Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade

Abstract

The concept of energy services is used in different contexts and scientific fields mainly to emphasize that it is the services provided by energy rather than energy carriers that people demand and that generate well-being. While the value of the concept is widely acknowledged, there are remarkable differences in how energy services are conceptualized.

This article proposes the 'Energy Service Cascade' (ESC) as a conceptual framework aimed at clarifying and bridging different approaches. The ESC is inspired by Haines-Young's and Potschin's (2011) 'Ecosystem Service Cascade', which distinguishes: a) structures, b) functions, c) services, d) benefits and e) values. When used to systematize the debates around energy services, we argue that these differentiations reflect a) energy conversion chains comprising natural structures, human-made capital and labor; b) physical functions performed by energy chains; c) services humans demand to foster well-being; d) the actual contributions to human well-being (health, life satisfaction, …); e) individual preferences and attitudes that create willingness to pay, encourage business models, etc. 'Values' influence how services and benefits are perceived and affect 'structures' through various mechanisms (investment decisions, environmental and economic policy, …).

To showcase the usefulness of the ESC as conceptual framework, we provide a review of literature to reveal the differing scopes of four main contexts in which energy services are being studied. We call them 'energy chain context', 'energy demand context', 'well-being context' and 'entrepreneurial context'. Given the diversity of how energy services are interpreted and the various scopes and research aims, a full harmonization of concepts seems out of reach. Nevertheless, a more unified understanding of what is considered as 'service' and differentiation from 'functions' and 'benefits', as provided by the ESC, could be a first step towards more systematic terminology and may support interaction between the different discourses.

Keywords: Energy service, Energy service cascade, Energy chain, End-use service, Well-being, Sustainability transformation

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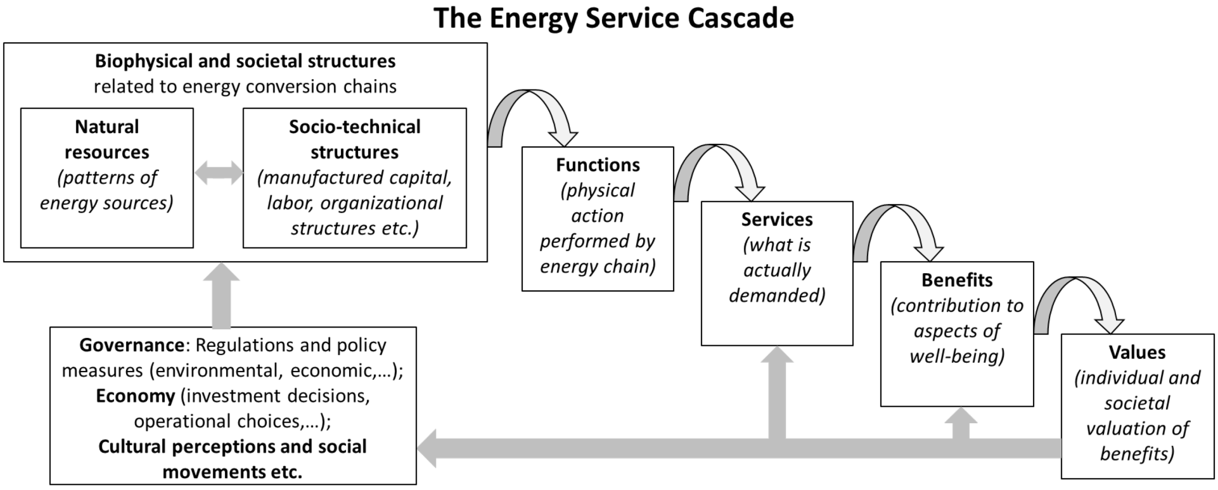
Graphical abstract



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1 The confusion about energy services

The concept of 'energy services' is used in very different contexts and scientific fields, reaching from environmental and sustainability science to economics and social research. The use of the concept is usually motivated by the recognition that it is generally not energy or energy carriers that are demanded by people. Instead, it is commonly argued, it is *services delivered by energy* that provide benefits for society and human well-being. Common examples used to illustrate the difference between energy carriers and energy services are: heating fuels vs. conditioned living space; electricity vs. illumination; transport fuels vs. mobility. Hence, demand for energy services is also regarded as the ultimate driver of energy consumption. The energy services concept has also shaped a number of highly relevant policy efforts, such as the seventh goal of the Sustainable Development Goals [1] or the EU Energy Efficiency Directive [2].

In a recent article, Fell [3] aimed to clarify how the term 'energy service' is understood in the scientific literature. This article revealed remarkable differences in how energy services are defined and classified by researchers, particularly between different scientific fields focusing on different aspects of energy use. For example, if energy services are 'what is actually demanded by the consumer' it is inappropriate to consider freight transport as energy services and quantify the service level in ton-kilometers. What humans demand is having goods and products available at a certain time and place. Similarly, passenger transport quantified in person-kilometers – one of the most frequently mentioned energy service categories in the scientific literature – is an inappropriate measure for the actual services provided: for example, the ability to reach a workplace or recreational facilities, or to participate in social life. Such a distinction between physical functions and what they effectuate [3,4] may seem subtle, but has strong implications on how we conceive the relationship between energy consumption, services and well-being, as will be elaborated in this article.

Another issue in the energy service literature is the highly inconsistent way in which industrial energy use is conceptualized. For researchers with an engineering background, who tend to think in terms of energy conversion chains and statistical classifications of energy use, it seems to be straightforward that high-temperature heat, electrochemical applications etc. represent energy services just like residential heating or transport. On the other hand, studies focusing on the well-being aspect of energy services often entirely exclude industrial energy use and only consider direct energy consumption at the household level. Both perspectives can be criticized for at least being imprecise: The 'engineering perspective' is not consistent with common definitions of ES, as industrial energy use does not by itself satisfy human demands or contribute to well-being. And the household-level 'well-being perspective' neglects the fact that in industrialized societies more or less all energy services at the household level indirectly depend on "upstream" industrial processes; and that energy 'embodied' in commodities, end-user devices etc. is often just as large or even larger, than the energy directly consumed by households [5–7].

These examples and considerations illustrate that there are conceptual issues to be resolved to move the debate forward. Precise definition and classifications of energy services are tricky and methods of quantifying service levels are not straightforward – maybe sometimes infeasible due to lack of data. Inconsistencies in how energy services are conceptualized and measured are sometimes acknowledged (e.g. [8]) but more often pragmatically ignored.

The aim of this article is to introduce the systematic conceptual framework of the 'Energy Service Cascade', which aims to integrate the varying aspects of energy services and the related concepts used in different contexts. Our conceptual framework draws on the debate around ecosystem services [9], where the 'Ecosystem Service Cascade' was successfully used to create the Common International

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Classification on Ecosystem Services, a standardized accounting system at EU and UN level ([10]). It is not the only conceptual framework for research on ecosystem services[1] but represents a widely used approach to clarify the complex interrelations in ecosystem research and has contributed substantially to the practical operationalization in a broad range of contexts [14]. In a similar way, we hope that the 'Energy Services Cascade' concept will further the debate around a common conceptual reference system for studies dealing with energy services and might facilitate a more homogeneous understanding of this important issue. For this purpose, we herein present a review of the energy service literature in the light of our conceptual considerations and draw some suggestions on how the ESC could inform further empirical studies. Our approach can be described as 'narrative review with convenience sample', i.e. the least structured approach according to the categorization of review types suggested by Sovacool et al. [15]. Due to the highly diverse nature of studies using the energy service concept, we consider such an 'exploratory investigation of literature' ([15], p.23) that is not restricted to specific research questions to be the appropriate method of choice.

2 Deriving the Energy Service Cascade

Similar to energy services, the scientific discourse on ecosystem services has been characterized by diverging definitions and use of terminology and several attempts at resolving the tensions between them [16]. Major issues addressed within these debates were the distinctions between functions and services, the latter linked to societal definitions, and between services and benefits, e.g. to avoid double counting [17]. In the following, we translate the Ecosystem Service Cascade model to the case of energy services, thereby conceptualizing an Energy Service Cascade (ESC). We proceed by introducing the components and rationale of the original Ecosystem Service Cascade (see [9,18]) and adapting them to the case of energy services. These components are: 'structures', 'functions', 'services', 'benefits' and 'values' (Fig. 1)[2].

The first element in the cascade is 'biophysical and societal structures'. We explicitly discern natural structures, i.e. naturally occurring energy resources, and socio-technical structures, including manufactured capital and labor required to make energy available to end-users and convert it to useful energy. In the Ecosystem Service Cascade, only 'biophysical' structures are explicitly mentioned, due to the key argument of this debate that the provision of services depends on functioning ecosystems. However, it is sometimes emphasized that ecosystems are rarely natural systems untouched by humans; usually, they have been modified through targeted human intervention [19]. So one could argue that the first element in the Ecosystem Service Cascade also involves human labor and technologies.

'Structures' in the ESC includes the entire energy conversion chain: primary energy conversion to secondary and final energy and ultimately useful energy (or exergy; see section 3.1). Apart from structures performing energy conversion, we argue that 'structures' also comprises artefacts which are often disregarded in the context of the energy conversion chain, such as building envelopes in the case of space heating or road and rail infrastructures and their spatial structures in case of freight and personal transport [20]. Cullen and Allwood [21] introduced the term 'passive system' for these non-energy converting technical components.

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[1] Beside the cascade, some other conceptual frameworks exist, developed within other studies or reports like the Millennium Ecosystem Assessment [11], The Economics of Ecosystems and Biodiversity [12] or the Intergovernmental Platform on Biodiversity and Ecosystems Services (IPBES; [13]).

[2] Haines-Young and Potschin use the singular form in their Ecosystem Service Cascade; we consider the plural to be more fitting for the Energy Service Cascade.

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The second element in both cascades is 'functions'. A function is a physical action performed by an energy conversion chain, for example accelerating a vehicle, transmitting thermal energy to living space or emitting photons for illumination. Hence, functions are measurable in physical units but not necessarily energy units. In their introduction of the Ecosystem Service Cascade, Haines-Young and Potschin [9] describe functions as capacities humans 'find useful' about certain ecological structures (p.115). This feature is directly applicable to functions as understood in the ESC: Humans find it useful that a vehicle is accelerated by a vehicle's internal combustion engine, or that food is kept fresh in a fridge. But – and this is the crucial difference to services – these useful capacities are not per se generators of well-being and merely help to provide a service, like enabling a person to reach a workplace or consuming fresh and heathy food.

Services represent the next step in the cascade and are conceptualized as what humans actually demand. Services enhance well-being but are not identical to well-being contributions. To help distinguish them from functions, the following definition proposed in connection with ecosystem services appears useful: While functions are conceptualized as being independent from actual beneficiaries, 'a service is only a service if a human beneficiary can be identified' (Potschin et al. [18] p.578). For example, no service is attributable to illuminating and heating vacant buildings, although the functions are in place.

In the ecosystem services debate it was emphasized that ecosystem services are a stakeholder driven concept [22], where culturally specific perceptions play an important role [23]. It must be critically scrutinized what the actual demands of certain societal groups are, how they are articulated and who gets to participate in defining the actual 'service'. Requested service levels are to some degree defined by subjective benefits they provide and influenced by historical and cultural backgrounds (see [24,25]). Just like in the case of ecosystem services, energy services generate 'benefits': actual contributions to human well-being such as health and life satisfaction, which are associated with human needs as defined for example by Max-Neef et al. [26] (e.g. subsistence, protection, idleness etc.). Benefits are the outcome of services: Not having to freeze in winter (i.e. thermal comfort; an energy service) contributes to bodily health (a benefit and contribution to well-being). Similarly, illuminated living space (a service[3]) enables the inhabitants to be active after sunset; to enjoy various forms of entertainment or participate in social life (benefits). The relationship between energy services and human needs is often emphasized in connection with energy poverty (e.g. [27]), but is central to all energy use, as Brand-Correa and Steinberger [28] emphasize.

Within the ecosystem services debate, strong concerns emerged whether such benefits are linked to a narrow utilitarian approach reducing benefits to economically measurable preferences in monetary units (e.g. as willingness to pay), or whether a broader scope must be applied that also takes cultural perceptions, moral concerns and human freedom into account [29,30]. Individual attitudes and preferences play a major role for services demanded and benefits derived from them: Driving a car might be considered to be fun (service: entertainment) and as a major contribution to life satisfaction (benefit) by some, while many others might consider it an inevitable part of a daily routine to earn a living (service: mobility; benefit: subsistence). These concerns are also increasingly reaching the energy and climate change mitigation discourse, where they are debated as part of demand-side contributions to mitigation and to overcome various lock-in effects [31–33]. Thus, the actual benefits from energy services can be seen quite differently and in conflicting ways.

[3] The difference between the function 'emitting photons for illumination' and the service 'illuminated living space' may seem subtle, but if nevertheless relevant if we consider that requirements on illumination depend on spatial and architectural settings.

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The final component of the ESC is ‘values’ and refers to individual attitudes, preferences and habits as well as societal norms and their manifestations. In the context of the Ecosystem Service Cascade, Haines-Young et al. [18] propose a differentiation into economic and non-economic values that is also applicable to the ESC: In economic terms, values translate into willingness to pay for energy services. Moreover, benefits influence individual preferences and trigger behavioral patterns that are not economically motivated. Two examples: 1) A person living in an urban region and appreciating the benefits of good access to public transport will likely have other convictions regarding an ideal place to live or questions related to traffic policy than a rural dweller used to moving by car. 2) People with an IT savvy social circle and frequently engaged in communication via the internet might be more inclined to support public spending in data infrastructures than people with traditional, local jobs and mostly regional social connections.

Conversely, habits and societal preferences (‘values’) also influence the demand for an energy service as well as the perceived benefits from it. These mechanisms are represented by the feedback arrow from ‘values’ to ‘services’ and ‘benefits’. And finally, ‘values’ exert influence on the evolution of biophysical structures through numerous, diverse and complex mechanisms involving governance, economy, culturally motivated claims articulated by e.g. social movements etc.

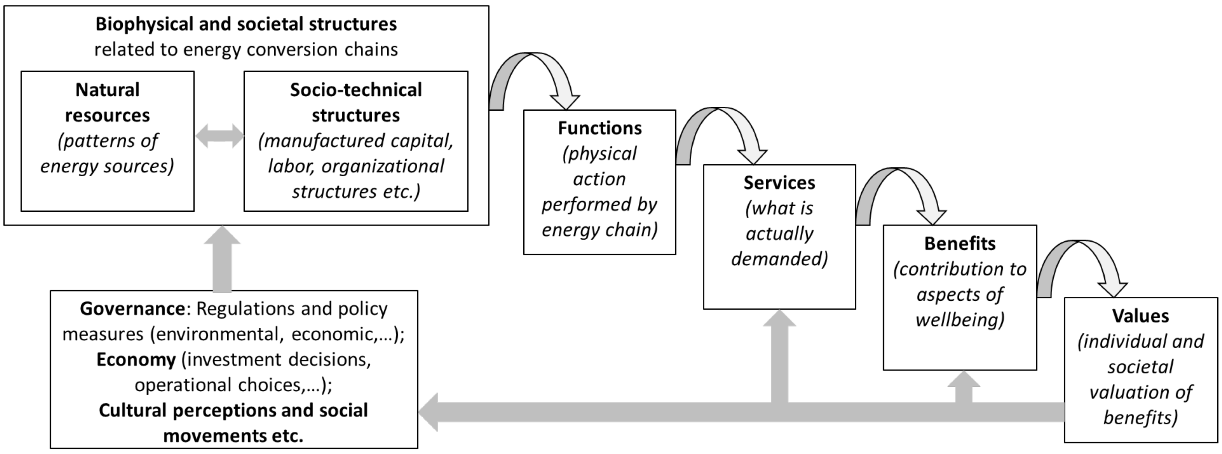

Figure 1. The ‘Energy Service Cascade’ (ESC) as adapted and expanded from Haines-Young and Potschin [9,18]

As elaborated above, there are strong parallels between the Ecosystem Service Cascade and our conceptualization of the ESC. Perhaps the most significant difference is that ‘biophysical structures’ and ‘functions’ in the Ecosystem Service debate are attributed to the environment [14] or biosphere [34]. For the ESC, this refers only to natural resources such as deposits of energy carriers, flows of solar radiation, wind and water or the productive capacities of ecosystems to produce useful biomass. In the ESC, socio-technical structures, are also highly important, and the majority of the ESC is part of the socio-economic system and relies on technologies along the energy conversion chains as well as ‘passive systems’ of manufactured capital, which themselves also require maintenance and therefore induce energy and material flows [35–37]. So far in the literature, these socio-economic stock-flow relations have been conceptualized within the discussion on the socio-economic metabolism [37,38], using different but often overlapping terminology, e.g. artefacts [37], manufactured capital [35], in-use stocks [39] or socioeconomic material stocks [20,36]. Functions depend on combinations of material and energy flows (derived from natural resources) and the socio-technical structures involved

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in their conversion from primary resources extracted from the environment to useful energy respectively exergy [20,35,36].

Drawing on the analysis of Potschin-Young et al. [14] on the value of the Ecosystem Service Cascade, the main purpose of the ESC, as proposed herein, can be summarized as follows: It is not intended as a rigorous concept with strict and predefined categories for the different elements; it should rather encourage researchers to scrutinize the distinction between the different elements, create awareness of these differences among researchers and practitioners, help to harmonize relevant energy service categories and contribute to a more consistent understanding and application of the energy service concept.

3 Using the cascade model to characterize research scopes

As stated above, the energy service concept is used in different contexts and research fields. The motivations for distinguishing between energy flows and services generally depend on research questions and scopes. In this section, we propose a classification of the relevant literature into four broad contexts and discuss how they relate to the ESC model. Fig. 2 gives an overview of these contexts and lists some associated aspects. In subsequent sections, the contexts' scopes are discussed with regard to the ESC. A mapping of the respective scopes in the ESC is provided in section 3.5.

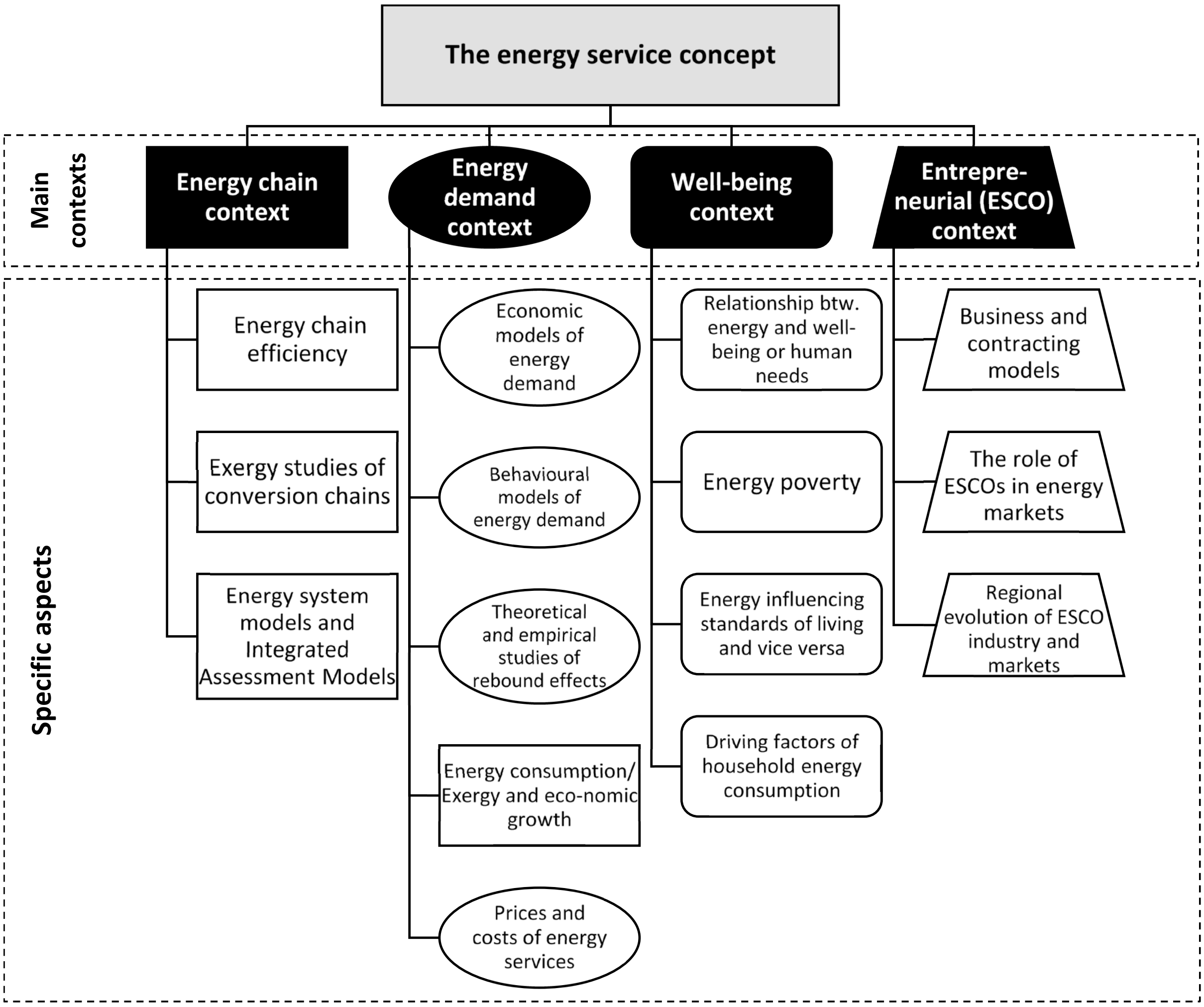

Figure 2. The contexts of energy service literature and specific aspects being investigated (own categorization)

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3.1 Energy services in the energy chain context

The 'energy chain context' comprises a wide range of topics and methodologies used to investigate the energy conversion from primary energy extraction to final consumption. Studies in this context generally assume that energy services represent the final stages of energy conversion chains and are the actual reason for energy demand. Studies in this context are usually quantitative and aim for a thermodynamically correct and systematic allocation of energy flows along conversion steps.

Some examples: Efforts have been made to describe global or national energy conversion chains more comprehensively than common energy statistics [40–43], but only to the stage of useful energy respectively exergy (see below). The conversion to energy services poses considerable difficulties in terms of data and methodology, as they are not measurable in energy units [28,41], which is a core aim of studies in this context. Nakićenović et al. [43] provide estimates of global energy efficiency based on conversion chains from primary to useful energy. They state that 'ideally, the analysis should be extended to include actual delivered energy services' but 'data are scarce and only rough estimates can be given'. Useful energy is calculated from final energy by taking the physical efficiency of the energy conversion processes into account, e.g. the ratio between the light produced by a light bulb and the electricity consumed or the ratio of thermal energy delivered by a heating system to the energy of the final energy used. Although falling short from actually measuring services, such 'useful energy analyses' represent a relevant contribution to the energy service literature because useful energy can to some extent be considered a better proxy for energy services than final energy.

To provide insight into the actual amount of *useful work* delivered, energy chain studies often use the concept of exergy[4]. Long-term trends in overall exergy efficiencies or intensities are considered in connection with economic development, economic transitions, resource efficiency and environmental impacts (e.g. [40,41,44–46]). Depending on whether they focus on the whole energy chain or on final energy demand, exergy studies can be categorized under the 'energy chain' or the 'energy demand context' (see below).

Cullen and Allwood [21] investigate the global flow of primary energy in 2005; initially without considering conversion or transmission losses. By providing a Sankey diagram of energy flows from primary extraction to service, they illustrate the primary energy amounts attributable to eight energy service categories in a mutually exclusive and complete manner. They [21] also assign proxies for the delivery of services differentiated into specific categories (e.g. communication measured in bytes or illumination measured in petalumen-hours). Based on this assessment, theoretical and practical efficiency limits for global energy efficiency improvements are estimated in subsequent studies ([47] and [48], respectively).

The importance of considering energy services as drivers of energy demand is also reflected in the structures of energy system models (ESMs) and integrated assessment models (IAMs).[5] The purpose of such models is to gain insights into complex systems and to derive projections of future developments, aiming at consistency within certain scopes. They usually employ scenario analysis to investigate consequences of different assumptions about future developments (policy intervention, technological development, economic conditions etc.). The energy system representation of ESMs/IAMs typically comprises the whole conversion chain, from primary energy extraction to ES. Final

[4] 'Exergy is a thermodynamic measure of energy quality, measuring the availability to perform work of a certain amount of energy, given reference environmental conditions. Exergy is extensively presented in the literature as a good variable for economic and sustainability assessments of energy, as it accounts for the quality in use and conversion of energy vectors and materials.' [44]

[5] While the scope of ESM is more or less limited to the energy sector, the scope of IAMs is broader and integrates modelling techniques from different disciplines, such as land-use, energy, economics and climate sciences.

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energy demand is often determined by specific demands like total illuminated living space, road transport quantified in passenger- and freight-kilometers etc. together with efficiencies of end-use devices (e.g. lighting technologies, passenger cars and trucks). Demands are in turn influenced by scenario parameters like population trends, economic development and lifestyles. Well-known ESMs/IAMs using energy services as model drivers or intermediate 'commodities' include TIMES [49], IMAGE [50], MESSAGE-GLOBIOM [51], REMIND [52], WITCH [53], POLES [54] and AIM/CGM [55,56].

By definition, the scope of studies in the 'energy chain context' extends from primary energy extraction to at least final energy consumption. Final energy is sometimes further converted to useful energy or exergy delivered to final consumers. Nevertheless, energy service categories are often directly derived from sectors that are using energy, such as transport (measured in passenger- and freight-kilometers), residential heating (heated floor space) or industry (low- and high-temperature heat). Accordingly, energy services in this context can typically be described as physical action of a technical conversion chain; i.e. 'functions' according to the ESC concept. The actual reason for energy consumption and connections to human well-being are therefore largely disregarded for the sake of measurability, i.e. straightforward connectivity to energy statistics and its energy use categories.

3.2 Energy services in the energy demand context

In contrast to studies aiming at describing the whole energy conversion chain (section 3.1), many other studies explicitly aim at understanding the role of energy demand and consumption in general. For the case of economic models of demand, Hunt and Ryan [57] argue that, with few exceptions (e.g. [58–60], demand models rarely take account that energy is required not for its own sake but for the service it produces, which makes them deeply flawed. They further highlight the empirical implications, such as biased price elasticities, and develop 'an explicit model of consumer behavior in which utility derives from consumption of energy services rather than from the energy' (p.ii). Economic studies are usually quantitative and utilize monetary information. Studies that explicitly differentiate between energy and energy services in connection with price elasticities include those by Fouquet et al. [61–63] and Guertin et al. [64]. In related studies, Fouquet et al. [65,66] investigate historical price data and derive long-term trends in the costs of energy services. They emphasize the importance of this distinction and argue that only a focus on energy services reveals true long-term trends in energy-related costs.

A growing number of studies use social science informed theories and methods to understand the role of energy services in consumption and everyday life, thereby overcoming the limitations of rational choice models of consumers. These studies highlight how energy use is shaped by the material devices enabling the energy service, by the infrastructure and urban form, as well as the societal arrangements, all shaping differential levels of agency and lock-in [32,67–69]. However, most of these studies do not utilize a systematic quantitative framework for allocating energy to services, but rather aim for a deeper understanding of specific activities, practices and societal arrangements [70–73].

An intensively researched aspect in connection with energy demand and energy efficiency is the rebound effect, also known as 'Jevons' paradox' (see [74])[6]. In this context, it is widely recognized that energy consumption must be considered from an energy service perspective to fully understand why actual energy savings resulting from technical measures often fall short of efficiency gains [65,66,75–78]. There are different mechanisms at play and rebound effects can generally be observed for energy

[6] The term 'rebound effect' refers to the phenomenon that efficiency gains often do not yield according reductions in consumption because of accompanying cost/price decreases and price-elastic demand. Simply put, if prices for a certain good or service decrease, demand often rises ('direct rebound effect'). Moreover, reduced expenditures for the good or service in question might lead to an increase in consumption of other goods or services ('indirect rebound effect').

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services as well as products and material consumption [79,80]. Numerous studies quantitatively analyze energy rebound effects in specific countries and sectors based on empirical data [59,62,63,81–95] or on a theoretical basis with micro- or macroeconomic models (e.g. [96–101]).

Another topic within the 'energy demand context' is the role of energy in economic growth (e.g. [102–104]. In particular, exergy (i.e. the ability of energy to deliver useful work) has been proposed as the third production factor in production functions, in addition to capital and labor. Several analysts [40,46,102,105] claim that including exergy as a third production factor can eliminate the "residual" (i.e. the part of GDP growth not explained by capital and labor), which is usually interpreted as technological progress [103].

The conceptualization of energy services in the 'energy demand context' is usually similar to the one in the 'energy chain context', with final functions of conversion chains being considered as services. For example, Fouquet [61] mentions 'illumination', 'transportation', 'space and water heating and cooling' as well as 'powering of devices'. Such categories have the advantage of being quantifiable, but have limited validity as indicators for well-being. In our cascade model, they all represent functions rather than services.

3.3 Energy services in the well-being context

A large body of literature focuses on energy services being satisfiers for human needs and contributing to well-being ('well-being context'). A prominent example are the United Nations' Millennium Development Goals (MDGs) [106][7] and the Sustainable Development Goals (SDGs) [1]. In the context of the MDGs, energy services are defined as 'the benefits that energy carriers produce for human well-being' [107], and target 7.1 of the SDG is to 'ensure universal access to affordable, reliable and modern energy services' by 2030. This highlights the high relevance ascribed to energy services for well-being and satisfaction of basic needs, while emphasizing that it is energy *services* that are demanded rather than energy carriers. Studies in this context often apply quantitative frameworks and deploy a multitude of indicators to understand the overlapping relationships between energy, services and well-being.

While energy service conceptualizations in the two previous contexts are centered around the functions energy provides, the 'well-being context' focuses on the benefits individuals derive from using energy. Common themes of studies belonging to this group are energy poverty, energy consumption patterns on the household level, and (urban/rural) development [108–112]. Studies in this context often consider living conditions and investigate how access to specific energy carriers can improve quality of life [108,113]. For example, Kaygusuz [114] explains how modern energy services enhance the life of the poor: 'Electric light extends the day, providing extra hours for reading and work. Modern cook-stoves save women and children from daily exposure to noxious cooking fumes. Refrigeration extends food freshness and avoids wastage. Clinics with electricity can sterilize instruments and safely store medicines through refrigeration.' Apparently, this conceptualization puts strong emphasis on the functional chains of specific energy uses. In another article, Kaygusuz [115] differentiates between energy services for basic needs (e.g. cooking, lighting) and such for income generation (e.g. irrigation water-pumping, motive power for rural industries).

The energy poverty discussion usually considers specific household-level energy functions and their minimum thresholds for well-being [116–118]. For example, the function of being able to properly heat

[7] The MDGs are quantified targets for reducing extreme poverty in its many dimensions by 2015 (income poverty, hunger, disease, exclusion, lack of infrastructure and shelter) while promoting gender equality, education, health, and environmental sustainability [107].

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a dwelling contributes to the benefit of a healthy living space. Energy poverty is then often related to household budgets and affordability of energy carriers, as well as building characteristics (leaking roof, damp walls, rotten windows) [71,117,119–121].

Without explicitly mentioning the energy service concept, Mattioli [122] provides an interesting conceptualization of transport needs: He describes car travel as part of a ‘chain of need satisfiers’, which ultimately serves needs like ‘subsistence’ (food shopping; participation in the labor market) or ‘health care’ (visits to the doctor or hospitals).

Following a more comprehensive approach to energy and wellbeing, Rao and Min [123] define prerequisites for ‘decent living standards’, which are directly related to material requirements and energy services. For example, they consider ‘living conditions’ (as contributor to physical well-being) to be determined by a minimum floor space, modern heating and cooling equipment, in-house improved toilets and accessible water supply, and mention electricity, water and sanitation infrastructure as associated ‘collective requirements’.

Another stream of research approaches the question of energy services and human well-being from a macro-perspective, linking different indicators of aggregate energy consumption, to indicators of human well-being and development [68,124–129]. Efforts are also ongoing to use household level data on consumption, energy and emissions footprints, and well-being/happiness surveys to investigate these relationships [118,130,131]. These studies highlight pronounced saturation effects in the relationship of energy use and well-being. However, they usually do not scrutinize the mechanisms between the functions provided by energy and specific benefits and well-being.

Recent studies also investigate the multiple and overlapping contribution of several energy services to different categories of well-being, utilizing a transdisciplinary participatory framework [132]. This new research has parallels in the original ecosystem services discussion, which also increasingly includes stakeholder driven processes [22]. From this work, it becomes clear that depending on the specific context of each community, (e.g. rural versus urban), the contributions to well-being and necessity for energy services are perceived differently [132].

Studies belonging to the ‘energy chain context’ typically apply systematic and clearly attributable top-down approaches: Total energy use is systematically decomposed to gain insight into (mostly quantitative) relationships between energy consumption and end-use functions. In contrast, the ‘well-being context’ is dominated by bottom-up perspectives and its main scope may range from functions to benefits: Specific needs, services or functions on an individual or household level are usually the starting point for considerations about energy requirements. Hence, the ‘energy chain context’ is typically characterized by a comprehensive perspective, the ‘well-being context’ by a specific one.

3.4 Energy services in the entrepreneurial context

The term ‘energy services’ is also used for activities pertaining to Energy Service Companies (ESCOs), emphasizing that such companies not only sell energy but services related to energy use (see [3]), such as energy management and audits, monitoring and evaluating energy savings, equipment supply etc. [133,134]. There are strong parallels between energy services as understood in this context and the concept of ‘Product Service Systems’, which puts services provided by products into focus instead of products themselves. In both cases, the change of perspective is considered to enable new business models while promoting resource efficiency (see [135,136]).

The meaning of energy services in this context is maybe best described by the definition according to the EU Energy Efficiency Directive [2]: “‘energy service’ means the physical benefit, utility or good derived from a combination of energy with energy-efficient technology or with action, which may

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include the operations, maintenance and control necessary to deliver the service, which is delivered on the basis of a contract and in normal circumstances has proven to result in verifiable and measurable or estimable energy efficiency improvement or primary energy savings”. Although there are strong parallels between this definition and the energy service concept described above, it is of a more technical nature and primarily refers to energy efficiency measures performed under a contractual arrangement between an ESCO and a customer. This ‘Entrepreneurial’ or ‘ESCO context’ is not within the core focus of this paper and shall therefore only be described briefly here.

Okay and Akman [137] provide an overview of ‘ESCO literature’ as of 2010. They describe ESCOs as ‘private-sector instruments that offer energy-/emission-improvement (energy saving, energy efficiency, energy conservation and emission reduction) projects, or renewable-energy projects, in the developed and in some developing countries. The entrepreneurial field of ESCOs was driven by a restructuring of the electricity and gas sectors (privatization, vertical and horizontal unbundling) initiated by governments around the world since the 1990. More recently, policy targets and measures promoting energy efficiency provided additional impetus. Noteworthy scientific work in this field focuses on regional evolution of ESCO industry and markets, business and contracting models and the role of ESCOs in energy markets (e.g. [133,138–148].

Depending on the market segments, in which the respective ESCOs operate, energy services in this context typically include providing space heat and cooling, developing energy concepts for buildings or monitoring energy consumption before and/or after implementation of efficiency measures. Such activities are associated with technical conversion chains as well as functions, but marketing strategies of ESCOs might also have specific consumer benefits and values in focus, or aim at harnessing specific values (e.g. environmental consciousness).

3.5 The four contexts in the light of the Energy Service Cascade

The following figure summarizes the focus of the different contexts in the cascade model. Although it is not possible to draw universal boundaries for what is considered in each context and what is not (the shaded arrows signify this ambiguity), there are clear differences between the respective scopes and what is typically understood as ES. Common energy service categories in literature are located in the ‘function’ and the ‘service’ section of the cascade, with ‘services’ (as understood here) being mostly represented in studies belonging to the ‘well-being context’.

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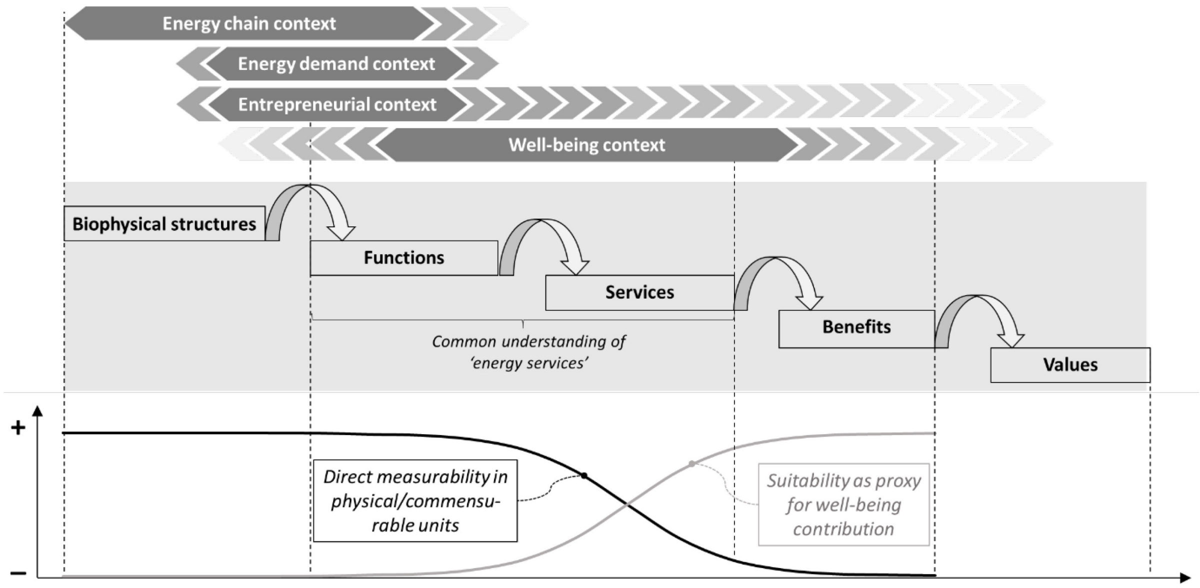

Figure 3. Schematic illustration of typical research scopes of studies belonging to the four contexts (top) and the trade-off between direct measurability and suitability as proxy for well-being contribution (bottom)

The figure also indicates schematically which elements in the cascade are directly measureable in physical or commensurable units. This typically applies to 'structures' and 'functions', whereas assessments of 'benefits' and 'values' can only be based on qualitative indicators that depend on cultural and individual contexts. 'Services', in the capacity of mediators between 'functions' and 'benefits', are typically measurable through proxies but not in precise and indisputable ways. Individual mobility, for example, can be quantified by average time it takes to get to a workplace, or communication by number of outages per year or average bandwidth available.

The value of considering 'benefits', on the other hand, is their close relation to well-being, while 'structures' and 'functions' are poor indicators for contributions to well-being. The bottom part of Fig. 3 illustrates this trade-off between measurability and appropriateness in reflecting contributions to well-being, which is central to the confusion that confounds the energy service concept. We argue that recognition of this trade-off and explicit differentiation between 'functions', 'services' and 'benefits' could further quantitative and empirical work on the complex relationship between energy use and well-being.

4 Discussion

4.1 Functions, functional chains and services

Although energy services are usually defined as 'the benefits that energy carriers produce for human well-being' [107,108,149], they are in fact often operationalized as the functions provided by energy use. However, functions are not per se generators of benefits for well-being. Moreover, such conceptualization bears the risk of blurring the view on what actually matters and likely leads to the exclusion of alternative ways of providing the actual service [20]; Instead of aiming at efficient ways of increasing passenger kilometers, forward-looking spatial planning might reduce passenger transport demand, thereby enabling time-saving and more convenient ways of satisfying mobility needs. In this case, a reduction in person-kilometers is likely to even increase subjective well-being. Likewise, local supply chains for food could drastically reduce freight kilometers in comparison to global supply chains without impairing the actual service (i.e. providing access to food).

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In the context of long-term transformations towards sustainability, it is therefore essential to challenge existing structures and practices, and to focus on what people and societies require to further well-being [150–154]. A precise understanding of what actually constitutes services can help reveal sustainable alternatives to current practices. For example, the energy services of mobility could be understood as 'the opportunity to reach a workplace, participate in social life etc.' ('opportunity for participation') rather than a certain amount of passenger-kilometers. Such conceptualization is more flexible in terms of functions and more consistent with the definition of energy service as being what is actually demanded and creates well-being, i.e. what is valuated accordingly.[8]

With regard to freight transport, 'access to goods' could be considered as actual service. In contrast to the commonly used freight-kilometers, this does not entail a differentiation between long-distance/global and local supply chains. Is does however, raise the questions whether having goods available per se creates well-being. In general, it is rather the functionalities of goods that people aim for. For example, entertainment provided by a TV set, health restored by medicine, or sustenance provided by food. Hence, 'freight transport' as well as 'access to goods' can be considered subsequent links in a functional chain culminating in different services and, subsequently, benefits. In general, such functional chains (or 'chains of need satisfiers', see [122]) are characterized by energy inputs at each stage. However, these chains are not only about energy inputs: functions usually also depend on material goods (e.g. vehicles, infrastructures). This leads us on to the question of how material inputs and upstream energy consumption can be conceptualized in connection with ES.

4.2 Methodological challenges and suggestions

It has often been stated that energy is not the only input factor to energy services. Material inputs are required as well [4,8,20,155,156]; not only as conversion devices (e.g. heat generation and distribution systems) but also as 'passive systems' (e.g. building envelopes, passenger cabins in transport systems; [21]) and consumables (e.g. water for clothes washing or body hygiene). Energy required in production processes, specified as 'embodied energy' in the context of life-cycle assessment (LCA), is indirectly attributable to the provision of energy services. Haas et al. [8] therefore suggest the term 'indirect energy service', whereas Jonsson et al. [4] suggest using 'service' rather than 'energy service' to indicate that they generally depend on both inputs.

If we aim at a precise definition of energy services as generators of well-being, a crucial question arises that has so far mostly been evaded: How should energy uses that are not directly attributable to one specific service be treated? Considering the complexity of modern economies, it is hardly possible to assign each human-made structure and device to one specific service. For example, energy infrastructures (power plants, electricity and gas grids etc.) or raw material processing facilities (steel works, wood processing plants etc.) and their energy demands are part of complex and interwoven supply chains that indirectly contribute to many if not all services. Taking this into account necessitates data-intensive approaches like LCAs or input-output modelling and entails a number of difficulties related to measuring services, issues of double counting, allocation methods and data availability.[9]

These difficulties can be avoided by pragmatically defining industrial energy demands as energy service categories (e.g. 'process heat'/'high temperature heat'), which is in fact inconsistent with common definitions. This is one reason why studies classified to the 'energy chain context' (which take a

[8] A similar understanding of 'energy services' is expressed by Hertwich et al. [155] (see Note 2), but we would argue that functional units in life cycle assessments often fall into the category of 'functions'.

[9] For example, the embodied energy of vehicles would have to be distributed among the various services depending on their function.

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comprehensive approach of assigning all energy use to services) usually consider functions rather than services. Another way of avoiding the difficulties related to embodied energy – usually applied by studies focusing on the well-being aspect of energy services – is to consider only energy services on a household level and disregard all the rest. Such bottom-up approaches are suitable for relating specific services to specific energy supply chains, but are unfit for describing relationships between services and energy use comprehensively.

For quantitative studies aiming at comprehensiveness as well as conceptual consistency, a more sophisticated approach is required. Combining a top-down approach focusing on technical energy conversion chains and functions with a bottom-up approach relating services to functions could be a viable option. Linking functions to biophysical structures and energy consumption in a quantitative way is straightforward from a methodological point of view: Based on energy statistics and technical information on typical characteristics and efficiencies of end-use devices (e.g. fuel demand per kilometer, electricity demand for a certain operating time, energy required for heating a certain amount of water to a specific temperature) direct relationships can be derived. In contrast, relating services to functions is methodologically challenging. First, because services can often not be quantified in physical units. Second, because it is not straightforward to identify the contribution of different functions to specific services. And third, because these relationships depend on multiple influencing factors: customary practices and legacy effects, cultural specific perceptions [4,157], individual values and priorities as well as natural framework conditions.

4.3 Human needs, benefits and values

Identifying the benefits that humans derive from specific services is considered equally challenging, but has already been attempted under a slightly different framing: Building on Max-Neef's taxonomy of fundamental human needs, Brand-Correa et al. [132] propose community-level participatory approaches to identify connections between energy services and human needs satisfaction. Their results from two workshops undertaken in an urban and a rural area of Colombia illustrate that while it seems intuitive that energy services are means of needs satisfaction, the perceived relationships between specific services and needs are far from unequivocal or universal. An interesting finding is that from the perspective of these communities, all human needs require at least one energy service, even 'idleness' and 'identity'.

Day et al. [27] provide another example for how the relationship between energy services and benefits has been conceptualized in previous studies. Building on the 'capabilities perspective' pioneered by Sen (e.g. [158,159]) and Nussbaum (e.g. [160]), they differentiate between 'energy services', 'secondary capabilities' and 'basic capabilities'. Their understanding of 'services' differs from ours (their examples for domestic energy services correspond to 'functions' in the ESC) but the examples for basic capabilities ('maintaining good health', 'having social respect', 'maintaining relationships', 'being educated') are very much in line with what we understand as benefits. Such conceptualization of benefits might even be more expedient than Max-Neef's human needs, because it is less abstract and more oriented towards everyday activities.[10]

As mentioned in section 2, the relationship between benefits and values is characterized by mutual interference: On the one hand, individual preferences, willingness to pay etc. are shaped by experiencing – sometimes also by merely observing – the benefits humans derive from services. On the other hand, existing values and moral stances influence how certain contributions to well-being are perceived. Furthermore, it has been argued that human well-being can be conceptualized in

[10] In the context of the Ecosystem Service Cascade, Berbés-Blázquez et al. [161] have also pointed out this similarity between 'benefits' and Sen's capabilities.

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fundamentally different ways. Lamb et al. [162] and Brand-Correa et al. [28] have brought the ancient Greek philosopher's schools of thought into the debate about energy and well-being. They advocate for a 'eudaimonic' (need-centered) understanding of well-being, as opposed to 'hedonic' ('pleasure-seeking') one and argue that this shift in perspective is crucial for achieving universal human well-being within environmental limits.

For empirical studies on the relationship between energy and well-being on a national/societal level, we suggest statistical approaches for relating subjective well-being indicators (e.g. World Happiness Report [163]; Gallup-Sharecare Well-Being Index) to indicators associated with specific services or functions (e.g. SDG indicators [164] on access to electricity, sanitary facilities and clean water). A basket of indicators can also be useful to describe the multiple dimensions how functions and services contribute to well-being [123].

5 Conclusions

It is widely acknowledged that energy is not demanded for its own sake; nor does energy use per se contribute to well-being. Recognizing that it is actually the services derived from energy use that matter, the concept of energy services has found entry into many different scientific fields and debates, and has even shaped policy efforts. Still, there is no widely accepted definition or understanding of what 'energy services' constitute. Inconsistencies prevail in ad-hoc categories of energy services, and so far no conceptual frameworks suitable for reconciling issues related to energy uses in industry and other upstream sectors has been proposed. For this purpose, we propose the Energy Service Cascade, a framework that has the potential of establishing a more consistent understanding of how energy use contributes to human well-being.

Given the diversity of how energy services are interpreted in the literature as well as the various scopes and research aims of studies using the energy service concept, a full harmonization of the concept seems out of reach. Still, a more unified understanding of the contexts in which the concept is used as well as the understanding of the term 'service' could be a first step towards a more universal terminology, and may support interaction between the different discourses. With regard to a sustainability transformation, this could yield interesting new insights; for example, if aspects of well-being are more thoroughly integrated into IAMs/ESMs. Moreover, especially with regard to quantitative approaches, we believe that a rigorous differentiation between 'functions' and 'services' would be an important step towards harmonizing energy service classifications.

Investigating energy consumption and related environmental impacts from a 'service perspective' is often seen as crucial in connection with transformation towards sustainability and decoupling societal well-being from resource requirements [4,20,28]. In quantitative analyses, classifications are currently determined rather opportunistically and with little consideration of conceptual consistency. Reference to the ESC, with its differentiation between 'functions', 'services', 'benefits' and 'values' might also encourage researchers to scrutinize the scopes and limitations of their respective approaches.

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Conflicts of interest

The authors declare no conflict of interest.

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