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End-user centred infrastructure operation: towards integrated end-use service delivery

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ABSTRACT

Reliable provision of water, energy and transportation, all supplied through infrastructure, is necessary for the most basic human and economic development to occur. Such development however, is not enabled by specific end-use products (e.g. litres of water, kWh of electricity, litres of diesel and petrol), or by infrastructure itself (i.e. the systems of energy, transport, digital information, water, waste and flood protection assets), but rather through the infrastructure end-use services (e.g. hygiene, thermal comfort, communication, or accessibility).

The present form of infrastructure operation consists of supply systems provisioning unconstrained demand of end-use products, with larger consumption volumes corresponding to higher economic revenue. Providing infrastructure capacity to meet unmanaged growing demand is ultimately unsustainable, both in environmental and economic terms. Past research has focused on physical infrastructure assets on the one hand, and sustainable consumption and production on the other, often neglecting infrastructure end-use services. An important priority for sustainable infrastructure operation is therefore to analyse the infrastructure end-use service demands, and the variety of end-users' wants and behaviours.

This paper outlines the key aspects of an end-user and service-centred approach to infrastructure operation. It starts with an overview of relevant research areas and literature. It then describes the infrastructure end-use services provided by different infrastructure streams quantitatively, with the UK domestic sector as an illustration. Subsequently, insights into infrastructure integration at the end-user level are presented. Finally, the infrastructure end-use service perspective is described as a holistic framework for intervention: understanding technological changes in context, acting directly on end-use demand, and including social implications of service-based solutions.

1. Introduction

Our physical infrastructure – the systems of energy, transport, digital information, water, waste and flood protection assets – is a means to an end: it is built, maintained and expanded to enable the functioning of society. Reliable provision of water, energy and transportation, all supplied through infrastructure, is considered necessary for the most basic human and economic development to occur (UN, 2013; Wilkinson et al., 2007). The role of infrastructure as a key intermediary between socio-economic activities and consumption of environmental resources is less well understood, and the operation of existing infrastructure is a key link between consumption and resource use.

In the present form of infrastructure operation, reliable and affordable supply (of water, transportation capacity and energy) is prioritized at any level of societal demand – despite the fact that aggregate demand levels are constantly growing (DECC, 2014; DFT, 2011; EEA, 2001), and that affordability is in fact far from guaranteed (Healy and Clinch, 2004; Liddell and Morris, 2010). Shortages, price spikes or congestion are considered to be short-term crises mostly addressed with emergency measures and, although they could be seen as opportunities for change, they do not trigger long-term systemic change (Castán Broto et al., 2014). The existing infrastructure strains under the requirements for added capacity. Budget policies in the richest countries in the world neglect investment in basic infrastructure maintenance – let alone development of sustainable alternatives. Environmentally, it has long been clear that drastic reductions in levels of resource use are needed, but privatised utility companies, whose profit model

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depends on volume sales, do not prioritise these reductions. Such form of infrastructure operation is therefore inherently unsustainable, and by itself is enough to prohibit any sustainability transition (Unruh, 2002). A step change towards more resource-efficient infrastructure operation is therefore required to meet crucial societal targets, such as drastically reducing greenhouse gas emissions (CST, 2009; UNFCCC, 2008).

Considering infrastructure, human and economic development is neither enabled by the physical infrastructure (i.e. systems of energy, transport, digital information, water, waste and flood protection assets), nor by the utility products per se (i.e. the physical vector provided by utility companies, such as water, gas and electricity), but rather through the end-use services provided by infrastructure (i.e. thermal comfort, illumination, sustenance, hygiene, and mobility). Such service perspective places end-users, or "consumption couplers" as lined out by Pauliuk and Müller (2014), and infrastructure end-use services at the heart of analysing the role of infrastructure as a key intermediary between socio-economic activities and consumption of environmental resources.

This paper aims to provide broad intellectual access to the analysis of infrastructure end-use services from a systemic perspective, considering their final demand, active conversion technologies and their passive context (Cullen and Allwood, 2010a) and is structured as follows: Section 2 examines relevant research areas regarding infrastructure operation and infrastructure end-use services. Based on this review and using a bottom-up perspective, Section 3 continues by elaborating the physical and socio-economic aspects of end-user's interrelation with infrastructure operation from an end-use service perspective. This perspective requires alternative metrics, centred on service delivery, which we discuss in the UK domestic context in Section 4. Subsequently, the implications for infrastructure interdependencies are considered in Section 5, with the potential for performance-based service contracting. Section 6 discusses the infrastructure end-use service perspective as a holistic framework for intervention: understanding technological changes in context, acting directly on demand, and including social implications of service-based infrastructure solutions. Section 7 concludes key findings and highlights potential strands of future research.

2. Overview of relevant research area

The following section firstly provides a general overview of relevant research fields related to infrastructure operation as a key intermediate between resource consumption and socio-economic activities. Secondly, the inclusion of end-users as essential elements of infrastructure operation, performance-based service provision, and infrastructure interrelations is highlighted as a requirement for a sustainable infrastructure transition.

2.1. Research fields related to infrastructure operation

Industrial Ecology and Sustainability Science are the two fields generally considered when investigating the environmental impacts and resource consumption of socio-economic activities. While both fields have systemic ambitions, Industrial Ecology tends to study production-consumption chains, with emphasis on minimizing waste through recycling and efficiency (Jelinski et al., 1992). Sustainability Science on the other hand is more focused on conceptualizing, modelling and measuring society–nature interactions, with a goal of encouraging science and technology to look beyond individual components (Kates et al., 2001).

Environmental impacts of socio-economic processes are most often considered broadly through the analysis of production and consumption activities. Powerful analytic tools, such as Life Cycle Analysis (Finnveden et al., 2009; Rebitzer et al., 2004) and Environmentally-Extended Input-Output analysis (Duchin, 1992; Minx et al., 2009) link consumption and production together, enabling the comparison of products and economic sectors in terms of their environmental impacts. More recently, the research area of Sustainable Consumption and Production (SCP) has undertaken the challenge of studying the social and economic aspects of production and consumption (Spaargaren, 2003; Tukker et al., 2008), and the potential for environmentally innovative product delivery, such as Product Service Systems (Mont, 2002; Mont and Tukker, 2006).

Although recently Akenji (2014) highlighted the importance of infrastructure for mainstreaming sustainable consumption, in most of the studies the emphasis remains at the product and production chain level. The underlying physical infrastructure is included partially, as it pertains to production, mainly through electricity and transportation processes. However, these methods do not include infrastructure (and its interdependencies) in its own right, and are too aggregated and product-focused. Indeed, production and consumption occurs within a given infrastructure context, and most importantly changing infrastructure inevitably implies altering production processes and consumption patterns. These interdependencies can be conceptualized through the co-evolution of society and technology (Foxon, 2011), highlighting the causal, systemic interconnections linking social institutions and business models with the technologies and physical processes they rely upon, and vice-versa. According to co-evolutionary theory, it is not possible to simply alter the technological underpinnings of society, from dirty to green, or unsustainable to sustainable, without altering the fundamental social, economic and institutional relations, which regulate our daily lives.

Taking such a system perspective three further areas have clear links to infrastructure research. The first is Stocks and Flows Modelling (Baccini and Brunner, 2012; Hu et al., 2010; Muller, 2006), which quantifies the resource use of technological and demand level changes in infrastructure and the built environment. For example, Müller et al. (2013) highlighted the significance of emissions embodied in the infrastructure stock for achieving future climate change targets. In contrast, our goal is to understand the influence of infrastructure design and operation on resource use beyond that of the infrastructure itself. The second is Urban Metabolism (Kennedy et al., 2007, 2009; Newell and Cousins, 2014; Ramaswami et al., 2012; Weisz and Steinberger, 2010) and Low Carbon Cities (Chavez and Ramaswami, 2011; Grimm et al., 2008; Sullivan et al., 2012), which consider the specific challenges and opportunities related to reducing resource use and emissions in urban settings. Urban metabolism obviously considers infrastructure through the transport networks and built environment of cities, but since the urban system is studied as a whole, the key aspects of different infrastructure systems are often not given special attention. The third is the sociological approach to analysing consumption through the understanding of social "practices" (Ropke, 2009; Shove, 2003; Shove and Walker, 2010). This research area comes perhaps closest to our perspective on infrastructure by defining a broad category of "systems of provision" (Spaargaren, 2003) of crucial importance in the practices of ordinary consumption (McMeekin and Southerton, 2012): the daily consumption activities that are not particularly visible or do not entail complex decision-making on the part of the consumers, but that account for a large fraction of their resource use budget.

2.2. Sustainable infrastructure transition requirements

The above review highlights the importance of consumption, or final demand, as the ultimate driver of environmentally intensive industrial activity, as well as the key role of infrastructure in meeting human needs and economic development. Therefore end-users and infrastructure end-use services are at the heart of researching the role of infrastructure as a key intermediary between socio-economic activities and consumption of environmental resources. A transition towards more sustainable end-user centred infrastructure operation can be characterized by several innovative, and disruptive, requirements.

First and most importantly, the end-user, and their demand, must become the essential element of the operation of infrastructure. Demand can only be understood, managed, and brought down to sustainable levels through end-user integration. The end-user chooses and operates key conversion technologies, such as appliances and vehicles, which are the intermediaries between end-use service demand and infrastructure supply, as well as a common locus of infrastructure integration. Indeed, end-use technologies hold the greatest potential for climate mitigation (Grubler et al., 2012a; Wilson et al., 2012), but there are challenges in terms of sufficient research and development, widespread adoption as well as appropriate maintenance and usage.

Secondly, infrastructure end-use service demand must replace product demand as the focus of supply chains and networks. The concept of service, rather than product, is analogous to the idea of functional unit rather than product unit in Life Cycle Assessment. The idea is to focus on the ultimate benefit that the end-user seeks from the consumption of utility products. The concept of services replacing products is far from new and has been put forward under the titles of performance, functional or service economy (Mont, 2002; Mont and Tukker, 2006; Stahel, 2010), and developed in parallel from a business and marketing perspective (Gronroos, 2011; Vargo and Lusch, 2008). Product Service Systems, might lead to extended product life-time and higher supply efficiency (Mont, 2002; Mont and Tukker, 2006), but usually do not include contractual agreements on achieved resource savings. Sustainable and resource-efficient infrastructure operation therefore requires a shift from a traditional throughput-based economy, where transactions are based on units of products delivered, to a performance-based economy, where profits are based on savings compared to business-as-usual (Steinberger et al., 2009). Performance-based service contracts go beyond the point of product delivery, and incorporate efficient end-use technologies as well as service demand levels. These contacts are the basis of the business model of Energy Service Companies (ESCos), providing guaranteed energy services at lower level of energy consumption (Bertoldi et al., 2006; Sorrell, 2007; Vine, 2005). While ESCos are mainly active in business-to-business transactions, high transaction costs for small clients and high asset specificity for large customers have been identified as obstacles for adopting more business-to-consumer transactions. Standardized contracts, monitoring and accreditation schemes might help to overcome these barriers (Hannon, 2012; Sorrell, 2007).

Thirdly, sustainable infrastructure operation should not be limited to single systems (such as electricity or transportation), but aim to encompass multiple systems by understanding their interconnections and exploring possibilities of substitution between them. Indeed, many infrastructure end-use services rely on more than one infrastructure system or utility product (e.g. hygiene services require water and heat). One infrastructure system might also enable micro-generation of other utility products (e.g. energy enables pumping and cleaning of grey water) and substitute to a certain extent other infrastructure systems. Exploring infrastructure interconnections and the potential for substitution between infrastructure streams is conceptually enabled by the focus on the end-use service they deliver.

3. End-user centred infrastructure operation

3.1. The need for end-user integration

Although it is broadly acknowledged that societies' requirements for water, energy, communication, transportation and waste removal are determined by the end-users' level of demand (Roelich et al., 2015), the end-users themselves are rarely included in infrastructure operation, apart from very targeted demand management measures aimed at reducing peak demand (Carley, 2012; Russell and Fielding, 2010). The total resource consumption of an infrastructure service is defined by demand levels, the efficiency of the conversion technologies, their operation and maintenance, and the efficiency of supply and distribution networks. Thus, for resource-efficient infrastructure operation, integrating the end-users is of particular importance, as end-users' behaviour determines quantity and quality of the infrastructure end-use services as well as the adoption of end-use technologies, their lifetime and mode of operation. Based on existing work, we elaborate in the following two sections on the physical and socio-economic aspect of end-user centred infrastructure operation, which is graphically represented in Fig. 1.

3.2. The physical level: active and passive technologies and their operation

We depict the physical layer of infrastructure end-use service provision in the lower half of Fig. 1, showing the supply chain from supply or generation processes via distribution networks, active conversion devices and passive systems (Cullen and Allwood, 2010a) and their operation, to the level of end-user demand for infrastructure end-use services. Although displayed as one infrastructure stream in Fig. 1 we emphasis the infrastructure interrelations at various levels, which are further discussed in section 5.

Cullen et al. (2011) highlighted the importance of the passive systems in maximising system-wide efficiency, by demonstrating their large untapped energy saving potentials (e.g. 98% for space heating/cooling, 91% for passenger car and 54% for freight truck transport). According to the authors, these savings are possible from existing best practice designs such as lightweight cars and Passivhaus building standards, and are additional to the relatively high savings from the active conversion devices itself (e.g. 67% for appliances in the building sector).

Such improvements can only be achieved when these technologies are operated and maintained appropriately. Design-performance gaps in low-energy buildings are a well-known example of unrealised efficiency savings due to inappropriate usage or inappropriate design for the intended use (Andrews et al., 2011; Boardman, 2007). Besides the appropriate operation of the conversion devices and passive systems, the type of operation mode is important. For private vehicle mobility, cars can be operated in ownership or car-sharing mode (i.e. as a product-service system). Mont (2004) shows that a switch from ownership to leasing, renting, or sharing agreements leads to more efficient cars, a variety of different car models available, as well as environmental sound solutions with reduced car numbers and shorter travel distances. Furthermore, end-use services are always provided by a mix of active conversion devices and passive systems (Cullen et al., 2011). In some cases this combination can lead to a trade-off off potential efficiency gains between the two (e.g. solar water heater with storage vs. instantaneous water heater).

In addition to the end-use conversion of utility products, upstream efficiencies in the generation and distribution networks (including options for decentralised provision) are key for an

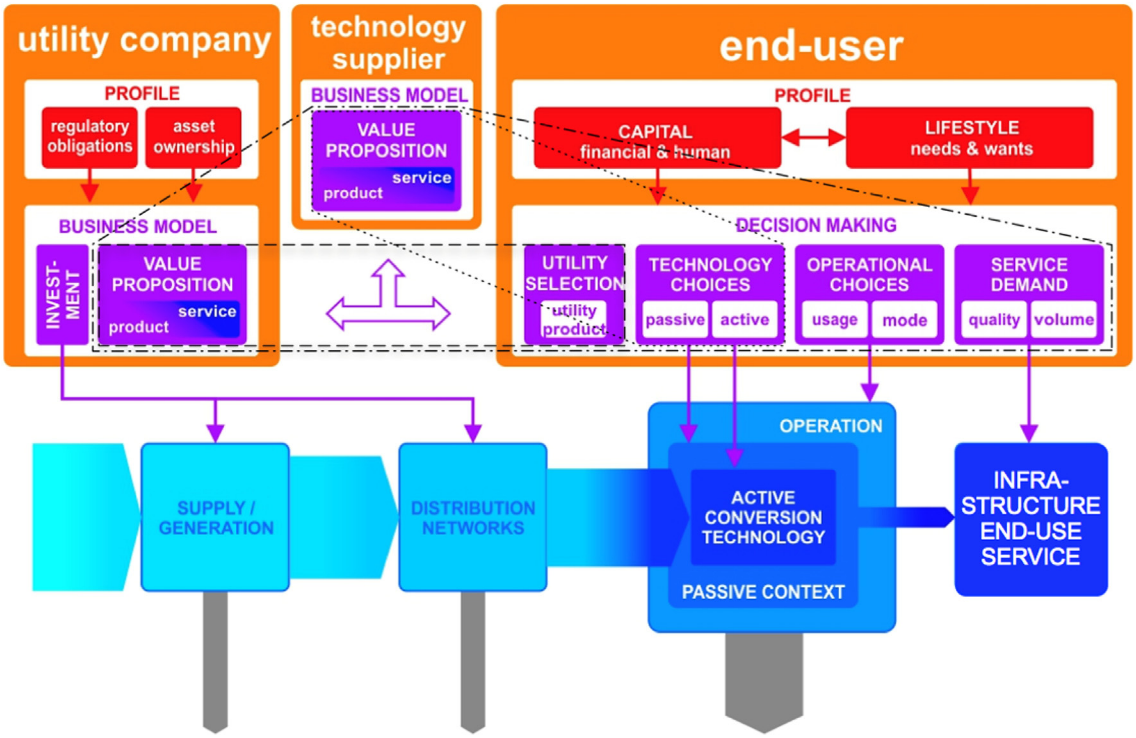

Fig. 1. End-user centred infrastructure operation: the lower half depicts the physical layer of infrastructure end-use service delivery, blue boxes indicate processes, blue arrows product or energy flows, and grey arrows corresponding losses; the upper half depicts the socio-economic layer, with orange boxes representing socio-economic actors, red boxes their profiles, and magenta boxes decisions directly affecting the physical level or other actors. Contractual boundaries are delineated for the traditional utility (dashed line) and technology provision (dotted line), and for a performance-based service contract situation (dash dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overall resource efficient provision of infrastructure end-use service (Cullen and Allwood, 2010b). For energy systems, Cullen and Allwood (2010b) show that losses in fuel transformation and energy generation and distribution account for 40% of all conversion losses. Similarly for water, where losses during capture, treatment, and distribution are estimated at around 30% (Coelho and Andrade-Campos, 2014). With the focus of this article on the end-user integration details on upstream conversion is not depicted in Fig. 1.

All the efficiency improvements along the supply chain, however, depend on the quality and quantity of end-use service demand. Although often considered independently from technical solutions, end-use service demand is interrelated with the active conversion devices, passive systems, and their operation. On their own, technical efficiency improvements have a high potential of direct rebound effects, where efficiency gains are offset by increases in usage (Greening et al., 2000; Hertwich, 2005; Sorrell et al., 2009).

3.3. *The socio-economic level: end-users, utilities and technology suppliers*

The upper half of Fig. 1 depicts the socio-economic layer of end-user centred infrastructure operation enabling and constraining changes throughout the physical supply chain. Besides the end-users, utility companies and technology suppliers are the key actor groups, interacting with each other to determine different parts of the supply chain. Since our analysis focuses on the end-user, the "utility company" is a simplified representation of the full supply chain actors, including generators, network operators and suppliers. Each actor has an impact on the physical throughput through its business model, decision-making, or behaviour, which themselves depend on the actors' profiles (e.g. socio-economic situation, regulatory obligations, or needs and wants).

End-users are referred to as the consumers of the infrastructure end-use services, which are used to satisfy their needs and wants in accordance with their profile (i.e. lifestyle and human and financial capital). In the current setting, their decision-making consists of four key aspects: they select the utility company to deliver the utility product, choose certain technologies (both active conversion devices and passive systems) to convert the product into a service, define how these technologies are used and in what operation mode, and finally determine the quality and volume of the end-use service itself. These decisions are not independent from each other, as they restrict the available options in other arenas; for example a specific conversion technology will require specific utility products and hence utility companies, and constrains potential operation modes. The service demand is particularly interlinked with the other decisions. On the one hand, it is the main driver for subsequent decisions, setting to a large extent the manoeuvre space for these decisions. On the other hand, end-use service demand might change as new technologies are installed. Such change has been observed as a rebound effect offsetting efficiency gains, but can also take the form of a spillover effect where already resource efficient solutions raise awareness and lead to a decrease in service demand (Hertwich, 2005). For example photovoltaic installations have been found to reduce electricity consumption in the households (Hondo and Baba, 2010; Keirstead, 2007). Furthermore end-users' decisions depend on the value propositions from utility companies and technology suppliers.

Technology suppliers are companies supplying active conversion devices and/or the technologies for the passive system. The value proposition might range from a traditional appliance sale, to rental or leasing agreements to performance-based service contracts. In the traditional setting they interact directly with the end-users. In a performance-based service contract setting they could either supply to the utilities, which then sell to the end-user (e.g. British Gas selling boilers with maintenance contracts), or offer a performance-based service contract to the end-user encompassing the utility product purchased from the utilities.

Utility companies provide utility products to the end-users through generation and distribution networks. Depending on their regulatory obligations, asset ownership and investment strategies, they may have more or less control over the physical supply infrastructure, but still mainly determine the resource efficiency up to the point of utility product sale. Their current value proposition is dominated by utility product offers (e.g. gas, electricity, and water) leading to contractual agreements with little to no influence on utility product demand levels. Extending the value proposition towards a performance-based service contract would by necessity not only include the crucial end-user conversion technologies but also set the benchmark for appropriate operation, efficient operation modes, and potentially sufficient quality and quantity of end-use service demand.

4. Alternative infrastructure end-use service metrics

Extending infrastructure operation towards end-user centred operation as outlined in the previous section, requires a more detailed analysis of infrastructure end-use services and their measurement as a key driver. In the following section we elaborate on shortcomings of current utility delivery metrics, discuss infrastructure end-use services, and propose alternative metrics for their measurement.

4.1. Shortcomings of current utility delivery metrics

The way utility product delivery to the end-user is currently assessed and measured has three basic shortcomings: (i) billing metered quantities instead of services prevents efficiency solutions; (ii) flat rate charges disincentivise efficiency and sufficiency behaviour; and (iii) highly standardized “one size fits all” solutions lead to technological lock-in ignoring the variety of service required by the end-users.

We address these in turn. Firstly, currently delivery is measured and billed as utility products or metered quantities (e.g. kWh of electricity, gas or litres of water) delivered, rather than the end-use services the end-users actually need or want. The product focus limits the revenue generation of utility companies to the volume of utility products purchased, and disincentivises more resource-efficient solutions, such as energy or water conservation measures at the end-user level. Two examples illustrate this. In the UK, although regulators place duties on water utility companies to promote water efficiency and to conserve water, where it is cost effective to do so, most of them prefer leakage prevention over demand management measures (OFWAT, 2011). In Australia, extensive water conservation measures were successfully implemented during the drought, but utilities encouraged end-users to increase their consumption again as soon as the supply was secure, in order to generate the revenue to cover their drought-incurred capital costs (Beal and Stewart, 2011).

Secondly, several utility products for domestic end-users in the UK are charged with almost no relation to their actual consumption. For example, in most communities, end-users pay for waste removal through the council tax on a per-capita rather than a per-service base (DEFRA, 2011a), and the same is true for the 65% of unmetered homes in the UK paying for water at a fixed rate (along with homes which are metered, but where the utility company does not conduct readings) (DEFRA, 2009). These flat rate charges disincentivises any sort of sufficiency behaviour (i.e. consume up to sufficient levels and not beyond) or the implementation of efficiency measures, despite the wealth of evidence showing the effectiveness such costs-by-cause principle (Chambouleyron, 2004; Miranda and Aldy, 1998).

Thirdly, most current utility products are delivered at quality standards which have been established historically, and are maintained regardless whether they are still required to meet the needs of the end-users (Roelich et al., 2015). These high standards prevent resource-efficient solutions where bespoke or multiple qualities match the characteristics of conversion technologies more closely. Examples are potable water for all household uses, where in fact we could use grey- or rainwater for 50% of all uses (Butler et al., 2011), and inefficient AC/DC converters for most household appliances (Calwell and Reeder, 2002). Established quality standards leave little room for alternative resource-efficient solutions and lead to a technological lock-in (Unruh, 2000).

4.2. Infrastructure end-use services for satisfying needs and wants

Rather than gas, electricity or water, end-users demand infrastructure end-use services to satisfy their specific needs and wants. Such needs and wants vary widely, and may be difficult to determine in physical terms. Illumination, for example, has a wide range of associations from mood (Jean-Louis et al., 2005) to mental health (Espiritu et al., 1994), roads and community safety (Monsere and Fischer, 2008; Painter, 1996), and productivity (Hedge et al., 1995). Needs and wants, as measures of quality of life, are notoriously difficult to operationalize, as examples from health care and social services show using a range of 125 indicators (Schalock, 2004). While such depth of analysis might be required in the context of disabilities and aging, it is not practicable in an infrastructure context, where changes in the quality of infrastructure end-use services have to be measured and billed. The challenge therefore is to define sensible metrics of these services, which are physically measurable, but still describe end-users needs and wants better than volumes of utility products do.

4.3. Measuring infrastructure end-use services

Based on available data, we present some initial infrastructure end-use service metrics as an intermediate step towards measuring end-users needs and wants for performance-based service contracts. Referring to past work on energy services (Cullen and Allwood, 2010a; Fouquet, 2011; Haas et al., 2008; Marshall et al., 2013) and intensity of energy intensity of economic activity (Farla and Blok, 2000; Schipper et al., 2001), we specify thermal comfort, illumination, hygiene or cleanliness, sustenance, communication, and mobility as the infrastructure service classes in a domestic setting. These classes are subdivided, based on data available and technologies installed, in physically measurable functional units and exemplified with quantitative service measures for average UK households (Table 1). By focussing on UK household data, we can quantify the magnitude of different services, and discuss the implications of monitoring these for potential performance-based service contracts. Details and data sources are provided in the Supporting Information. Since data availability is biased toward current infrastructure delivery metrics, we highlight the intermediary nature of the metrics presented and discuss the individual service classed in more detail below.

Measuring *thermal comfort* as usable floor area at a certain average temperature takes the metrics away from throughput of energy carriers closer to end-users needs and wants, incentivising the implementation of efficient end-use technologies (e.g.

Table 1
Services classes, service metrics, average weekly demand measures for UK households (2.35 occupants).

Services class	Service metrics	Weekly average UK household service measures
Thermal comfort	Usable floor area (UFA) at average temperature	11% < 50 m^2, 52% 50–90 m^2, 37% > 90 m^2 UFA at 17 °C
Illumination	Lumen perceived by the user (in the lit environment calculated as 1/3 of the emitted source-lumen)	0.05 Mlm/m^2 UFA or 4.6 Mlm total provided by 34 lights
Hygiene/cleanliness	Textile cleaning (laundry): number of weekly cycles	5.5 washing cycles (1–23) at 4.8 kg average load with 6 kg capacity, 5 drying cycles
	Personal hygiene: number of showers, baths, sink, & tap uses	10.3 showers 7 min with 9 l/min (3–15 l/min), 6.6 baths with 80 l/bath (60–160 l/bath), 135 tap uses
	Human waste disposal: number of toilet flushes	21.1 full (25%), 63.5 reduced toilet flushes
Sustenance	Food conservation: kg of food cooled and frozen	16.1 kg (60%) food cooled to 5C (200 l refrigerator), 5.4 kg (20%) food frozen to −18C (200 l freezer)
	Cooking: number of meals, times of hob, oven, microwave, kettle, tap uses	12 meals: 8.1 hub, 3 oven, 1.8 microwave, 30 kettle uses, 1 h range hood: 135 tap uses (227 l water)
	Food cleaning: number of dish washing cycles, sink use volume	Dishwasher: 4.9 times a 12 place settings equivalent (58 l) sink: 144 l (50% hot water 50C)
	Gardening: tap uses & water volume	6.3 external tap use total 177 l water for irrigation and cleaning
Communication	Entertainment: hours of use	32.7 h primary TV, 19.2 h secondary TV, 5.2 h video player, 16.1 h compact audio system, 7.8 h video game
	Home computing: hours of use	38.5 h laptop, 25 h desktop + monitor
	Internet: hours of use	7.7 h internet use, 74% with broadband connection
	Telephone: hours of use	3.3 h landline, 3.6 h mobile phone use
Mobility	Work, business & education trips	12.8 trips at 12.7 km average distance (163 km)
	Shopping, escort & personal trips	17.3 trips at 7.7 km average distance (133 km)
	Leisure trips	13.2 trips at 14.6 km average distance (193 km)

insulation or condensing boilers) by providers. However, the need for a certain temperature has significant diurnal and annual variability (Mihalakakou et al., 2002) and might differ between the individual rooms, depending on occupancy rate and type. Including such variability in the metrics might require more automation (Ferreira et al., 2010) or smart meter technologies (Rashidi and Cook, 2009). In addition, end-users adapt to new standards of thermal comfort and a more "comfortable" service provision might even accelerate energy consumption (Shove, 2003). If incorporated in a service contract, the actual infrastructure end-use service becomes visible and behavioural changes (e.g. choice of clothing, ventilation) might also lead to an absolute reduction of energy consumption (Steinberger et al., 2009).

Illumination measured as perceived lumen by the end-user takes the metrics one step further towards end-users' actual needs and wants. On average about one third of the source lumen emitted reach the lit environment and are perceived by the end-user (IEA, 2006). Placing lumen meters in every lit environment around the house might be less practicable than measuring room temperature. Performance-based service contracts including illumination might therefore rely on theoretical measures based on emitted source lumen of the technology installed. In addition, the general preference of end-users for day light (IEA, 2006) as well as the remarkable variation in recommended illumination levels for different tasks (Mills and Borg, 1999) should be considered.

Communication is the third service class mainly related to in-house energy consumption, operationalized here as hours of entertainment system, home computer, internet and phone use. Measuring "on-time" of devices used for this service might be relatively simple, while actual needs and wants they are used to satisfy are far more complicated to define, as boundaries between services vanish (e.g. internet phone services and mobile internet) or more devices fulfil multiply purposes (e.g. smart phones, TV's, laptops, and tablets). Furthermore, some of these devices such as phones have permanent standby functions which establish a service on its own in addition to actual hours of use. Performance-based service contracts in this class might therefore concentrate on primary TV's with increasing screen sizes and significant power consumption.

Hygiene is subdivided here into textile cleaning, personal hygiene and human waste disposal. Measuring textile cleaning as numbers of weekly washing and drying cycles, personal hygiene as number of showers, baths and tap uses, and human waste disposal service as number of toilet flushes, still measures throughput but provides more detail on the quality of service demand than measuring utility products. Integrating hygiene services in contractual agreements would require measuring and monitoring behaviour in a sphere of life, which people traditionally consider as one of the most private (Waterwise, 2009). A further difficulty is the broad variability in quantity and quality these services are demanded and how they change over time. Textile cleaning and personal hygiene, for example, both exhibit a roughly five-fold escalation over the last century as a result of a co-evolution of suites of technologies and practices (Shove, 2003).

Sustenance is referred to as food preparation, cooking, food cleaning, and, for the purpose of this article, water usage for gardening. Similar to hygiene services, the suggested metrics still measure throughput (e.g. kg of food cooled or frozen for food conservation or number of dishwashing cycling) but provide much more information about how we convert the infrastructure products (i.e. mainly energy and water) with numerous kitchen appliances. The variation in peoples' diets is far higher than expected from a simple metabolic perspective, which is further exaggerated for infrastructure end-use services required in house for sustenance by different lifestyles, occupancy rates, and economic and human capital. The 12 full meals cooked on average and 16 kg of food cooled every week in UK households therefore gives only a first approximation and further research into how sustenance services relates to occupancy and lifestyles is required.

Mobility as the movement of people or goods can be seen as the intermediary of transportation measured as traffic (i.e. vehicle movement) and as accessibility referring to the ability of people to reach goods, services, activities and destinations (Litman, 2003). Mobility can be described as number of trips for work, business, education, shopping, personal, and leisure activities purposes. The average distances travelled for these activities are shortest for shopping activities, but are compensated with their higher frequency, bringing the average weekly distance travelled for shopping up to 133 km compared to the 163 km for commuting, and 193 km for leisure activities (DFT, 2011). It has been argued that access to activities and places, not mobility, is the infrastructure end-use service people want (Bertolini et al., 2005; Ferreira and Batey, 2007; Handy, 2002). Measuring accessibility, however, is an intricate problem starting with place or individual accessibility to more elaborate concepts taking into account urban environments as well as person-specific space-time autonomy of individuals (Kwan, 1998). Measuring infrastructure end-use service as accessibility instead of mobility might open a new range of options in infrastructure operation (Ferreira et al., 2012; Geurs and van Wee, 2004), but the question is whether accessibility is a sufficient measure? Motives for car use for example might be more symbolic and affective than instrumental (Sheller, 2004; Steg, 2005), or driving itself might become the valued activity (De Vos et al., 2013; Sager, 2008). A comprehensive metric therefore might need to distinguish between accessibility and mobility for its own purpose.

The discussion on the individual metrics demonstrates that, although some data on infrastructure end-use service demand is available, it may be a long way from this to standardized performance-based service contracts on a household level. There are several reasons for this: firstly, as soon as we move away from delivering a simple quantity of a utility product to a performance-based service delivery, the metrics become immediately multi-dimensional. For example the electricity bill would go from kWh of electricity to frequency, duration, and intensity of use of a plethora of appliances. Secondly, measuring such use would require a significant involvement of information and communication technology (ICT) such as smart meters. Such equipment would not only monitor the delivered service but as well related end-user behaviour, and has the potential to reduce resource demand through intelligent feedback (Darby, 2010; Hargreaves et al., 2010). Nevertheless, such feedback has to be presented appropriate and context dependent and needs to strike the balance between automation and freedom of consumption related decisions (Roelich et al., 2015). Thirdly, taking an end-use service perspective it becomes evident that such service rarely can be provided by one infrastructure stream or utility product.

5. Infrastructure integration at the end-user level

5.1. Infrastructures interrelations

Interconnections in infrastructures occur among different technical infrastructure systems (CST, 2009; Rinaldi et al., 2001) and between technical and socio-economic systems (Foxon, 2011; Hall et al., 2012). Such interrelations potentially increase infrastructure's vulnerability to failure (Zimmerman and Restrepo, 2006), but might also present opportunities for more efficient solutions (Frontier Economics, 2012). Therefore, infrastructure must be seen as a complex, interconnected system of technologies embedded in society and the environment, interacting with public and private institutions (Roelich et al., 2015).

In the construction phase, infrastructure relies heavily on transportation and consequently on energy infrastructure for the movement of the massive amount of bulk materials needed (e.g. Sahely et al., 2003; Weisz and Steinberger, 2010), but, infrastructure interconnections are even more accentuated in the operational phase, where most infrastructure systems require contribution from energy and communication. The “Water-Energy-Nexus”, describing how the two resources are inextricably intertwined (Schnoor, 2011), is probably the most famous example of such operational interrelations. Such interactions happen at multiple levels (Geels, 2011, 2012) implying that physical infrastructure does not only have a supporting role, but stands in complex interrelation with socio-economic-ecological systems. Governance of interconnected infrastructure systems is therefore an often underestimated but particularly difficult task (Roelich et al., 2013). End-use service demand stands at the origin of these interconnections, since some end-use services (e.g. textile cleaning, personal hygiene, and food preparation and cleaning) require more than one utility product (e.g. water and energy). Therefore, end-use service demand is itself the locus of crucial infrastructure streams interconnections and is a particularly important but often overlooked aspect when considering infrastructure interconnections.

5.2. Infrastructure interrelation at the end-user level

Considering the utility products required to deliver infrastructure end-use services reveals insights regarding bulk consumption and end-user level infrastructure integration. For the domestic infrastructure end-use services, satisfying UK's households' needs and wants, we draw a narrow system boundary around the UK homes and therefore consider only final energy and water consumption (Grubler et al., 2012b) (Fig. 2).

Annually, all UK households consume roughly 1833 TJ, or 29%, of the total final energy consumption in the UK (DECC, 2014), and 3.45×10^6 m^3 of water, or 154 L per person per day (DEFRA, 2011b). UK households' water consumption is clearly dominated by hygiene services, with 33% used for personal hygiene and 30% for toilet flushing, while sustenance requires another 27% with about equal shares for food preparation, cleaning and gardening, while textile cleaning is only responsible for 13%. Moving on to energy, space heating for thermal comfort (66%) and hot water for personal hygiene (17%) dominate the energy consumption within UK households. Kitchen appliances for food preparation, cleaning, and conservation account for 8%, and washing machine and dryer for 2% of the energy consumption. The generally low comparative energy consumption of electric appliances demonstrates the importance of the room and hot water heating systems, mainly provisioned through gas.

5.3. Potential of combined infrastructure end-use service delivery

Fig. 2 shows the physical combinations where the two utilities are needed to deliver a given service. These are typically services that require heated water, such as personal hygiene, textile cleaning, and food preparation and cleaning. Textile and food cleaning combinations are related to the conversion appliances, where usually both utility products are delivered straight to an appliance with integrated water heaters. In contrast, personal hygiene and food preparation use mostly centrally heated water distributed to point of use, requiring two active conversion units (e.g. boiler and tap/shower heads) and pipes throughout the house (i.e. passive system). Appliance leasing contracts (e.g. boilers or washing machines) are some of the first product-service-systems in this field, although they do not go as far as to include performance-based contracting on energy/water consumption. Nevertheless, since boiler service contracting is already offered by some utility companies (e.g. British Gas), this provides an ideal opportunity for moving onwards to performance-based service contracts and, eventually, multi-utility service provision. Such solutions, however, are currently hampered by economic regulation of utility contract length, which limits the ability of suppliers to engage in long-term contracts with end-users (Sorrell, 2007) as well as constraints on cross-utility operation caused by regulation in silos (Roelich et al., 2013).

Another locus of end-user infrastructure is between communications and energy, and in particular electricity. A direct provision of the communication service (e.g. hours of screen use at a certain quality) would incentivise more energy efficient appliances, and might be facilitated through service provision business models and

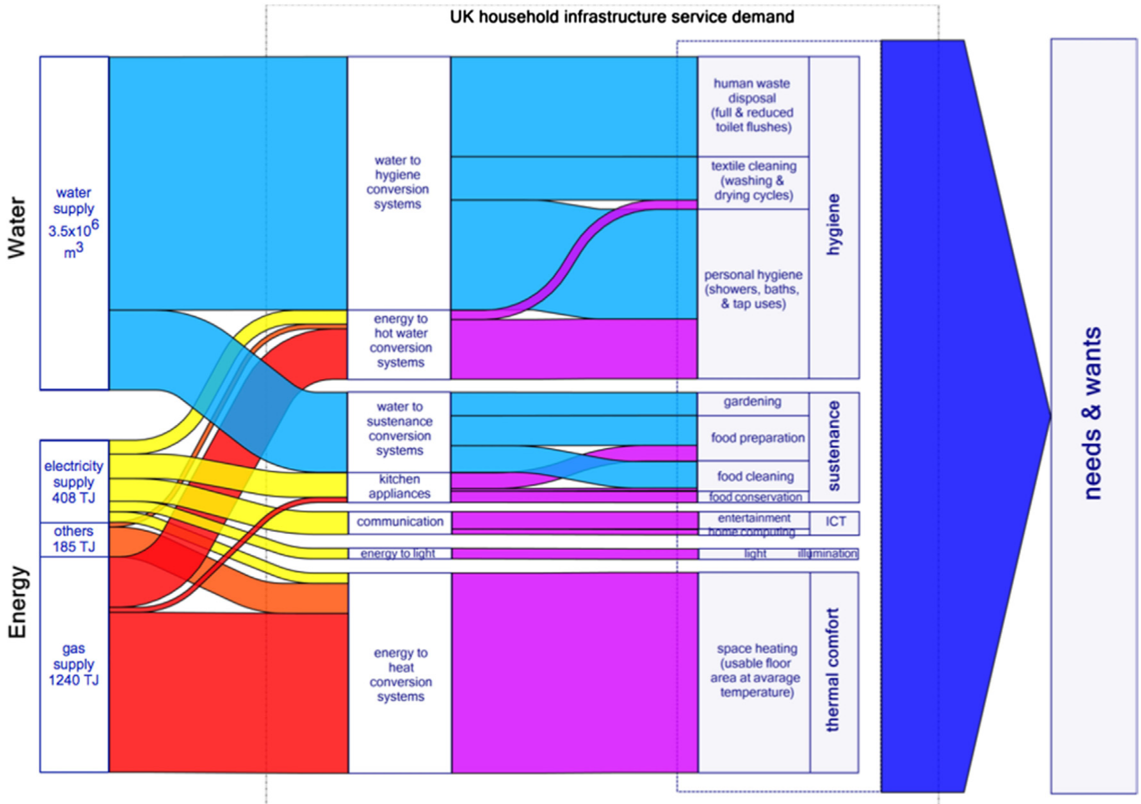

Fig. 2. Infrastructure integration at the end-user level, water and energy consumption of different domestic end-use services in the UK, total energy and water consumption are set to the same thickness of lines for comparability, calculated consumption of all 26,258 thousand UK households with an average occupancy of 2.35 persons per household, lines indicate the amount of water and energy consumed (light blue – water, magenta – energy, red – gas, orange – solid fuel and other energy carriers, and yellow – electricity) (data source: DECC, 2014; DEFRA, 2008; Waterwise, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bundling of different services (e.g. broadband, phone, TV) already prevalent in the communication sector. Probably an even more important role communication might play as an enabling technology for performance-based service contracts and infrastructure combinations between other sectors. Measuring and monitoring infrastructure end-use services requires more information and communication technology involvement than just measuring input flows (Roelich et al., 2015). In addition, enabling end-users to make informed decisions about their service demand requires more elaborate feedback than simple energy or water consumption (Neenan et al., 2009).

The third area of infrastructure interconnections is between transportation and energy. Car use is the dominant passenger transport mode in the UK (78% of distance and 64% of trips), whereas public transport systems are used for 19% of the distance and only 3% of the distance is walked or cycled (DFT, 2011). In addition personal car-use is inherently inefficient with an average petrol consumption of 6.4 L/per 100 km and a car occupancy of 1.6 people per vehicle in the UK (DFT, 2011). Consequently, passenger transport is inherently energy consuming, and accounts for two thirds of the UK road and rail energy consumption (DECC, 2014). Public transport services have long demonstrated how more efficient infrastructure end-use services, in this case mobility, can be provided. However, their high levels of energy efficiency comes from transporting people in groups, while the current trends of low public transport use and low car occupancy indicate a preference for a more flexible (i.e. individual) forms of mobility (DFT, 2011). A potential service provision taking such individualism into account is car-sharing (Mont and Tukker, 2006; Prettenthaler and Steininger, 1999). Similar to a home appliance lease, the vehicle is not owned by the end-user, but they still pay for the utility product, in this case vehicle-kilometres. The dependence on the utility product could change with the roll out of battery driven vehicles, closer incorporated into smart grids through the dual use of batteries as storage and scheduled charges to balance the grid (Deilami et al., 2011; Peterson et al., 2010). This incorporation opens a door for grid operators and utilities for new business models offering infrastructure end-use services and optimizing the systemic efficiency.

6. Discussion

In the previous sections we discussed three requirements for a sustainable infrastructure transition, the need for considering end-users as essential elements of infrastructure operation, moving towards performance-based service provision, and infrastructure interrelations at the end-user level, as introduced in Section 2. End-user centred service based infrastructure operation has additional implications, as it might facilitate understanding technology change in context, sufficient infrastructure end-use demands, and social implications such as rebound or spill over effects, which we address in turn.

6.1. Understanding technology changes in context

Although understanding the co-evolution of social and technical systems is generally seen important for sustainable technology transitions (Akenji, 2014; Foxon, 2011; Geels, 2005; Janssen and Jager, 2002; Rycroft and Kash, 2002), current infrastructure operation still lacks this perspective and is instead focused on provision of unmanaged growing demand (Roelich et al., 2015). We therefore analysed the physical and socio-economic aspects of an end-user centred infrastructure operation and their interrelations, providing the conceptual understanding end-users' technology change. In a functional or performance economy, service-based contracts address all three contextual aspects of end-users' technology change (Mont and Tukker, 2006; Stahel, 2010). The shift away from selling products to selling infrastructure end-use services and guaranteed resource savings requires the inclusion of active and passive technologies, their appropriate operation and operation mode. Such contracts are per se more complex than simple product purchase arrangements, and consequently high transaction costs and monitoring issues have been outlined as barriers to their adoption (Sorrell, 2007; Steinberger et al., 2009). The presented metrics for domestic infrastructure end-use services provide a first step to overcome these barriers with standardized contracts, as suggested by Hannon (2012). Such transition towards performance-based service provision does include changes in stakeholders' attitudes (i.e. values and knowledge), facilitator (i.e. incentives and constraints) and infrastructure (i.e. systems of provision) as suggested by Akenji (2014) for mainstreaming sustainable consumption. It thus might be able to sufficiently change consumers' circumstances to unlock more of their sustainable consumption potential (Sanne, 2002).

6.2. Sufficient service demand

Changing end-use technologies and their operation alone is insufficient, as long as the demand for infrastructure end-use services keeps increasing. While traditional demand management studies focus on shifting peak infrastructure product demand (Carley, 2012; Russell and Fielding, 2010), this study analyses what needs and wants end-user satisfy with these products. This focus raises the issue of how much of such infrastructure end-use services might be required or sufficient for well-being, which links to new concepts such as sufficient consumption, human needs, degrowth, shared and circular economy (Kerschner, 2010; Martínez-Alier et al., 2010). The core focus of circular economy research is minimal and closed-loop use of materials on the company, industrial park and city level (Andersen, 2007; Yuan et al., 2006). Infrastructure end-use services extend this view to the end-users allowing for a further resource reduction at the same level of service. Similarly to a service perspective, degrowth requires a re-evaluation of human progress or well-being metrics, away from more products to enough services (Dietz and O'Neill, 2013).

6.3. Social implications of end-user centred, service based infrastructure solutions

As outlined in Section 3.3 current infrastructure operation leaves the end-user with a variety of fragmented but interrelated decisions to make. To optimise resource-efficient service provision these decisions have to be addressed adequately and jointly; however the human and financial capital to do so varies vastly among different domestic end-users. Fuel-poor households for example usually do not have the financial capital required for efficiency measures (Jenkins, 2010). Performance-based service contracts cover both passive and active systems, and are billed based on guaranteed saving: they therefore have the potential to go beyond publicly funded insulation schemes, and reduce fuel poverty by incentivising most efficient solutions instead of simply doing without heat. Rebound effects of such efficiency improvements, in the sense of increased end-use service demand (e.g. thermal comfort), are known to be larger in fuel poor households than where the infrastructure end-use service is already at a desired level (Chitnis et al., 2013; Druckman et al., 2011; Milne and Boardman, 2000). From a social rather than environmental perspective, "spill over effects" such as reduced winter deaths and general increased physical and mental health will be overall beneficial (Steinberger et al., 2009). There remains a need for programs, which jointly tackle carbon-savings and fuel poverty demonstrating effectiveness in both areas.

7. Conclusion

We described infrastructure as a means to an end to support the functioning of society. This function is challenged by the current form of infrastructure operation, which is inherently unsustainable, as it prioritizes affordable but reliable supply at any level of societal demand. Since infrastructure plays a key role in meeting human needs and enabling economic development, analysing infrastructure as a crucial intermediary between socio-economic activities and consumption of environmental resources becomes a core research goal. Therefore, end-users and infrastructure operation are at the heart of environmental sustainability challenges. Sustainable infrastructure operation therefore requires that the end-user, their demand for infrastructure end-use services and not utility products, and interrelation among infrastructure streams must become part and parcel of infrastructure operation. Taking a service-performance perspective this research presents an overview of end-user centred infrastructure operation, suggests alternative metrics for infrastructure end-use services and infrastructure interrelations at the end-user level.

End-users determine the level and quality of infrastructure end-use service demand, as well as (at least in part) which active conversion devices and passive corresponding systems are used and how they are operated. These decisions are interrelated, depend on lifestyle choices, ownership patterns and financial means, among other factors, and are made in interaction with technology suppliers and utility companies. Whereas traditional utility supply is based on sheer volume of products (e.g. water, electricity, etc) delivered, performance-based service contracts have the potential to include the crucial end-use technologies and their operation. Such contracts will be more complex than billing based on metered quantities; however they could simplify the fragmented and poorly informed decision-making of end-users, and incentivise efficient solutions rather than throughput. The infrastructure end-use service metrics we propose provide a first step towards simplified and standardised contracts in a domestic context, and prompt a discussion of how much of such services might be sufficient. The service-performance perspective of infrastructure delivery revealed infrastructure interrelations and potential combinations at the end-user level. The various challenges to a broader uptake of performance-based service schemes, from a regulatory, business and end-user perspective, highlight the need for further research in this area. Nevertheless, making profits based on resource savings as suggested be performance-based service schemes is inherently more sustainable than traditional throughput-based economies, marking a step in the right direction.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.08.079.

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