Near-Term Actions for Transforming Energy-Service Efficiency to Limit Global Warming to 1.5°C

Charlie Wilson [1,2]

Nuno Bento [1,3]

Benigna Boza-Kiss [1]

Arnulf Grubler [1]

[1] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[2] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK

[3] Instituto Universitário de Lisboa (ISCTE-IUL), DINÂMIA'CET, Lisbon, Portugal

Abstract

A global 'Low Energy Demand' (LED) scenario published in 2018 shows how global warming can be limited to 1.5°C by transforming the way energy services are provided and consumed (Grubler et al. 2018). We follow up this long-range scenario study by setting out a wide range of near-term actions for improving energy-service efficiency through a combination of technological, organisational and behavioural innovation. We focus on three energy services: heating and cooling in buildings, ownership and use of consumer goods, and passenger mobility. We identify a set of 28 actions across these three energy services ranging from multi-functional end-use devices and area-based procurement of whole-home retrofits to shared urban mobility services and open digital platforms. For each action we identify the lead implementation actor, scale of action, and the extent of policy and financing requirements. For selected actions, we also provide examples of best practice from around the world, drawing on both peer-reviewed and grey literature. Finally we identify six basic strategies which are the means by which our diverse set of actions achieve their goal of transforming energy services: electrification, functional convergence, usership, utilisation rates, efficiency frontier, and user-oriented innovation.

Introduction

The 2018 IPCC Special Report on Limiting Global Warming to 1.5°C synthesised available evidence on transformation pathways for the global energy system consistent with the 1.5°C ambition of the Paris Agreement (IPCC 2018). Almost all transformation pathways show continued growth in energy demand and consequently a heavy emphasis on supply-side decarbonisation including massive deployment of renewables and fossil carbon capture and storage (CCS) as well as negative emission technologies (Rogelj et al. 2018). One pathway stood out as an outlier as it shows how global energy demand could be reduced by 2050, which makes decarbonising the energy supply more feasible and without need to rely on negative emissions (Grubler et al. 2018). Given its distinctiveness, this 'Low Energy Demand' or LED scenario was included by the IPCC as one of four marker scenarios for bounding the future possibility space of a 1.5°C-consistent future (IPCC 2018).

The LED scenario emphasises rapid transformation in the way energy services are provided and consumed (Grubler et al. 2018). It shows how potentials for improving technical conversion efficiencies and energy-service efficiencies can be combined to reduce global energy demand by 40% to 245 EJ over the period 2020 to 2050, while allowing for rising activity levels in the global South as populations, incomes and aspirations rise (**Error! Reference source not found.**). This is a critical feature of the LED scenario as it shows not just how to meet ambitious climate-change mitigation goals, but also the broader UN Sustainable Development Goals (SDGs). The technical details of the LED scenario are explained in full, with extensive supporting documentation of key assumptions, in an article in *Nature Energy* (https://www.nature.com/articles/s41560-018-0172-6) which is openly accessible in a read-only version (https://rdcu.be/SOJx).

The LED scenario is strongly normative: it is designed to show how the desirable goals enshrined in the Paris Agreement and the SDGs can be reached. This paper explores how the LED scenario could become reality. Specifically, we ask the question: What near-term actions can improve energy-service efficiency while raising living standards? We draw on a wide range of academic and grey literature to identify best-practice examples for each action from around the world. Our examples combine technological, organisational and behavioural innovation related to three different energy services: heating and cooling, consumer goods, and mobility.

We use the term 'action' in a literal sense to mean 'doing something to achieve a goal'. The goal is to improve energy-service efficiency while raising living standards. Actions therefore capture a wide range of measures, initiatives, projects, programmes, and interventions. For each action we identify the key implementation actor. These can be service providers, innovators, consumers, city mayors, regulators, or policymakers. In some cases our actions link directly with policies; in other cases non-state actors rely indirectly on supportive policy or regulatory frameworks. We use the term 'policy' to mean "*a regulatory, financial, fiscal, voluntary or information provision instrument formally established and implemented* …" (Article 2(18) of the EU Energy Efficiency Directive (EED, 2012/27/EU)).

We also use the term 'strategy' to describe the underlying means by which actions achieve their aim. As a simple example, if two actions are 'installing LED light bulbs' and 'buying fuel-efficient cars', then the underlying strategy is 'improving energy-conversion efficiency'. Strategies are therefore objectives pursuant to the overall goal. We identify six main strategies: electrifying energy end-use; converging multiple functions onto single devices; shifting from owning goods to accessing services; increasing utilisation rates of technologies and infrastructures; diffusing energy-conversion technologies and passive systems at the efficiency frontier; and stimulating user-oriented innovation combining business models and technologies for new energy-service provision. We derive these strategies from the LED scenario narrative which shows how they can yield a 40% reduction in final energy demand to 2050 (Grubler et al. 2018).

Table 1. Impact of LED Scenario on Final Energy Demand in 2050. Source: (Grubler et al. 2018)

	region	change in activity levels (2020-2050)	change in energy demand (2020-2050)	* activity levels in 2050	energy demand in 2050 (EJ)	total (and per capita) energy demand in 2050 (EJ)
thermal comfort	North	+6%	-74%	47 x 10^9m^2 [a]	8	16 (1.8 GJ/pop)
	South	+63%	-79%	218 x 10^9m^2 [a]	8	
consumer goods	North	+79%	-25%	67 x 10^9 units	13	41 (4.5 GJ/pop)
	South	+175%	+54%	186 x 10^9 units	28	
mobility	North	+29%	-60%	25 x 10^{12}p.km [b]	16	27 (3.0 GJ/pop)
	South	+122%	-59%	73 x 10^{12}p.km [b]	12	

* Activity level units vary per end-use service and upstream sector: [a] billion m^2 of floor space; [b] trillion passenger-kilometres; [c] billion tonnes of materials; [d] trillion tonne-kilometres.

Near-term actions (1): Heating & cooling in buildings

In the LED scenario, activity levels approximated by floor space increase in the global South to converge on a global average of 30 m^2/capita by 2050, particularly in multi-family dwellings given pervasive urbanisation and densification. The energy intensity of service provision dramatically falls as a result of Passivhaus-equivalent energy performance standards. In the global North, retrofit rates double to around 3% of the housing stock per year stimulated by low-cost, low-hassle techniques for installing pre-fabricated high-efficiency building shells (BPIE 2018). High service-efficiency thermal end-use technologies (heat pumps, fuel cells) contribute further to reduce energy intensity by 75% to around 160-170 MJ/m^2. In the global South, improvements in building quality, best practice designs (Passivhaus standards with forced ventilation and advanced regenerative room conditioning systems), and incentivised enforcement and compliance with building standards reduce energy intensity by 86% to 40 MJ/m^2. Economies of scope (heating, cooling, hot water) create energy-service efficiency gains relative to traditional single-purpose systems (gas boilers, air-conditioning units). The thermal comfort rows of **Error! Reference source not found.** summarise the quantitative impact of the LED scenario on energy demand over the period 2020 to 2050.

In Table 2 we identify a range of near-term actions for improving energy-service efficiency in line with the longer-term LED scenario narrative. In the text that follows Table 2 we provide examples of best practice for selected actions (marked by *) evidencing where and how they have been implemented. For each action in Table 2 we identify the relevant scale, key implementation actor, and world region. We also characterise the extent to which the action depends on policy and the extent to which the action requires upfront cost investment. In both cases we use simple high, medium, low criteria, assessed subjectively. 'High' denotes direct dependence on policy, or substantial new upfront implementation costs likely involving new capital raising. 'Medium' denotes indirect dependence on enabling policy environments, or some new upfront costs (relative to mainstream practice). 'Low' denotes no or low dependence on policy, no or low new capital requirements.

Table 2. Near-term actions for transforming heating and cooling.

	Near-Term Action	Scale	Key Actor	World Region	Link to Policy	Upfront Cost	Strategy †
H1*	demonstration & scale-up of Passivhaus energy performance	national	policy-makers	North, South	high	high	Y,I
H2	uptake of multi-functional devices (heat pumps, fuel cells)	national, city	policy-makers	North, South	med.	med.	E,F,I
H3*	building code enforcement and compliance incentives	national, city	regulators	South	high	low	Y
H4	competitions to build locally-adapted high-efficiency housing	national, local	mayors, innovators	South	high	high	I
H5	legal tenure in informal settlements in exchange for improved building quality	national, city	mayors	South	high	low	I
H6*	urban climate proofing to mitigate heat islands & weather extremes	city	service providers	South	med.	low	Y,I
H7*	area-based procurement of whole-home retrofits with potential for serialisation	city	service providers	North	med.	high	I
H9	securitised third-party financing of urban-scale retrofit portfolios	national, city	service providers	North	low	high	I
H10	real-time energy monitoring in retrofit portfolios to reduce transaction costs	national, city	service providers	North	low	med.	I
H11	consequential improvements to energy performance of rented or sold properties	national	policy-makers	North	high	med.	Y

* denotes actions for which examples of best practice are provided in the text.
† strategies are: (E)lectrification, (F)unctional convergence, (U)sership, utilisation (R)ates, efficienc(Y) frontier, user-oriented (I)nnovation. See discussion for details.

H1. Demonstration & scale-up of Passivhaus energy performance.

Brussels Capital, one of the three federal states in Belgium, introduced stringent building codes for all new buildings and major renovations in 2011.[i] The codes stipulated maximum space heating demand of 15 kWh/m^2/yr as well as minimum airtightness and maximum overheating thresholds.[ii] Enforcement of the codes followed an extensive consultation and testing phase through the BatEx 'Exemplary Buildings' programme which incentivised 621,000 m^2 of new and renovated buildings over the period 2007-2013 through a combination of project subsidies (€5-18 million/yr) and broader industry support (€29 million/yr).[iii] In 2012, 16% of construction activity in Brussels was BatEx funded, generating €319 million in turnover, creating over

1200 jobs, and avoiding 13,000 tCO_2 emissions per year. By 2015, Brussels had over 3000 Passivhaus-equivalent buildings.[iv]

H3. Building code enforcement and compliance incentives.

Compliance with well-designed and implemented building codes can result in significant energy savings (Tulsyan et al. 2013; Yu et al. 2014).[v] In Chile, the Ministry of Housing and Urban Planning enacted the continent's first building code for thermal performance in 1994 with specific requirements for roofs, walls, windows, floors, and then whole dwellings introduced sequentially over the period to 2016 (Silvero et al. 2019).[vi] Compliance was facilitated by a subsidy program which benefitted over 32,000 families from 2009-2012. Energy consumption in the residential sector fell by 11% over the period 2000-2016 even as national energy consumption rose by 40%.

H6. Urban climate proofing to mitigate heat islands & weather extremes.

Techniques for urban climate proofing include green or high albedo roofs, natural shading, and passive solar designs to mitigate heat islands and air pollution concentration amid dense high-rise buildings which obstruct natural ventilation and air circulation (Byrne et al. 2016). Hong Kong implemented two incentive programmes in 2010 for building designs with green features including sky gardens and communal podium gardens. By the end of 2010, a total of 221 government building rooftops were greened, or under construction. Analysis of the programme's potential benefits under more ambitious promotion and financial incentives estimated a neighbourhood cooling effect of 0.6 - 1.5°C, with energy savings of up to 1.66×10^8 kWh and up to 10.5 $kgCO_2/m^2$ of avoided emissions (Peng and Jim 2013; Peng and Jim 2015).

H7. Competitions and tenders for innovative whole-home retrofit solutions with potential for serialisation.

Whole-home retrofit solutions comprising external wall insulation, window upgrades, solar PV and heat pumps can be designed off-site in quality-control manufacturing facilities and installed rapidly and externally with minimal disruption to household life (BPIE 2018). In the Netherlands, the 'Energiesprong' (energy leap) concept was initially developed through a government-funded innovation programme for net zero-energy home retrofits, focusing on social housing as an initial market niche with implementation scale economies.[vii] In an initial 2014 pilot phase, 200 refurbishments were completed within one week each; the 2015 programme expanded to 2000 homes, with 40 year performance guarantees and upfront costs repaid through energy savings (Jacobs et al. 2015). Nottingham city council has piloted the Energiesprong concept in the UK by investing up to £85,000 on select council-owned homes whose energy bills fell by up to 50% as a result.[viii] The city plans to expand the programme to 150 homes, supported by £5m from the EU’s European Regional Development Fund, with the aim of driving down costs through scale economies.

Near-Term Actions (2): Owning & Using Consumer Goods

Consumer goods are not energy services *per se* but provide for cooking, lighting, hygiene, entertainment, communication and other useful services principally within the home. In the LED scenario, activity levels approximated by numbers of devices increase by 80% in the global North and by a factor of 3 in the global South pulled by rising incomes and living standards. In particular, information and communication technologies (ICTs) proliferate and diversify to provide new and improved energy services. The energy intensity of service provision dramatically falls as a result of improving energy conversion efficiencies driven by a dynamic ratcheting up of performance standards. Global average electricity intensity, weighted by share of total devices, falls from 93 to 82 kWh/device, with the strongest reductions in lighting and appliances. Energy intensity further reduces through a strong trend towards multi-functional devices (particularly smartphones) which displace the need for dozens of single-purpose devices (radio, TV, answerphone, scanner, music system, etc.) and yields power savings of up to 100-fold while in use and up to 30-fold while on standby. Connected, responsive, 'smart' devices improve controllability, help reduce passive losses (e.g., lighting unoccupied rooms), and open up potential for system integration including load management and demand response. Online platforms also enable peer-to-peer and commercial exchange of surplus capacity increasing utilisation rates of physical goods. 'Usership' starts to weaken cultural norms of 'must-have' ownership. Consumers demand service quality, variety, flexibility, convenience, and low lifecycle costs. The consumer good rows of **Error! Reference source not found.** summarise the quantitative impact of the LED scenario on energy demand over the period 2020 to 2050.

As with heating and cooling, we identify near-term actions consistent with this narrative of energy-service transformation for the ownership and use of consumer goods (Table 3).

C1. Dynamic ratcheting up of product efficiency.

In Japan, the Ministry of Economy, Trade and Industry (METI) implemented the 'Top Runner' programme in 1999.[ix] Best-in-class products define future efficiency standards over near-to-medium timeframes (typically 5-8 years). By the predetermined target year, manufacturers commit to exceeding the standard at the level of their average product efficiency, weighted by sales across their entire range (Kimura 2014). Standards are then ratcheted up as best-in-class products improve further. Applied initially to 11 product categories (e.g., cars, AC units), Top Runner has now expanded to more than 30 product categories from rice cookers to electric toilet seats. Compliance with the standards grants an efficiency label. Non-compliance is punished with a well-publicised 'name-and-shame' penalty and a fine. Energy efficiency improvements average around 40% (with a range from 4% to 85%), often significantly exceeding expectations.[x] The Top Runner programme has helped curb growth in household electricity use and reduce annual emissions by 50MtCO_2 from the residential sector (Matsukawa 2016).

Table 3. Near-term actions for transforming ownership and use of consumer goods.

	Near-Term Action	Scale	Key Actor	World Region	Link to Policy	Upfront Cost	Strategy †
C1*	dynamic ratcheting up of product efficiency	national	policy-makers	North, South	high	med.	Y
C2*	media consumption on low-energy mobile devices	national	consumers	North, South	low	low	F,U,R
C3*	open digital platforms for low-energy service providers	national, city	regulators	North, South	med.	low	F,U,I
C4	competitions & incentives for low-energy designs & business models	national, city	innovators	North, South	med.	low	I
C5*	neighbourhood-scale testbeds for novel energy-service provision	city	mayors	North, South	high	high	E,I
C6	opinion leadership to challenge stigma of sharing and reuse	city, local	consumers	South	low	low	U,R
C7	virtual aggregators for one-stop service provision requiring multiple skills or tools	city, local	innovators	North	low	low	R,I
C8*	leasing or exchange of appliances linked to energy performance	national, local	service providers	North	med.	low	Y,I
C9*	space allocation for repositories of peer-exchanged appliances & tools	city, local	mayors	North	med.	med.	U,R
C10 *	incentives for high-efficiency, long-lived, reusable products	national, local	policy-makers	North	high	med.	Y,I

* denotes actions for which examples of best practice are provided in the text.
† strategies are: (E)lectrification, (F)unctional convergence, (U)sership, utilisation (R)ates, efficienc(Y) frontier, user-oriented (I)nnovation. See discussion for details.

C2. Media consumption on low-energy mobile devices.

In 2016, more time was spent watching online video on mobile devices than on desktop or other non-mobile devices.[xi] In the US in April 2017, 8 billion minutes of Netflix content was viewed on smartphones. Although this only represents 10% of total Netflix viewing time[xii], the potential displacement of TVs, monitors, and other screens by smartphones as media content viewers offers significant potential energy savings (see LED scenario above). This secular consumer trend towards mobile media devices has not been actively promoted by policy.

C3. Open digital platforms for low-energy service providers.

Open platforms allow third parties to develop and deliver services to end-users through popular hardware devices. Voice control devices offering households virtual assistants to support everyday living at home currently dominate sales of smart home technologies.[xiii] In addition to voice-enabled internet access, virtual assistants can perform multiple energy-related functions from home automation (lighting, heating, security) to control of smart appliances or plugs. Amazon's Echo and its virtual assistant Alexa launched in 2014 and by late 2018 had captured two-thirds of the US market[xiv] and expanded into 41 countries worldwide.[xv] Echo's open platform has enabled third party developers to provide households with voice-enabled smart controls over a range of energy-using appliances.[xvi]

C5. Neighbourhood-scale testbeds for novel energy-service provision.

Pecan Street is a research and development (R&D) organization providing a real-world test bed for new end-use technologies. In 2009 Pecan Street began equipping homes in the Mueller neighbourhood of Austin (Texas, US) with advanced energy monitoring equipment, making the high-resolution energy and water consumption data available for researchers and service providers. The dataset now covers over 1000 residential and commercial buildings, including 250 solar-powered homes and 65 electric vehicles.[xvii] Pecan Street also provides a commercialization lab for testing and verification of technology solutions.

C8. Leasing or exchange of appliances linked to energy performance.

In Colombia, the Return and Save programme ('Campaña Entrégala y Ahorra') grants a reduction in VAT from 19% to 5% for low and medium income households which exchange an old refrigerator or freezer for a new high-efficiency substitute costing up to $1200.[xviii] The old appliances are delivered to authorized agents for refrigerant disposal and recycling, with an estimated 75% of the appliance by weight being recycled back into production.[xix] The programme has directly created 2,000 jobs and a further 10,000 indirectly in the recycling and materials supply chain. The programme's goal is to substitute at least one million refrigerators and freezers within 5 years (IEA-UNEP 2018).

C9. Local space allocation for repositories of peer exchanged appliances & tools.

Peer-to-peer exchange of new and used goods - from tools, equipment and appliances to toys, clothing, and furniture - is one of many possible models for a sharing economy (Frenken 2017). In Portland (Oregon, US), a local community organisation founded the North Portland Tool Library in 2004 with a primary purpose of making available and sharing tools among its 5,000 members (Cooper and Timmer 2015). In 2013, cost savings were estimated around $0.5m for a total of 7,364 tool loans based on assumed rates of avoided tool purchases.[xx] The tool sharing also resulted in more than 143 tCO_2-eq. of avoided emissions, equivalent to 30 cars being taken off the road each year. More broadly, the economic benefits of repair, reuse and rental of a wide range of household goods were estimated at $1.1bn in gross sales, more than 9,000 direct jobs, and avoided emissions of 400,000 tCO_2-eq (Cooper and Timmer 2015).[xxi]

C10. Incentives for high-efficiency, long-lived, reusable products.

Austria implemented a label of excellence in 2014 for "durable, repair-friendly designed electrical and electronic appliances", extending an earlier durability mark from 2006 for white goods (>10 years average lifetime) and consumer electronics (>5 years).[xxii] The label also mandates that the guarantee and spare parts availability follow the product's lifespan. A more dramatic example of regulatory challenge to short-lived throw-away products is a recent French law making planned obsolescence a criminal offence punishable by up to two years imprisonment and a penalty of €300,000 or up to 5% annual turnover.[xxiii]

Near-Term Actions (3): Moving People Around Cities

In the LED scenario, activity levels measured by passenger-kilometres (p-km) increase by a factor of 2 across all modes in the global South (particularly flexible-route shared vehicles), but fall by 20% in the global North with larger reductions in road-based modes offsetting increases in rail and air. Further growth in mobility is constrained by dense cities, shared modes, and some substitution of physical mobility by virtual modes including telepresence. The energy intensity of service provision dramatically falls as a result of pervasive electrification of vehicles with factor 3 improvements in power-train efficiency. Real-time information via mobile devices support shared vehicle fleets available on demand and flexible transit systems (including micro-transit or taxibuses) which rationalise vehicle usage and reduce congestion. Increasing vehicle occupancy by 25% and vehicle usage per day by 75% delivers the same intra-urban mobility with 50% of the vehicle fleet. By 2050 total vehicle numbers have halved to around 850m light duty vehicles. New forms of mobility-as-a-service with trip planning and payment systems integrated across multiple modes are characterised by ease of use, flexibility, and variety of choice. High-frequency, high-capacity public transport routes emphasise use of existing infrastructure (e.g., rapid transit buses) rather than lumpy new infrastructure with high sunk costs (e.g., trams, trains). Global average energy intensity weighted by modal share falls by 70% with the strongest reductions in road-based modes.

As with the previous two end-use services, we identify near-term actions consistent with this narrative of energy-service transformation in urban mobility (Table 4).

Table 4. Near-term actions for transforming urban mobility.

	Near-Term Action	Scale	Key Actors	World Region	Link to Policy	Upfront Cost	Strategy †
M1*	open real-time data on traffic flows & infrastructure usage	city	consumers	North, South	med.	med.	U,R,I
M2*	shared, responsive modes integrated into public transport networks	city	innovators	North, South	high	med.	E,U,R,I
M3*	point-of-use integration between multiple public & private modes	city	mayors	North, South	high	high	F,R
M4*	co-location of EV charging points with local economic activities	national, city	service providers	North, South	high	high	E,F
M5	public procurement of EV fleets (inc. on-demand shared modes)	city	mayors	North, South	high	high	E,I
M6	repurposing of road infrastructure for leisure, food, parks	city	mayors	North	high	high	U,Y,I
M7	enabling market access by new low-energy service providers	national, city	regulators	North	high	low	I

* denotes actions for which examples of best practice are provided in the text.
† strategies are: (E)lectrification, (F)unctional convergence, (U)sership, utilisation (R)ates, efficienc(Y) frontier, user-oriented (I)nnovation. See discussion for details.

M1. Open real-time data on traffic flows & infrastructure usage.

The UK National Infrastructure Commission identified many potential economic benefits from collecting and sharing infrastructure data ranging from lower consumer bills and environmental impacts to enhanced security, smart cities, and improved transport (UK NIC 2017). Real-time data on traffic and transport supports open access and analysis by citizens, researchers and service providers, helping cities improve day-to-day transport services as well as inform strategic investments. Open data from public transport providers is unproblematic. Trip-planner apps like Ridescout scrape data on different modes from different sites to provide real-time information to users on congestion, delays, alternative routes. Transport for London has estimated that making real-time transit network data publicly available has saved users the equivalent of £15-58m per year in time.[xxiv] Open data from private firms is more contentious, particularly if it undermines competitive advantage. Some cities have negotiated access to user data in exchange for licenses to operate, light-touch regulation, or preferential market access. The city of Portland (Oregon, US) negotiated access to user data from ride-hailing companies, Uber and Lyft, as a quid pro quo for allowing access to the city with light-touch regulatory oversight (e.g., on peak time fares). The city of Los Angeles (California, US) signed a data exchange agreement with Waze, the leading traffic and navigation app. The city provides details of roadworks and closures in exchange for real-time data on traffic patterns and road conditions. Seattle (Washington, US) required Car2Go, a free-floating car-sharing company, to provide user data including member surveys in exchange for an operating license. Survey data are used to build the social case for car-sharing in the city in terms of its net impact on vehicle.miles travelled and public transit usage (p89, 182, 186 in Cooper and Timmer 2015).

M2. Shared, responsive modes integrated into public transport networks.

Shared taxis, taxibuses, or 'micro-transit' can offer cost-effective alternatives to public transport in low density areas poorly served by arterial routes (ITF 2017b). These shared, responsive (on-demand) modes can be hailed or booked through apps and use real-time data to plan flexible routes with limited stops to accommodate pick-ups and drop-offs (much like ride-hailing apps but with multiple passengers). Simulation modelling by the OECD's International Transport Forum shows that micro-transit effectively act as feeders from suburban residential areas into public transport hubs addressing the 'last mile' problem (ITF 2017a). Several cities have gone this route, with micro-transit services like Bridj in Syndey (Australia) partnering with city transit operators.[xxv] Micro-transit providers which compete with high-capacity transit routes can face regulatory restrictions or bans, as happened with Chariot in San Francisco (US) and ten other cites.[xxvi]

M3. Point-of-use integration between multiple public & private modes.

Mobility-as-a-service (MaaS) combines trip-planning for multiple transport modes with a single digital payment or subscription, allowing users to move seamlessly between modes without having to pay anew each time (Kamargianni et al. 2016). Originating with urban public transport providers to facilitate integration between trains, subways and buses, MaaS is expandable to include any transport mode, from car-share and shared taxis to bike-share and electric scooters. To work effectively, MaaS requires co-location of modes to reduce transition times and effort (e.g., from train to bus, or bus to bike-share).

In Helsinki (Finland), the Whim app provides universal timetabling, trip planning, and payment functionality for the city across bus, train, bicycle, taxi, car-sharing and other modes.[xxvii] From its launch in 2016 to October 2018, Whim has grown to have 60,000 active users booking almost 2m trips (although this is less than 0.5% of all non-vehicle trips in the city).[xxviii] Further growth is currently undermined by a lack of integration with the municipal transit agency's ticketing and payment system. However, the national government recently introduced a law requiring any transportation provider to allow third parties access to its ticketing functionality. In Montreal (Quebec, Canada), the public transport authority, STM, has negotiated agreements with other mobility providers including bike-share (Bixi), car-share (Communauto), and 'taxibuses' (shared taxis operating on both fixed routes and on-demand services) to link in to its own network of bus, metro, and rail (p94, Cooper and Timmer 2015). This 'combined mobility' concept offers users discounted, bundled transportation services at preferential rates for multi-modal journeys. STM improved physical co-location through bike parking at, and connections between, key nodes of the bus and metro system.[xxix]

M4. Co-location of EV charging points with local economic activities.

Public investment in electric vehicle (EV) charging infrastructure is a necessary precursor to widespread consumer adoption (Leibowicz 2018). Although incumbent oil companies and vehicle fuel retailers are moving to locate charging infrastructure in existing refuelling stations, the pollution and safety concerns which led to these being built on main roads and out of cities do not apply to recharging points. These can be co-located with local economic activities of similar duration to maximise consumer utility and economic benefit: fast charging (~15 minutes) with cafes, convenience stores and supermarkets; slow charging (2-3 hours) with restaurants, retail and leisure centres. Such locations are highly visible in and around city centres stimulating social diffusion and public awareness (Bakker and Trip 2013). The Austin (Texas, US) demonstration neighbourhood, Pecan Street, is also co-locating EV charging with distributed renewable electricity generation to reduce the net additional load on centralised power grids.[xxx]

Discussion

Tables 2-4 set out a wide range of near-term actions for improving the efficiency of three energy services relevant for individuals and households particularly in urban environments (Figure 1). We identify three important meta-issues which apply generically to all these actions: strategy, policy, and cost-effectiveness.

Strategy. The means by which our actions improve energy-service efficiency can be grouped into six main strategies. As noted earlier, these were derived from the LED scenario narrative and analysis as integral features of a low-energy 1.5°C future which allows for rising living standards in the global South (Grubler et al. 2018).

1. Pervasive <u>electrification</u> of energy end-use including electric vehicles for mobility and heat pumps for heating and cooling;
2. Rapid <u>functional convergence</u> of multiple services onto single multi-function devices, appliances or business models, reducing the need for single-purpose products or services (i.e., economies of scope);
3. Shift from ownership (of material goods) to '<u>usership</u>' (accessing services) for transport, consumer goods and space, challenging norms of material consumption;

4. Proliferation of sharing-economy business models and other means of increasing utilisation rates of consumer goods, vehicles, and physical infrastructure;
5. Widespread consumer adoption of homes, appliances and transportation modes at the efficiency frontier, pulled by cost, performance, health and other benefits;
6. User-oriented innovation to develop, test, and scale up new technological, organisational, and institutional forms of low-energy service provision with strong consumer value propositions.

Taken together these strategies define a set of objectives for guiding efforts to reduce global energy demand in pursuit of the global Paris Agreement and the UN Sustainable Development Goals. Tables 2-4 show how the six strategies correspond with each near-term action. The strategies are clearly interdependent, with many actions corresponding with several strategies. There is some variation between energy services with actions on heating and cooling corresponding more with the efficiency and innovation strategies. Homes are wasteful passive systems, and both the construction and renovation industries are relatively slow to implement low-carbon innovations (Heffernan et al. 2015). This opens up scope for rapidly diffusing frontier efficiency standards and practices through new business models and service offerings with appeal to consumers. In contrast, actions on consumer goods correspond more with the usership and utilisation strategies as ways to dematerialise end-use consumption while increasing the amounts of welfare-enhancing energy services consumed.

Figure 1. Examples of Actions Discussed in the Paper. (Created with Maptive).

Policy. Many of the actions depend directly or indirectly on policy or supporting regulatory environments to ensure their viability, accelerate their impact, or improve their cost-effectiveness. This dependence is indicated by a high - medium - low assessment in Tables 2-4. High policy dependence is most evident for the actions with 'policymakers' or 'regulators' as the key implementation actor. Just as many of the actions depend to some extent on policy, so too do the six basic strategies. This is particularly the case for 'efficiency frontier' which relies on a sharp tightening up of the stringency and enforcement of energy-efficient performance standards for buildings, appliances and devices.

Of the three energy services, urban mobility and then heating and cooling are the most directly dependent on policy but for different reasons. Transport service providers depend on access to regulated public space and infrastructure, or effective integration with public transport networks. More efficient heating and cooling in buildings creates clear user benefits but requires standards, codes or other policy measures to incentivise service providers and finance incremental costs.

Many of the examples we used to illustrate selected actions also involve new policies or additions to existing policy packages. In some cases, actions were successful because policies boosted the impact of activity already underway (e.g., compliance subsidies to enhance national building codes in Chile, see H3 in Table 2). In other cases, actions were successful because of a shift in policy (e.g., from a voluntary subsidy-based renovation standard to a regulated close-to-Passivhaus renovation standard (e.g., BatEx in Brussels, see H1 in Table 2).

It is important to emphasise that the actions listed in Tables 2-4 are a complement to, not a substitute for, more conventional policies for climate change mitigation identified in IPCC assessments (Rogelj et al. 2018). These include: long-term emission-reduction targets; economy-wide carbon pricing; technology-specific market support and incentives; and pollution controls or emission standards.

Cost-effectiveness. The actions vary widely in the extent to which they require upfront capital investment, additional financing costs, or requirements for capital raising from new sources. This extent is indicated by a high - medium - low assessment in Tables 2-4 designed simply to show variability across the portfolio of actions. Actions with low upfront costs are potentially more accessible and less constrained by financial barriers, particularly if the key implementation actors are consumers (e.g., streaming media on mobile devices, see C2 in Table 3). Consumer-facing goods and services with high appeal or novel value propositions may also diffuse faster (Rogers 2003). Actions with high upfront costs may require innovative forms of finance (to access capital), public underwriting of private finance (to mitigate risk), or securitisation (to distribute risk). The climate change mitigation benefit from the actions legitimates the use of public funding to overcome cost barriers. However the cost-effectiveness of each action on a $/t CO_2 basis varies widely.

A full cost-effectiveness analysis lies outside the scope of this paper. However for a subset of actions for which we could find data (or make reasonable assumptions) on both implementation cost and CO_2 emission reductions delivered, we quantified order-of-magnitude $/t CO_2 estimates. The data, time horizon, methodology, and assumptions varied in each case, so the estimates should not be compared on a like-for-like basis.

For two actions on heating and cooling (H1, H7), we estimated strongly negative costs as low as -$1000/t CO_2 taking into account cost savings over the lifetime of the initial investments. However for one action (H3) we estimated strongly positive costs of up to +$4000/t CO_2 due to the high upfront investment required. For three actions on consumer goods (C1, C2, C9), we estimated negative costs from zero to three orders of magnitude (-$1/t CO_2 to -$1000/t CO_2, although some of these estimates omitted embedded technology development costs. For four other actions on consumer goods (C3, C5, C8, C10), we estimated positive costs also over a wide range from +$1/t CO_2 to +$1000/t CO_2. In more general terms, our cost-effectiveness estimates were more strongly negative if they included discounted future benefits (e.g., energy cost savings, foregone investment costs), allowed for economies of scale and learning, or applied to well-established practices in market settings. Conversely our cost-effectiveness estimates were more strongly positive if they included only upfront costs, related to early-stage demonstration or trials with high transaction costs, or required high levels of tacit knowledge or skills with limited capacity for repetitious learning. Further research is needed to evaluate the relative merit of our actions on cost-effectiveness grounds.

Conclusions

A global 'Low Energy Demand' scenario in which activity levels for end-use services rise while the energy intensity of energy-service provision dramatically falls shows that the ambition of the Paris Agreement and the UN Sustainable Development Goals can be met. Implementing this scenario requires a comprehensive and concerted programme of action involving a diverse set of actors at national, city and local scales including policymakers, service providers, technology companies, and end users. This paper provides examples of actions from both the global North and South. These actions correspond with six broad strategies: electrification of energy end-use; multi-functional end-use services or technologies; usership as an increasingly dominant norm of consumption; increased utilisation rates of energy and material-intensive infrastructure; market adoption of buildings, vehicles, and appliances at the efficiency frontier; and user-oriented innovation to deliver appealing energy services.

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Endnotes

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