters

* The early adopters are car drivers living in inner London, 78,120 of whom regularly use car club vehicles (CarPlus 2016a).

## Scaling

* Survey of membership in 2016 shows these car drivers reduce annual vehicle-kilometres driven by 33% on average (CarPlus 2016a).
* This provides an average estimate of avoided driving (91.2m v-kms per year) and related GHG emissions reduction (0.18 kg CO2e per v-km) associated with car club membership for car owners.
* This percentage is multiplied by average v-kms driven by all urban drivers in UK (Office for National Statistics 2011a; Department for Transport 2016; Office for National Statistics 2016).
* If adopted by all comparable urban car drivers in UK, the potential avoided GHG emissions are 0.77 MtCO2e per year.
* 18% of urban car drivers reduce their annual driving v-kms by 64% (CarPlus 2016a). This gives an upper bound estimate for potential avoided GHG emissions of 0.90 MtCO2e per year.

## Key assumptions

* Similar rates of adoption occur in all cities in the UK.
* Car club v-kms are equivalent in GHG emissions to privately owned vehicles.
* 18% of urban drivers who become car club members reduce the use of their own personal vehicles over time because they sell their own vehicles, reducing to the average v-kms for a London car club member (1,271 v-kms per year) (CarPlus 2016a).

## Emission reductions relative to sectoral totals

* UK personal transport sector (passenger and light duty vehicles) emissions were 96.8 MtCO2e in 2015 (BEIS 2017b) so this DLCI could result in a 0.8 – 0.9% reduction in sectoral GHG emissions.
* It is important to emphasise that the above calculation is based on the GHG emissions of the average UK urban car driver, driving an average emission vehicle. We take no account of low energy vehicles included in car club fleets or personal vehicle stock.

# E-bikes

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is an e-bike which is a bicycle with an integrated electric motor. Like traditional bicycles they require pedalling but the rider can choose to switch on battery-powered assistance to reduce the effort required. This assistance cuts out when the rider stops pedalling or when the bike exceeds specific speed thresholds as set out by legislation (25 kmh across Europe).

## Early adopters

* The early adopters are participants in an intervention study in Brighton in which 80 car commuters from two participating large organisations were loaned e-bikes over a 6-8 week period (Cairns et al. 2017).

## Scaling

* The study found 40% of daily commuting trips were replaced by e-bikes. Following the trial 0.06% of employees purchased their own e-bike (Cairns et al. 2017).
* This provides an estimate of potential avoidable GHG emissions associated with replacing 2 out of 5 daily commuting trips by car with an e-bike (Blondel et al. 2011).
* These percentages were multiplied by the number of employees who commute by car and work in similar sized companies for the whole of the UK (Gomm and Wengraf 2013; Office for National Statistics 2016; Office for National Statistics 2017).
* If adopted at a similar rate by car commuters working in large organisations across the UK, the potential avoided GHG emissions are 0.04 MtCO2e per year.
* If adopted at a similar rate by car commuters working in all large and medium sized organisations the potential GHG emissions double to 0.08 MtCO2e per year.

## Key assumptions

* 61% of all employees commute to work by car (Gomm and Wengraf 2013).
* Employees commute to work on average 200 days/year (assuming 6 weeks annual holiday and other business trips).
* Large organisations employ on average 250 people, medium sized organisations employ on average 175 people.
* Average commute to work is 10 miles (16 kms) (Gomm and Wengraf 2013; Cairns et al. 2017).

## Emission reductions relative to sectoral totals

* UK personal transport sector (passenger and light duty vehicles) emissions were 96.8 MtCO2e in 2015 (BEIS 2017a) so this DLCI could result in a 0.04% to 0.08% reduction in sectoral GHG emissions.
* It is important to emphasise that the above calculation is based on replacing the GHG emissions for an average UK vehicle (0.18 kg CO2e per v-km) with equivalent for an e-bike (0.022 kg CO2e per v-km).

# E-bike sharing

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is a sharing scheme for e-bike 'fleets'. One such scheme in Oxford offered 22 e-bikes through on-street docking stations located at the university campus, local railway station and local park- and-ride scheme. Its aim was to integrate e-bikes into the local public transport infrastructure. A second scheme in Bristol offered a workplace pool of 12 e-bikes aimed at replacing car dependency for inter-site and local business related travel.

## Early adopters

* The early adopters are participants in two intervention studies. In study one, 1,709 Oxford university students who joined an on-street docking e-bike hire scheme. In study two, 82 staff employed at three local government institutions in Bristol (University of West of England, Bristol City Council & Avon Fire and Rescue) who joined a pooled workplace e-bike scheme (Carplus 2016b).

## Scaling

* In study one, students made 366 trips of on average 4.80 kms per trip using hired e-bikes. In study two, employees made 917 trips between business locations of on average 6.4 kms per trip (Carplus 2016b).
* In study one e-bikes compete directly with a local bus route so potential avoidable GHG emissions are calculated on this basis. In study two, e-bikes competed with car use between nearby sites so avoidable GHG emissions are calculated in terms of replacing car use with a pooled e-bike.
* The percentages for study one were multiplied by the total number of students at UK universities (Higher Education Statistics Agency 2017). If study one is adopted at a similar rate by all students at UK universities, the potential avoided GHG emissions from replacing local bus service trips (0.10 kg CO2e per v-km) between local stations and park and ride services with e-bikes (0.002 kg CO2e per v-km) are 7.35 tCO2e per year.
* The percentages for study two were multiplied for the total number of public and private sector employees who drive to work and therefore likely to have access to a car for local business trips (Gomm and Wengraf 2013). If study two is adopted at a similar rate by all employees in UK the potential avoided GHG emissions from replacing car journeys (0.18 kgCO2e per v-km) with e-bikes are 0.085 MtCO2e per year.

## Key assumptions

* For all students in study one e-bikes substituted for the local bus service which offered identical routes. For all employees in study two e-bikes substituted for use of own vehicle for business trips of 6.4 kms.
* 61% of employees drive to work and therefore have access to their own car in the workplace (Gomm and Wengraf 2013).
* The Bristol car pool scheme was offered to 750 employees who drive to work based within 3 large institutions in Bristol.

## Emission reductions relative to sectoral totals

* UK personal transport sector (passenger and light duty vehicles) emissions were 96.8 MtCO2e in 2015 (BEIS 2017a) so this DLCI could result in up to 0.09% reduction in sectoral GHG emissions.
* It is important to emphasise that the above calculations are based on replacing the GHG emissions for a local bus for an e-bike for students, and private vehicle for employees (Blondel et al. 2011; BEIS 2017b).

# Mobility-as-a-service (MaaS)

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is mobility-as-a-service (MaaS) which is a single gateway and payment platform to a combination of transport modes based on personal preferences and can be paid based on actual use or membership.

## Early adopters

* The early adopters are 195 individuals aged between 16 and 60 who took part in a trial in Gothenburg, Sweden becoming paying customers of MaaS over a period of six months (Karlsson et al. 2016).

## Scaling

* Participants in the study decreased their use of private cars by 48% and increased their use of other modes (taxi (20%), bus services (50%), walking (21%) and cycling (23%)) (Karlsson et al. 2016).
* A carbon intensity value was calculated across the different modes of travel. This value is an average CO2 emission per km across all transport modes (Office of Rail Regulation 2014; BEIS 2017b; The Society of Motor Manufacturers and Traders Limited 2017; Zhao et al. 2017).
* These percentages were applied to the total urban population of the UK (Office for National Statistics 2016).
* The net change in CO2 was calculated by taking the amount of CO2 emitted using the average emissions per km across all modes prior to the trial, and the amount of CO2 emitted with the change in behaviour and frequency of using certain transport modes post trial. The difference in behavioural changes shows the amount of CO2 avoided.
* If the UK urban population between the ages of 16 and 60 years old adopted the same change in behaviour and frequency transport used as the urban population from Gothenburg in the study did, there would be a saving of 1.35 MtCO2e.

## Key Assumptions

* The UK urban population travel the same number of v-kms per year as the England urban population.
* Behavioural change in use of transport mode is 25% less or more of what the participants were using before the trial.

## Emission reductions relative to sectoral totals

* UK personal transport sector (passenger and light duty vehicles) emissions were 96.8 MtCO2e in 2015 (BEIS 2017a) so this DLCI could result in a 1.4% reduction in sectoral GHG emissions.

# Cultured meat

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is cultured meat, an animal-based meat that is grown using a bioreactor instead of an animal (Tuomisto and Teixeira de Mattos 2011). Cultured or lab meat is healthier and tastier but more like real meat than typical meat substitutes. Although not currently sold in the UK it is expected to appeal to ‘uncomfortable carnivores’ (Hopkins and Dacey 2008).

## Early adopters

* The early adopters are 580 meat eaters aged 18+ who in a survey of 1,950 people stated positive preferences towards purchasing cultured meat (Clifford 2017).

## Scaling

* There are 46.7m meat eaters in UK (Clifford 2017) consuming a total of 0.9m kgs of UK produced beef and veal per year (Agriculture and Development Board 2017).
* Beef/veal produces 72.6 kg CO2e per kg of meat (Scarborough et al. 2014), cultured meat produces 2.25 kg CO2e / kg of meat (Tuomisto and Teixeira de Mattos 2011).
* If beef and veal are substituted by cultured meat in accordance with the stated preferences of early adopters, the potential avoided GHG emissions are 0.02 MtCO2e per year.

## Key assumptions

* Early adopters were asked their preferences towards meat substitutes which are similar to real meat in taste, texture and appearance. We make the inference to cultured meat from this preference.

## Emission reductions relative to sectoral totals

* UK agriculture emissions were 51.1 Mt CO2e in 2015 (BEIS 2017a) so this DLCI could result in a 0.03% reduction in sectoral GHG emissions.

# Food waste reduction

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is food waste reduction through innovative means (e.g., social messaging, plate-size reduction, pay-per-weight) in food retail outlets including restaurants, cafes, hotels.

## Early adopters

* The early adopters are participants in two intervention studies in which a simple written social message was placed in an institution cafeteria or hotel restaurant, encouraging consumers to avoid food waste. The samples were students in a US university cafeteria (Whitehair et al. 2013) and the residents of 7 hotels in Norway (Kallbekken and Sælen 2013).

## Scaling

* The studies found a reduction in food waste of 15% (Whitehair et al. 2013) and 20.5% (Kallbekken and Sælen 2013) over a six week period.
* This provides a low and a high estimate of potential avoidable GHG emissions associated with reduced food production.
* These percentages were multiplied by the number of meals served in UK food service outlets in 2015 (Horizon Food Survey 2015) and by one third of the embodied GHG emissions of the UK-average diet per capita per day (Hoolohan et al. 2013).
* If adopted by all comparable food service outlets in the UK, the potential avoided GHG emissions are between 2.64 and 3.61 Mt CO2e per year.

## Key assumptions

* A typical meal from a UK food service outlet is assumed to be one third of the food-related GHG emissions per person per day, as it would constitute one of three daily meals.
* Only comparable food service outlets were included in the calculation, where the consumer can decide how much food to take. Outlets such as restaurants and pubs, which provide plated meals, were excluded because the consumer has no control over portion size.

## Emission reductions relative to sectoral totals

* UK agriculture emissions were 51.1 Mt CO2e in 2015 (BEIS 2017a) so this DLCI could result in a 5.2 – 7.1% reduction in sectoral GHG emissions.
* It is important to emphasise that the above calculation is based on the GHG emissions of the UK-average diet which includes the embodied emissions of food imported into the UK (Hoolohan et al. 2013). When imported food is taken into account, the GHG emissions for the UK is estimated to be 203 Mt CO2e per year (Hoolohan et al. 2013), and so the percentage of avoided emissions would therefore be more modest: between 1.3 and 1.8%.

# Urban farming

## DLCI

* The DCLI is urban agriculture involving the cultivation of land within city limits for the production of food (Garnett 2008). It can be a sustainable method for local food production reducing food miles and emissions from production systems (Aerts et al. 2016).

## Early adopters

* The early adopter is a community farm in the London Borough of Sutton established in 2010 in collaboration with two local charities (Kulak et al. 2013).

## Scaling

* The Sutton urban community farm covers 2.83 hectares and has the potential to reduce GHG emissions by 34 tCO2e per hectare per year. The reduced emissions represent the saving from the purchase of comparable produce from a local supermarket (Kulak et al. 2013).
* London is seen as a ‘leading’ city in terms of local food production (Federation for City Farms and Community Gardens 2010). The percentage of total land area in London used for allotments, community gardens and urban farms was used to scale up the Sutton case study (Greenspace Information for Greater London 2017).
* The total area (hectares) of 295 English urban districts (Office for National Statistics 2015) was multiplied by the percentage of total land area used for urban farms in London to estimate the total potential area for urban farms in English cities.
* Avoided GHG emissions were calculated by multiplying the total potential area for urban farms in England (hectares) by the known value from Sutton of emission reductions per hectare.
* If all suitable districts in England established an urban community farm, avoided GHG emissions would be 2.09 MtCO2e per year.

## Key Assumptions

* The total land used for allotments, community gardens and urban farms in London is as productive as the Sutton case study.
* Of 326 English districts, 295 districts with a population density between 1,000 and 10,000 people per km2 were deemed suitable for similar urban farming projects to Sutton and London.
* Scotland, Wales and Northern Ireland are not included.

## Emission reductions relative to sectoral totals

* UK agriculture emissions were 51.1 Mt CO2e in 2015 (BEIS 2017a) so this DLCI could result in a 4.09% reduction in sectoral GHG emissions.

**Vertical farming – integrated rooftop greenhouses**

*Disruptive Low-Carbon Innovation (DLCI)*

* The DLCI is vertical farming involving greenhouses retrofitted onto retail park roofs. The greenhouse is integrated with the building below to allow residual heat transfer (from waste heat).

*Early adopters*

* The early adopters are food producers who have retrofitted greenhouses on retail park roofs in Canada (Lufa Farms), US (Gotham Greens), Switzerland (ecco-jäger) and the Netherlands (UF002 de Schilde).

*Scaling*

* Sanyé-Mengual et al. (2018) found that 53 - 98% of retail park roofs are suitable for greenhouse retrofitting.
* Sanyé-Mengual et al. (2018) assert that producing tomatoes in rooftop greenhouses, close to the point of consumption, could result in avoided GHG emissions of 15.8 - 135.8 tCO2e per ha per year, when compared to conventional tomato production (based on life cycle analyses in 6 countries).
* Emissions savings from substituting local rooftop greenhouse grown tomatoes for conventionally produced tomatoes increase by a factor of 2.53 if the greenhouse uses waste heat from the building to raise growing temperatures (Sanyé-Mengual et al. 2018).
* There are 1740 ha of retail park rooftop space in the UK (Wood 2017). If all suitable roofs are retrofitted, the potential avoided GHG emissions are 0.04 - 0.59 MtCO2e per year.

*Key assumptions*

* UK retail parks are assumed to be similar in construction and retrofit potential to retail parks in Spain, the Netherlands, Germany, and Portugal.
* UK retail park floor space is assumed to equate to rooftop area.
* The GHG emissions per ha of conventional tomato production for the UK market is assumed to be similar to emissions for conventional production in Spain and the Netherlands, as the UK imports tomatoes from both these countries.

*Emission reductions relative to sectoral totals*

* UK agriculture emissions were 51.1 Mt CO2e in 2015 (BEIS 2017a) so this DCLI could result in a 0.07 – 1.15% reduction in sectoral GHG emissions.

# Reduced meat in diet

## DLCI

* The DLCI is the SV Group ‘ONE TWO WE climate protection programme’, which aims to reduce the GHG emissions from catering at staff restaurants and canteens (Jungbluth et al. 2016).
* The programme uses a lifecycle analysis to quantify the embodied emissions of the food served in participating canteens. Three key strategies for reducing GHG emissions are: reducing red meat content; offering high quality vegetarian meals; and sourcing food which is not transported by air or grown in heated greenhouses.

## Early adopters

* The early adopters are 300 staff canteens in Switzerland (SV Group 2015).

## Scaling

* Participation in the ONE TWO WE programme resulted in a GHG emissions reduction of 9% (SV Group 2016).
* This percentage was multiplied by the number of meals served in UK institution canteens in 2015 (Gain 2015) and by one third of the embodied GHG emissions of the UK-average diet per capita per day (Hoolohan et al. 2013).
* If adopted by all comparable canteens in the UK, the potential avoided GHG emissions is 0.74 MtCO2e per year.

## Key Assumptions

* A typical meal from a UK institution canteen is assumed to be one third of the food-related GHG emissions per person per day, as it would constitute one of three daily meals.
* Only comparable food service outlets were included in the calculation. Other outlets including quick service, leisure, pub, restaurant, and hotel were excluded because they are considered incompatible with the ONE TWO WE programme.

## Emission reductions relative to sectoral totals

* UK agriculture emissions were 51.1 Mt CO2e in 2015 (BEIS 2017a) so this DCLI could result in a 1.4% reduction in sectoral GHG emissions.
* It is important to emphasise that the above calculation is based on the GHG emissions of the UK-average diet which includes the embodied emissions of food imported into the UK (Hoolohan et al. 2013). When imported food is taken into account the GHG emissions for the UK is estimated to be 203 Mt CO2e per year (Hoolohan et al. 2013), and so the percentage of avoided emissions would therefore be more modest: 0.4%.

# Smart heating controls - Nest learning thermostat

## Disruptive Low-Carbon Innovation (DLCI)

* The DLCI is a Nest learning thermostat (NLT). This is a smart heating control system which can be programmed via a user-friendly interface or a mobile app. It also learns about occupancy behaviour (including through a motion sensor) and can 'anticipate' households' heating needs.

## Early adopters

* The early adopters are 138 households in medium or large-sized properties with gas heating systems who took part in a pilot scheme (Park 2017). The households are located in Yorkshire and the Midlands.

## Scaling

* The study found properties fitted with the NLT saved on average 5% of their total annual gas consumption compared to a baseline group with conventional heating controls.
* This percentage was multiplied by the total number of similar properties in the UK (Office for National Statistics 2011b; Department for Communities and Local Government 2016; Department for Communities and Local Government 2017).
* If adopted at a similar rate, the potential avoided GHG emissions range between 1.36 MtCO2e and 2.64 MtCO2e per year (BEIS 2017b).

## Key assumptions

* Around 76% of annual household gas consumption is used for space heating, increasing to 83% over the winter (Park 2017).
* Medium and large-sized properties use between 12,500 and 18,000 kWh/year of natural gas for heating (Park 2017).
* Medium and large-sized properties have floor spaces in excess of 90m2 (Department for Communities and Local Government 2017).

## Emission reductions relative to sectoral totals

# UK residential sector emissions were 112.1 MtCO2e per year (BEIS 2017a) so this DLCI could result in between 1.2% and 2.36% reduction in sectoral GHG emissions.

# Smart fridges

## DLCI

* The DLCI is a smart fridge which autonomously provides an energy balancing service to the grid.

## Early adopters

* The early adopters are participants in an intervention study in which 280 housing association properties were given a smart fridge between May and October 2010 (Open Energi 2012).

## Scaling

* The study found total emission reductions of 1.01 tCO2e over the lifetime of a fridge (average 15 years).
* This provides an estimate of potential avoidable GHG emissions associated with replacing conventional fridges with smart fridges.
* These percentages were multiplied by the total number of housing association properties in UK (Department for Communities and Local Government 2016).
* If adopted by all housing associations, potential avoided GHG emissions are 0.13 MtCO2e per year.

## Key assumptions

* Average household size is 2.3 people (Department for Communities and Local Government 2016).
* The average lifetime of a fridge is 15 years (Open Energi 2012).

## Emission reductions relative to sectoral totals

* UK residential sector emissions were 112.1 MtCO2e in 2015 (BEIS 2017a) so this DLCI could result in a 0.12% reduction in sectoral GHG emissions.

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