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Energy services: A conceptual review

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ABSTRACT

It is often stated that people do not desire energy itself but the ‘energy services’ it provides. Despite its importance, initial searches revealed no obviously dominant definitions of the term ‘energy services’, and inconsistent illustrative examples. This paper presents the results of a content analysis and literature review which aimed to answer the question: ‘what are energy services?’. One hundred and eighty-five articles from the journals *Energy Policy* and *Energy Research and Social Science* containing the term “energy service*” in the title, abstract or keywords were analysed, and additional documents relevant to the concept were identified for review. In total, 27 definitions of ‘energy services’ were recorded, and 173 separate examples (such as ‘space heating’ or ‘lighting’). Thematic analysis of the definitions revealed a number of recurring themes, such as ‘useful energy/work’ and the provision of ‘benefits’ to people. Previous literature suggested the importance of distinguishing between ‘energy services’ and the ‘end services or states’ which they help obtain. On the basis of the identified themes, examples and conceptual discussion, the following definition of ‘energy services’ is proposed: *Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states.*

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1. Introduction

As Hunt & Ryan ([1]: 1) observe: ‘Energy practitioners often emphasize that energy is desired not for its own sake, but for the services that it produces, such as space and water heating, cooling, lighting, cooking, etc.’ Although ‘energy services’ are often referred to (and exemplified) in this way, it is surprisingly hard to find widely cited definitions of the term by searching online or in bibliographic databases. Furthermore, even a brief skim of the literature quickly reveals inconsistencies between examples of what constitute energy services that have the potential to muddy the conceptual waters. For example, later on in Hunt & Ryan ([1]: 5) the authors refer to ‘thermal comfort or other energy services’. Is thermal comfort the energy service, or space heating and cooling as per the opening quotation? Or are they both?

The aim of this paper is to explore the ways in which the concept of ‘energy services’ has been interpreted and defined by researchers. This is achieved through a combination of content analysis (CA) and literature review. The final product constitutes a guide to the concept that will make it easier for researchers to communicate with clarity and precision about energy services in the context relevant to them. It also proposes a new definition of energy services based on the analysis and review.

Because the bulk of this paper is concerned with analysis and review of the concept of energy services, the conventional introductory review is replaced here by a detailed conceptual review in a later section. However, some brief contextual details are presented now to set the scene for further discussion. The first mention of the term ‘energy service’ according to the database Scopus¹ was in a 1955 article on ‘Recent developments in the technology of ceramic materials for nuclear energy service’ [2]. This immediately highlights the ambiguity of the term (a point that became increasingly evident during the research for this paper), as such a usage is quite different from more recent usage as exemplified in opening paragraph of this section. Fig. 1 shows a Scopus² analysis of the number of articles mentioning “energy service”³; and, for comparison, the number of articles mentioning “energy”. Energy services are rarely referred to until the early 1990s, when the rate of growth picks up relative to general energy articles. There is a spike of mentions in 2000, which closer inspection suggests is mainly due to an unusually high number of articles in the publication *Natural Gas Week* mentioning energy services companies. From the latter half of the 2000s the use of the term has grown at a similar rate to

¹ For older articles Scopus can only search titles, abstracts and keywords so there may be earlier occurrences in the bodies of articles.

² A bibliographic database, on which more details are included in the next section.

³ The inclusion of the * wildcard allows the search to capture both “energy service” and “energy services”.

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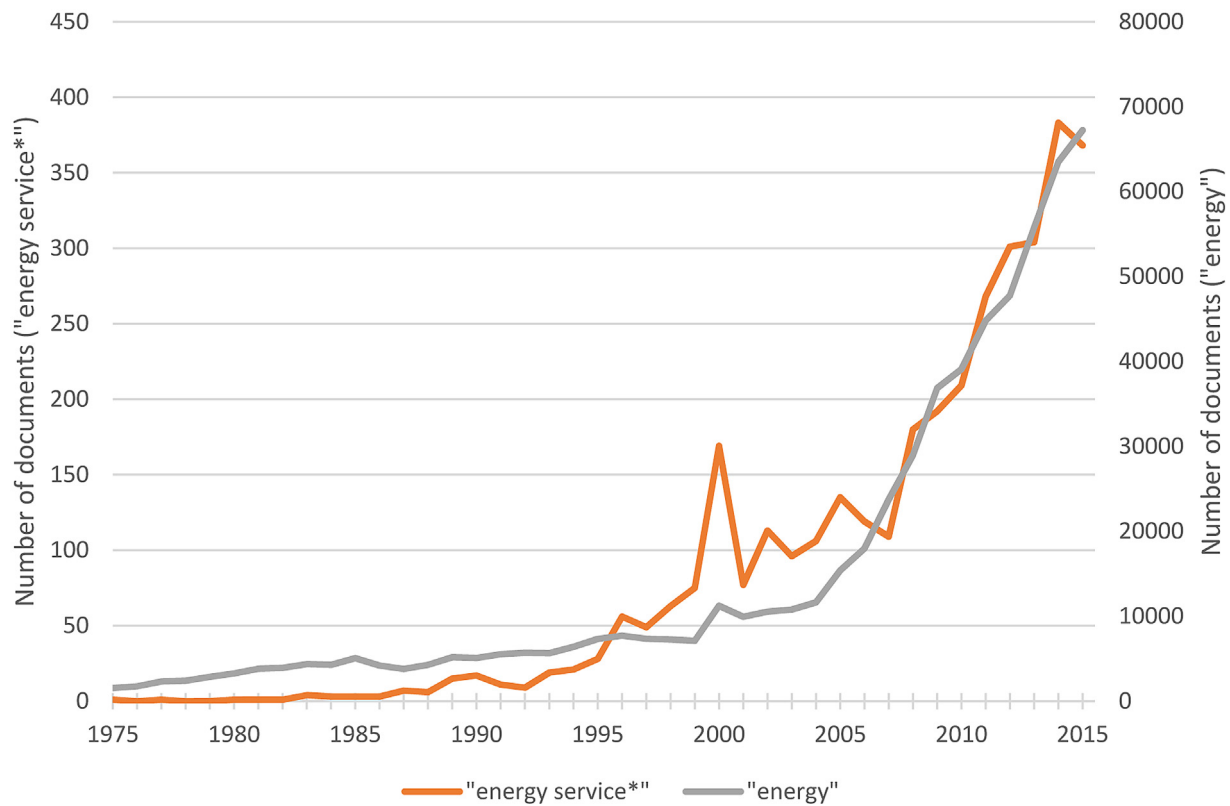


Fig. 1. Scopus analysis of documents mentioning "energy" or "energy service*", limited to sources categorized within the subject 'energy'.

general energy outputs, but as the chart shows, only approximately half a per cent of articles mentioning 'energy' each year explicitly mention energy service(s).

Given the concept of energy services has been around for so long, why is it useful to revisit it now? As well as the inconsistencies in its usage which have become apparent (and are further revealed by the CA presented here), there continues to be increasing recognition of the importance of the demand-side of energy (e.g. see [3]). This is prompted by considerations such as the growing need for demand-side management to make efficient use of existing infrastructure while minimizing costs and carbon emissions. In this case, conceptual clarity around what exactly needs to be managed is important in actually formulating action and research in this area. A brief example of this potential is given in the final section of this paper. Other important issues to which the energy services concept is central include energy poverty, justice and democratization, all of which feature in the subsequent discussion.

As stated previously, a combination of content analysis and literature review is used as the basis for this work. The next section gives an overview of the processes which were followed. Subsequent sections focus on definitions and examples of energy services, a more detailed dive into the literature considering the concept, and a final discussion drawing the strands together and attempting to answer the question: 'what are energy services?'. A concluding section sums up and considers the implications of this work.

2. Content analysis and literature review methods

Content analysis (CA) has been described as 'any technique for making inferences by objectively and systematically identifying specified characteristics of messages' [4]. It involves elements of systematic coding and extraction of content from source material and aims to be objective, transparent and replicable. [5] provides an example of the approach as deployed in the context of energy

research. This sub-section describes how the source material sample for this study was arrived at, while the next sub-section outlines the process of coding, extraction and analysis. The final sub-section describes the process by which a wider review of the 'energy services' concept was conducted.

2.1. Search strategy for content analysis

Searches for the content analysis (CA) were performed on Scopus, which describes itself as 'the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings'.⁴ Employing relevance sampling [6], an initial full-text search was undertaken for any document containing the words "energy service*" (to accommodate the term 'energy services'), yielding 8217 documents. Since this was considered an unnecessarily (and unfeasibly) large pool from which to draw, it was necessary to focus the search to achieve 'a manageable number of relevant texts' ([6]: 119). This could have been done in a variety of ways – by publication date, publication source, or by restricting the search to specific fields such as the title, abstract and keywords.

Restricting by publication date was undesirable since researchers draw on literature of all ages in informing their work, so capturing usage of the term over a long time period is important. The journal with the most articles mentioning the term, according to Scopus, was *Energy Policy* with 445. As well as being the most common destination for outputs mentioning energy services, this journal also has a broad coverage within the field of energy research, with a global scope and taking in all supply and demand sectors, with the latter including social, building, transport and commercial dimensions. It was considered likely

⁴ <https://www.elsevier.com/solutions/scopus>.

that this source would therefore be suitable to provide a useful sample of usages of the concept of energy services.

The search was therefore re-run for *Energy Policy* journal only, and with the further restriction of limiting the search to title, abstract and keywords. The rationale for this restriction was to include only those articles in which energy services might be expected to be a prominent theme. The search was also limited to include only published articles and reviews. Because the interest of this study is in the use of 'energy services' as a concept, and because this concept is an important one in the social science of energy, the decision also was taken to run an additional search with the same criteria for the relatively new journal *Energy Research and Social Science*. The inclusion of an additional source (as well as the subsequent wider review) also helps mitigate against selection bias associated with drawing on a single publication. The full Scopus search string, as run on 23 July 2016, was as follows: *TITLE-ABS-KEY ("energy service*") AND SRCITITLE ("energy policy" OR "energy research and social science") AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re"))*. The search yielded 185 documents (173 from *Energy Policy*) which were downloaded into a reference manager (a full list of these documents is available in the additional online material).

2.2. Coding for content analysis

Coding was performed in NVivo 11 by a single coder. The full text of each document was opened and read for specific mentions or allusions to energy services. This was facilitated by searching the text for occurrences of the word 'service', and close attention was always paid to introductory sections where definitions and explanation of concepts are often provided. Codes were used to record any definitions of the term 'energy service(s)', and examples of energy services such as 'lighting' or 'heating'.

A record was made of the precise terms used in any example of an energy service referred to in the documents analysed. For example, when Sorrell et al. [7] state, 'Energy services such as heating and lighting are provided . . .', this would be coded as 'heating' and 'lighting'. Sometimes examples were not explicitly claimed to be energy services; for example: 'the scope of energy access to include not just heat and light but other aspects such as mechanical power and mobility' [8]. In such cases the terms were still recorded with distinct codes⁵ – but because it is not completely clear that the authors intended to imply that these constituted energy services, they have not been included in the analysis presented here. The number of occurrences of each example was summed to provide an indication of the relative frequency of use of specific examples of energy services. Examples were not recorded when they clearly referred to those products or services required to provide energy, such as fuels or infrastructure.

As well as the above codes for definitions and examples, where additional themes were recognized (such as use of the phrase 'modern energy services') these were also coded for later analysis. Key references were pulled out to inform the subsequent review stage.

2.3. Review

As the CA was only able to identify the existence and prevalence of different definitions and examples in the selected sample, an additional review stage was conducted to identify documents which engage explicitly and in detail with the concept of energy services. The starting point for this review was the list of sources

and key references identified during the CA. Unlike the CA, these key references could be from any source including 'grey literature'. In a snowballing approach, these additional documents were worked through to determine whether they included substantive discussion of the concept of energy services and, if so, to extract definitions, details of that discussion and further references (with these references also being integrated into the review). In addition, a number of Google searches were used to identify any key documents which the above process may not have yielded – these included searches such as ["what are energy services"] and ["energy services" definition].

The review identified 38 additional documents, all of which were drawn on to add to the collected definitions and to inform the subsequent discussion. A sub-sample of these is discussed in detail in the section entitled 'Previous conceptual work'; these were selected based on their relevance to issues highlighted in the preceding CA section. Limitations associated with the CA and review approach presented here are discussed in the penultimate section of this paper.

3. Definitions of 'energy services'

Of the 185 documents included in the CA (drawn from *Energy Policy* and *Energy Research and Social Science* and including the term "energy service*" in the title, abstract or keywords); 19 (or just over 10%) were coded as including what could be considered a definition of energy services – all from *Energy Policy*. Twelve definitions were extracted during the additional review stage. Since some of the documents included in the CA and review used or cited the same definitions; a total of 27 more or less distinct definitions of 'energy services' have been identified – see Appendix A for the full listing. The definitions are numbered to allow them to be clearly referred to here.

Before turning to the definitions themselves, the first observation is that energy services are widely considered either not to need a definition, or in some cases that they may be best 'defined' by simply providing a list of examples, such as: 'energy service, for example, increase in room temperature, or more generally changes in comfort levels' [9]. Of the 166 documents that did not define energy services, 93 included at least one example of an energy service. Such examples are the subject of the next section. Seventy-three articles (39% of the total documents included in the CA) gave no definition or specific examples.

The CA identified several themes in the definitions that allow them to be grouped together. Two themes occurred most commonly:

'Useful energy/work'. Present in eight of the definitions (numbers 10, 11, 14, 16, 20, 21 and 23) was the idea that energy services constituted 'useful energy' or 'useful work' – of energy being put to work in a way that is distinct from the energy use itself. This is exemplified in the following excerpt of the Sorrell ([10], p20) definition: 'An essential feature of an energy service is the useful work obtained'.

'Benefit'. Equally common (although almost mutually exclusive, with only one definition in common) was the explicit idea that energy services entail some kind of 'benefit'. This theme was present in definitions 3, 9, 12, 21, 24, 25 and 27, and is best exemplified by the relatively widely cited Modi et al. ([11], p9) definition: 'Energy services are the benefits that energy carriers produce for human well being'.

Other commonly occurring themes were as follows:

- Circular definitions, where energy services are described as the services provided by energy without additional explanation e.g. 'the services that energy and energy appliances provide' ([11];

⁵ This distinction was made by including the prefix "i-" before any codes where the energy service was only implied, so "energy services such as lighting" would be coded at "lighting", but "energy for lighting" would be coded at "i-lighting".

p1). Constructions of this kind were observed in seven of the definitions (4, 5, 6, 13, 14, 17, 19).

- A suggestion that energy services are the thing that is actually delivered to or demanded by the ultimate consumer, e.g. ‘An energy service is a measure of the service actually provided to ultimate consumers by their own use of energy’ ([12], vi). Again, seven definitions resemble this (4, 7, 15, 16, 22, 23, 26).
- More technical definitions, where energy services are described as being the result of conversion of energy or combining its use with technology of some kind, e.g. “energy service”: the physical benefit, utility or good derived from a combination of energy with energy efficient technology and/or with action’ (TheEU Energy Efficiency Directive 2006/32/EC). Six definitions have this allusion (6, 8, 13, 17, 20, 28).
- Where the definition refers to some general or specific ‘measure’ of service, e.g. ‘a common and more technical definition of transport energy services are distances travelled’ ([13]; p4012). This is seen in four definitions (4, 8, 15, 18).

Less common, but still occurring on two or three definitions each, was reference to wellbeing (as per the first Modi et al. [11] definition mentioned above, see definitions 1, 2 and 12) or to energy services being distinct from other services in that energy is the dominant or necessary input, e.g. ‘the term “energy services” is best applied to those services where energy is a “dominant” input in financial terms and when dedicated conversion equipment is required’ ([14]; p7) (see definitions 5 and 19). Finally, two definitions refer explicitly to the provision of those services required to actually supply energy or energy services, e.g. ‘Energy services include a variety of activities, such as energy analysis and audits, energy management, project design and implementation, maintenance and operation [etc.]’ ([15], p1820). In this respect they are distinct in intent from the other definitions.

In understanding why these themes may or may not be present, it is useful to consider the field of study in which the definitions are employed. Broadly speaking, energy services were mentioned in the literature in five (sometimes overlapping) contexts:

- Work pertaining to Energy Service Companies (ESCOs), or companies that contract with consumers to supply energy services rather than billing directly for energy used. Forty of the 185 studies (22%) in the CA were coded as making significant reference to this.
- Work in the general domain of international development, where the phrase ‘modern energy services’ is commonly employed (according to [16]: 1), ‘access to energy services is a prerequisite to the achievement of all eight MDGs [Millennium Development Goals]’. Thirty-three studies (18%) were coded this way in the analysis.
- Energy modelling studies which attempt to understand the role of ‘energy service demands’. Ten studies (5%) were given this code.
- Work related to understanding energy efficiency or the rebound effect, where definition of the inputs and outputs under consideration is important. This theme was more diffuse and not specifically coded for, but 34 studies (18%) mention the term ‘rebound’.
- Other kinds of study, especially social science work which aims to emphasize social drivers for energy use. This was not specifically coded for.

These contexts may be viewed as taking technical (including energy demand/efficiency), commercial (including ESCO/supply/billing) and social (including development/social drivers) perspectives. Because such a low proportion of the studies analysed actually included a definition it is impossible to estimate statistical associations between themes in definitions and

the context of work. However, of the CA documents including definitions which have an international development focus, all three reference Modi et al. [11] or UNDP [16], which emphasize the ‘benefits’ to people resulting from energy use, and indeed this theme is also present in other definitions in development-focused work such as Kowsari & Zerriffi [17] (citing Pachauri & Spreng [18]). More technical definitions involving conversion of energy or combination with appliances tend to be seen in ESCO- or rebound-related work, such as in the Energy Efficiency Directive definition – although it is noteworthy that this also mentions ‘benefits’. The concept of ‘useful energy/work’ tends to be present in rebound-related definitions and has its roots in work linking energy and economic growth (see, for example [19]) which is now studied as ‘exergy economics’.

Before concluding this section, it is important to highlight two papers which have much to say in relation to the concept of energy services but do not feature either at all or at the length that would be necessary in the table of definitions. Haas et al. [13], while they do provide a definition included in the table, also discuss more specific concepts of short/long-term demands and direct/indirect energy services which are not included. Jonsson et al. [20] explore the subject of energy services at length and ultimately reject the term – hence the lack of a precise definition. Both of these outputs are covered in more detail in the section ‘Previous conceptual work’ below.

This section has presented the main themes identified in the various definitions of energy services that were collected during the CA and review, and related them to an extent to different areas of contexts of research. However, as mentioned above, energy services are often ‘defined’ simply by presenting examples. The next section reviews these examples and considers the extent to which they are consistent between papers and with the definitions collected.

4. Examples of ‘energy services’

In total, 173 separate examples of energy services were mentioned. As will become clear, many of these are minor variations on similar concepts (such as ‘household heating’ and ‘space heating’), but often the differences are more significant in terms of what they say about researchers’ understandings of the concept of energy services. Fig. 2 shows examples of energy services which occur in at least two separate sources, grouped by general area of service (which is sometimes slightly ambiguous, such as the inclusion of ‘space conditioning’ under ‘cooling’).

From these examples, three broad categories of energy service examples can be identified – energy services described in terms of actions, of products, and of technological means. The most commonly occurring examples, all occurring in at least 15 separate sources, are ‘lighting’, ‘cooking’, ‘heating’, ‘space heating’, ‘water heating’ and ‘refrigeration’.⁶ It may therefore be considered that there is the most consensus around these terms as representing examples of energy services. It is notable that all but one of these terms, while usable as nouns, are present participles of verbs (ending in ‘-ing’), representing on-going action or activity. All could be considered things that energy *does* for people, i.e. converting it performs the actual action of heating/lighting/cooking/refrigeration. Similar verbs associated with activity occur elsewhere in the list but less commonly, such as ‘[space] cooling’, ‘freezing’, ‘drying’ and ‘washing’.

Other examples in the list appear more associated with end products of some kind, and are represented by nouns: ‘heat’, ‘hot

⁶ No inference should be drawn from the relative frequency of these terms as to the level of research interest in these specific services, since the sample is not proportionally generalizable to the population of energy research outputs.

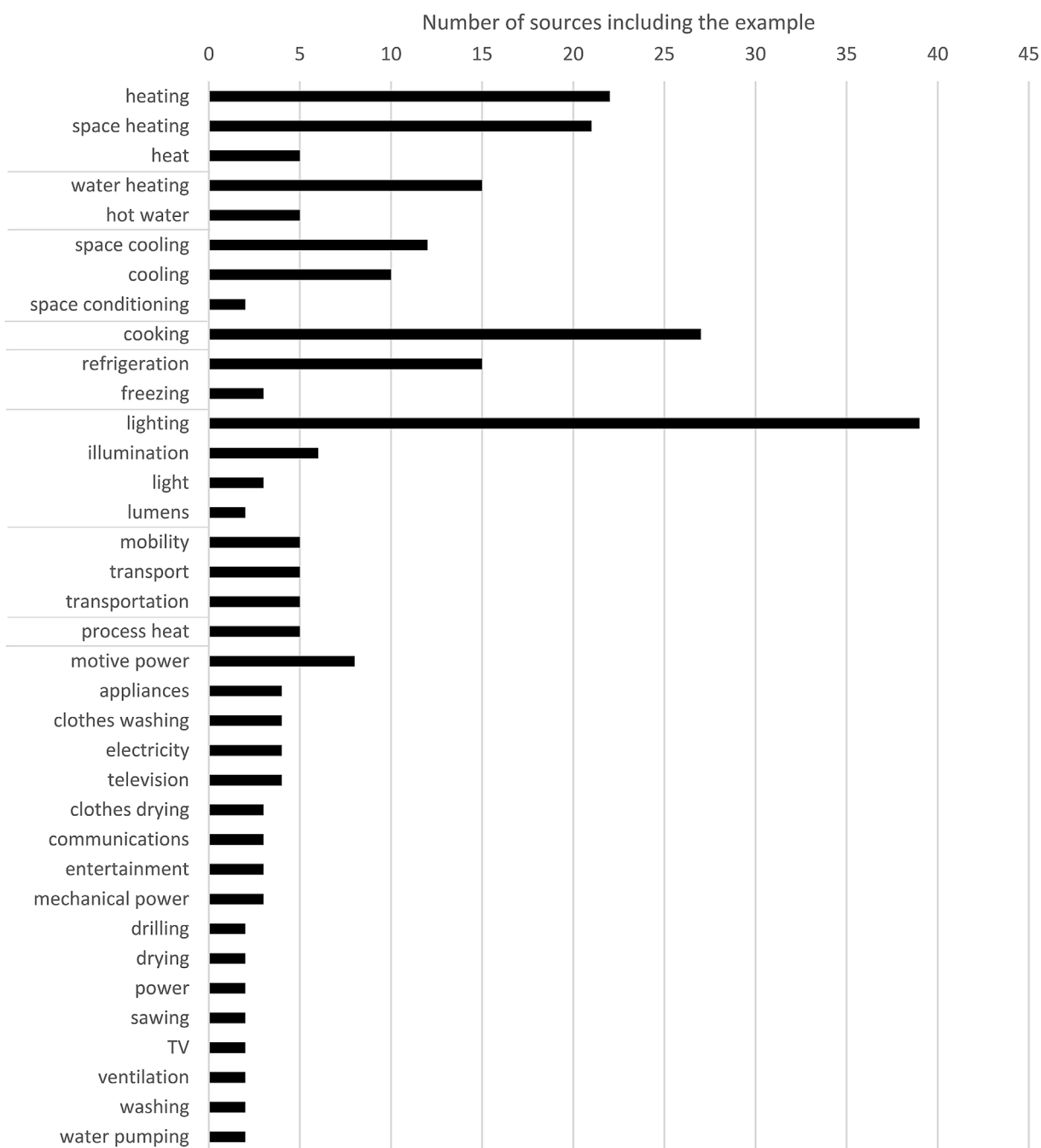


Fig. 2. Examples of energy services included in two or more sources. Services are grouped on the vertical axis with similar terms; from 'motive power' downwards were classed under an 'other' category.

water', 'entertainment', etc. These are products or services that the use of energy may permit, but could not be said directly to *do*. Some, such as 'hot water', are tangible products which can be easily imagined. Others, such as 'entertainment' or 'communications', are vaguer and could be understood in different ways (e.g. as an entertainment show on television, or a state of entertainment in a person). Also, while 'entertainment' may be considered an *end* of energy use, nouns such as 'electricity', 'appliances' or 'television' (depending on how precisely this latter is understood – see alter discussion) appear rather to be the *means* of energy conversion or, in the case of electricity, carriers. The list also includes an example of a measure, in the unit 'lumens'.

What is already clear is that there is some diversity in what exactly are understood to be examples of energy services. This diversity becomes even clearer when the 'long tail' of examples which appear in only one source are considered – see Table 1.

Looking through this list, the same broad mix is observable of actions ('boiling of hot water in kettles'), end products ('cooked meals') and technological means ('mechanical ventilation system') are observable. Sometimes examples appear to treat the *end* of a service differently – for example, is 'mobility' an end in itself, or is the ability 'to reach the shop where I can buy a certain product' (which [13] describes as 'the actual energy service' in the mobility sector)?

Table 1
Examples of energy services appearing in only one source, grouped by general theme.

Theme	Term
Heating	ambient temperature, boiler, changes in comfort levels, combined heat and power, comfortable office rooms, heating loads, household heating, increase in room temperature, nice indoor climate, satisfactory heating regime, temperature regulation, thermal comfort, to heat, warm houses, warmth
Water heating	boiling of hot water in kettles, heating water for bathing, hot water consumption, provision of warm water, swimming in a heated pool
Cooling	air conditioning, air conditioning for summer cooling, conditioned living spaces, coolant, cooling loads, to cool, water cooling
Cooking	clean cooking and heating fuels and technologies, cooked food, cooked meals, cooking meals, heat for a stove, heat for cooking, warm dishes
Refrigeration	cold beverages, cold food, cold storage, cooling food in a given volume, food cooling, food preservation, food refrigeration
Lighting	bright rooms, electricity for lighting, light switches, lighted offices, lights, space light
Transport	air freight, air passenger, car travel, commuting to work, distances travelled, locomotion, mobility services, passenger and freight transport, personal automotive transport, personal automotive transportation, personal transport, personal transportation, road freight, road passenger, to reach my office, to reach the shop where I can buy a certain product, transportation services, travel from A to B, vehicle km of driving
Commercial/ industrial	agro processing, compressed air, electro processes, heavy mechanic work in grinding mills, heavy mechanical work – crushing fruit, industrial gases, milling, office equipment, process heating, process uses, processing, steam, various manufacturing processes, welding
Other	advanced telecommunication, appliance, appliance services, clean clothes, computing, convenience, direct electricity use, dish washing, electric power for appliances, electricity for communication, electricity for community services, electricity for education, electricity for electronics and other equipment, electricity for health, electricity for other household uses, electric-specific applications, electronic appliances, electronic services, food processing, fossil fuels, going to the bathroom with a heated toilet to the sound of music, heating for ironing, ICTs, information and communication technology, ironing, irrigation, light mechanic work for electric sewing, machine drive, mechanical, Mechanical drive, mechanical energy for air circulation, mechanical force, mechanical power to drive a washing machine, mechanical ventilation system, Mobile machinery and service vehicles, mobile phone charging, Nutrition, other (radios, TVs, etc.), other domestic end uses, phone charging, plowing, pool pumps, power for a shower, power for a washing machine, pumping, radio, sending an email, storage, surfing the internet, telecommunication services, telephony, use of telephones, watching television, watching television while one cooks, water treatment and supply, working appliances

It is interesting to consider different conceptualizations of what may constitute the ‘same’ energy service. Take, for example, food refrigeration. In the examples recorded, among other things, this is variously referred to as ‘cooling food in a given volume’, ‘cold food’, ‘food refrigeration’ and ‘food preservation’ (although this latter could conceivably include other forms of preservation). In the first case the service of ‘cooling’ is given prominence, while in the

second refers to a specific product that results from cooling. In the third example the more precise (to food) idea of refrigeration is introduced. The final example specifies perhaps more exactly the final service which is desired – that is, extending the usable life of food through preservation. The question here, which is addressed in subsequent sections, is whether all such terms can correctly and/or usefully be viewed as representing ‘energy services’. To better inform this discussion, the next section discusses in greater detail a selection of papers which engage in some depth with the concept of energy services.

5. Previous conceptual work

Drawing the line between when an energy service ends and some later *end* begins is one of the key challenges that much of the most considered work on energy services sets out to tackle. Some of the earliest work to discuss energy services in detail is by Devine [12] and Reister & Devine [22]. These papers identify 15 (and only 15) energy services, which map quite closely onto the most common examples outlined above (their ‘general energy services’ are: ‘space heating’, ‘water heating’, ‘space cooling’, ‘refrigeration’, ‘cooking’, ‘drying’, ‘lighting’, ‘electronic services’ and ‘appliance services’). However, they are clear that these energy services (which can be measured, for example in joules of heat) are employed with the object of providing some separate final service or ‘ultimate satisfaction’ such as physical warmth (which, in theory, could be measured in units of satisfaction). They invoke Herman Daly’s definition of ‘service’ as ‘the final benefit of economic activity – the satisfaction experienced when wants are fulfilled’ (Daly [23] cited on p4).

Nissing & von Blottnitz [24], Haas [25] and Olerup [26] also all explicitly or implicitly make a distinction between energy services and a more final end service demand. Amongst these, Nissing & von Blottnitz [24] are clearest in stating that “energy services” represent the useful services delivered by end-user devices (e.g. space heating, heat for cooking, motive power) ... [while] “energy service demands” represent energy-related needs of the end-users’ (pp. 2375–2376). [27], on the other hand, use the terms ‘final energy services’ and ‘final services’ interchangeably in their work tracing the flow of energy from fuel to service. The categories of services they use (including ‘sustenance’, ‘hygiene’ and ‘thermal comfort’) suggest a closer alignment with the ‘final service’ view, and indeed they never refer to just ‘energy services’. However, it is noteworthy that the brief descriptions they provide of their final service categories (e.g. ‘heating and cooling of air in buildings’ for thermal comfort, and ‘preparation, storage and cooking of food’ for sustenance) bear greater resemblance to the more common examples of energy services encountered in the CA. While defining broad service categories is useful and practical in the context of tracing global energy flows, it necessarily obscures some nuance – for example, in how the cooking and consumption of a hot meal (classed under ‘sustenance’) could also deliver thermal comfort.

While much work by Sorrell and colleagues discusses the concept of energy services, Sorrell & Dimitropoulos [28] provides a concise summary of their key understandings. To explore the rebound effect it is necessary to have some measure of the energy service being discussed. They view this as the ‘useful work’ done in providing the service, such as vehicle or passenger kilometres for transport. However, they also state that energy services can have other ‘attributes’ that go along with the useful work, such as ‘speed, comfort, acceleration and prestige’ for cars, and from which people also derive utility. It is interesting here to consider these examples, especially that of comfort. As can be seen from Table 1, ‘thermal comfort’ has been used as an example of an energy service, and indeed it is used as such an example earlier in Sorrell &

Dimitropoulos [28] where they state: ‘energy services (ES) such as thermal comfort’. This is not necessarily a contradiction, since in the example of the car the main useful work is transport while comfort (presumably including thermal comfort) is an auxiliary consideration.⁷ What this does highlight, however, is that the same example has sometimes been viewed as either an energy service in and of itself, or an attribute of such as service.

A similarly nuanced understanding of energy services is presented by [29] in conceptualizing energy poverty. They introduce a framework whereby energy services such as lighting, space/water heating and refrigeration are positioned between energy sources on one side and ‘capabilities’ on the other. These capabilities may be either basic, such as maintaining good health or having social respect, or secondary, such as washing clothes and storing/preparing food. It is the energy service which allows the capability to be realised. What Sorrell & Dimitropoulos [28] might describe as an attribute of an energy service (e.g. prestige for a car), Day et al. [29] see as a capability (e.g. having social respect – although their example is likely to be of a more fundamental variety). For Day et al. [29] (similarly as for Devine [12]), the energy service is the thing that energy directly *does*, with a series of further *ends* (i.e. secondary and basic capabilities) as distinct concepts. They would likely view ‘thermal comfort’ as a capability of some level, with ‘space heating’ being the relevant energy service.

Sovacool [30,31] also makes reference to a distinction between ‘primary energy services’ such as cooking and lighting, and ‘broader driving factor(s)’ such as convenience or comfort (p1663). In an extensive treatment of the energy services concept Sovacool highlights many of the different way in which energy services are discussed in the literature. His key contribution is to propose a ‘ladder’ of the different energy services which become available to people of different incomes. These range from services such as lighting and cooking required to meet subsistence needs (or what Day et al. [29] might view as capabilities), through to conspicuous consumption such as ‘swimming in a heated pool’. There do appear to be some inconsistencies within Sovacool’s concept of energy services. For example, convenience is referred to as a ‘broader driving factor’ distinct from energy services (as above), but earlier in the paper it is stated that ‘Energy services . . . can be categorized based on sector . . . fuel . . . [or] even by the service itself, such as motive power, status, convenience, entertainment, and so on’ (pp1661–1662). It is debatable whether it is consistent to view ‘swimming in a heated pool’ as an energy service (as quoted above), rather than the more basic functions required to facilitate this (such as ‘water heating’).

Haas et al. [13] actually sub-divide the concept of energy services into more specific categories, namely short- and long-term energy service demands and direct and indirect energy services. While the difference between short and long term demands is not explicitly defined, it refers to the difference between aspects of energy service which might be expected to vary over the relatively short term (‘e.g. degree indoor temperature, intensity of light, distance driven’) and those that would tend only to vary on longer timescales (‘e.g. number and size of dwellings’). More relevant to our understanding of energy services (rather than demand for them), they distinguish between direct and indirect services. Again, no explicit definition is provided, but the basic distinction is between actions which energy either *does* or can help perform (e.g. ‘lighting’, ‘cooking’, ‘heating’, ‘cooling’) and the embedded/embodyed energy required in providing tangible goods or services which themselves provide services (e.g. ‘food’, ‘shoes’, ‘communication’). These latter may be thought of as energy services because energy is needed to produce them. the

concept of indirect energy services may help us categorise some of the ‘noun’ examples of energy services collected during the CA, such as ‘appliances’. However, it is not clear that authors of such examples are necessarily referring to the energy embedded in items such as appliances, or rather the services they themselves provide.

The final document which this section will discuss in detail is by Jonsson et al. [20]. Like the articles above, it engages deeply with the concept of energy services. Uniquely, however, the authors step back from the term ‘energy service’ in favour simply of ‘service’, which they define as ‘the functions and utilities by which a resource could, directly or indirectly, enable, facilitate or add value to human activities’ (pp362–363). They do this because they believe (as do Sorrell [14] and others) that energy services often require not just energy but other inputs too, such as water for ‘washing’. They also see ‘energy services’ as implying some supplied energy is necessary, masking the possibility that this could be done away with altogether (such as the lack of requirement for supplied space heating in a passive house). Putting aside for now the question of the precise term used, Jonsson suggests useful ways in which services can be broken down and viewed. Most pertinent to this discussion is the following, quoted in full from page 365:

- Volume is the quantifiable amount of energy service delivered, e.g. the amount of heated square metres or passenger-kilometres transported.
- Content corresponds to the experienced utility of service, e.g. a comfortable indoor climate or getting to work.
- Quality reflects experienced reliability, accessibility, safety and security, convenience and ease, e.g. confidence in continuous operation of electricity, easily comprehensible control panels for heating and ventilation, or acceptable congestion in the transport system.
- Motivation reflects why a service is called upon in terms of practical, symbolical or aesthetic.

It is possible to map onto this several of the concepts encountered in the work mentioned above. For example, the ‘content’ or experienced utility of a service is conceptually close to ideas of final service/capabilities, while ‘quality’ resembles Sorrell & Dimitropoulos [28] attributes and ‘motivation’, Sovacool’s [30,31] broader driving factors. As such this may be a useful framework in which to describe [energy] services. However, while Jonson et al.’s rationale for separating ‘energy’ and ‘services’ to focus on the latter is clear, from the point of view of an energy researcher it is useful to have a term that makes clear the role of energy in the provision. Also, use of the term ‘energy services’ distinguishes this concept from the much more general idea of ‘service’ which has a wide variety of meaning depending on the context. Finally, it could be argued that terms such as ‘content’ and ‘quality’ of an energy service are not a useful distinction, since both should be expected to impact the ‘experienced utility of service’.

So far this paper has presented a range of definitions and examples of energy services, and laid out some of the main previous conceptualizations present in the literature. Is it possible to bring this information together to determine what does actually constitute an energy service? This is the question tackled in the next section.

6. So – what are ‘energy services’?

6.1. Recap and discussion

The review of definitions identified several themes common to various understandings of energy services:

⁷ Or what Goldblatt [21] refers to, along with convenience, as ‘meta-energy services’ (p77).

- they provide 'benefits' to people
- they are services provided by energy
- they are what is actually demanded by and delivered to the consumer
- they result, at least in part from energy conversion in combination with technology (and some definitions only consider them to be energy services when energy is a major input in the provision of a service)

Other less common themes were those of measurability, human wellbeing, and services related to the actual provision of energy (e.g. of infrastructure).

The review of examples revealed a few key terms that were used across many sources as examples of energy services (e.g. heating, lighting, cooking, refrigeration), with a very long tail consisting of either modifications/variations of these terms or seemingly different classes of concept (such as 'thermal comfort'). Some modifications were to make an example more specific, e.g. space heating or water heating instead of simply heating. Others apparently refer to different stages in the chain of service delivery, such as the example of refrigeration (i.e. 'cold food', 'food preservation', etc.). Some references were to specific technologies such as television (although there is ambiguity here as this may refer either to the television set, which Haas et al. [13] would describe as an indirect energy service) or the whole system of reproducing images on a screen at distance.

The key theme emerging from the more detailed review of the concept in the literature was of a divide between the energy service and what it was actually needed/wanted for – the final service [12], the capability [29], the useful work and other attributes [28] or the broader driving factors [30,31]. Haas et al. [13] distinguished between direct energy services (the kind of energy service which has been the main focus of the definitions and example collected here) and indirect services which are represented in the embedded energy in goods and other services. Jonsson et al. [20] largely rejected the idea of 'energy services', preferring to deal with 'services' with volume, content, quality and motivation. Of these, the content (or 'experienced utility of service') is closely aligned with the various ideas of final needs/wants considered above.

Taking these findings together, to determine what energy services are, any definition and examples of energy services must make explicit distinction between the energy service itself, and any *end service or state* that it is employed to achieve ('state' is here understood to be 'combination of circumstances or attributes belonging at a particular time to a person or thing' [32]). It is not necessary for the purposes of this discussion to say where exactly we consider those ends to actually terminate – that is, whether it is at 'clean clothes' or the social acceptance that having clean clothes facilitates. However, it is necessary to determine where energy services end, and the end services begin.

For certain common examples of energy service this appears quite straightforward. We may state that the energy service of 'space heating' is done for the purpose of obtaining thermal comfort (end state). The energy service 'lighting' is done for the purpose of being able to see at night (end service). We recognise that the energy service is different and distinct from the end service or state, partly because we could imagine different end services or states for the same energy services – for example 'space heating' to get dry clothes, or 'lighting' to get a secure home.

From these examples we can also conclude that there may be examples of energy service which are more or less precise. 'Space heating' as referred to above is a special class of 'heating', or using energy to increase the temperature of something. More generally the energy service could legitimately be referred to as 'heating', and other classes such as 'water heating' for the purpose of getting hot water also exist, but may also be referred to as energy

services. Sometimes an alternative term exists for the special class – for example 'cooking' for applying heat to food for the purpose of getting cooked food.

If we accept that 'water heating' is a valid energy service, it is then interesting to consider the status of 'clothes washing' as performed by a washing machine. Really, clothes washing consists of 'water heating and movement' for the purpose of washing clothes, for the purpose of getting clean clothes. If we accept, as above, that 'clean clothes' is the end service or state resulting from an energy service, then it is not itself an energy service. We also accepted that 'water heating' is a valid energy service, it seems reasonable that 'water heating and movement' would be too. What then of the special class of 'water heating and movement for the purpose of washing clothes', referred to as 'clothes washing' – is this an energy service? It seems reasonable, in such a case, to consider 'clothes washing' to be another name (or shorthand, similar to 'cooking') for 'water heating and movement for the purpose of washing clothes', which in itself is not an end service or state – and therefore that 'clothes washing' is a valid energy service (albeit at a less fundamental level).

If we accept this, the door is open to viewing a range of things that energy facilitates being viewed as valid energy services, for example:

- 'showering' – as shorthand for 'water heating and moving for the purpose of washing the body' (for the purpose of getting a clean body, which is not itself an energy service but an end service or state resulting from energy use)
- 'clothes drying' – as shorthand for 'heating for the purpose of drying clothes' (for the purpose of getting dry clothes, which is not itself an energy service but an end service or state resulting from energy use)

What is clear from all the examples above is that all of these energy services are things which are done or *functions* ('Activity; action in general' [33]). In the case of energy services, the functions or activities are done or facilitated at least in part by the use of energy.

There is a risk that accepting examples such as 'cooking' as energy services, when they may also be interpreted as activities which people engage in, could result in conceptual confusion. However, there is no inherent inconsistency here – cooking is both done *by* people (as an activity) and as a service *for* people by the action of heat on food. In addition, from a pragmatic perspective, a useful concept of energy services should attempt to be both usable and broadly consistent with dominant usage in the field. To exclude terms such as 'cooking' from the concept in favour of more specific descriptions such as 'heating of food to get cooked food' would run contrary to this. Nevertheless, where there is a risk of confusion as to whether energy services or activities (or other concepts such as more general social practices) are being referred to, it is important to be precise and, if necessary, more explicit.

There remain some examples of energy services as gathered during the CA that remain difficult to categorise in this way – such as 'television'. At its most basic, and considering only that energy used within the home, the television set produces special kinds of lighting and movement (perceived as sound) for some purpose, usually people being entertained. In this case the lighting and movement for the purpose of entertaining people would be the energy service. We have accepted above that shorthand terms may be used to refer to ungainly phrases such as this – but what should it be in such a case? Two options could be available – 'television' or 'entertainment', which also appears in the list of examples of energy services. It may be helpful in this case to consider the range of end services or states which may be achieved through use of a television. One is certainly entertainment, but it may also be used for security (to

give the impression someone is at home) or as a light to see by, or to block out noise from elsewhere. It would therefore be incorrect to refer to 'entertainment' as the energy service provided by the television, since the entertaining element is not necessary for these other ends and is, rather, an end service. It would similarly be incorrect to consider a television set as a service of any kind, when it is simply an energy conversion device. The best option (although admittedly clunky) may be 'working the television' or 'television operation'. Such a formulation could be applied to every appliance, or a general term such as 'appliance operation' could be employed – this would still represent an energy service, but nested within it would be many other energy services such as clothes washing or radio operation.

7. Definition

On the basis of this discussion, it is now possible to attempt a definition of energy services. Such a definition should reflect the themes recognized in existing definitions where necessary and consistent with other requirements set out here. It should probably be pragmatic in admitting the commonly used examples of energy services as gleaned from the literature, since these represent the view of the research and practitioner communities. And it should reflect the distinction between the ends of energy use and the functions required to obtain those ends as emphasized in the conceptual literature and in the foregoing discussion. The following definition of energy services is therefore proposed:

Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states.

While this draws on terminology from existing definitions (see Appendix A and the definition of services by Jonsson et al. [20] above), unlike any single existing definition this definition is considered to meet the above criteria in the following ways:

- It captures the existing definition themes of providing a benefit ('desired'), of useful work (a 'function'⁸; that leads to achieving something that is 'desired'), of delivery to end-users ('obtain') and of requiring energy (although in the interest of flexibility it was decided not to require this to be a dominant input).
- All of the most commonly used examples of energy services gleaned from the literature would accurately be described by it (i.e. 'lighting', 'cooking', 'heating', 'space heating', 'water heating' and 'refrigeration').
- It makes explicit the crucial distinction between the energy service and end service or state as highlighted in previous conceptual work on energy services.

Notably, this definition does exclude some previous quite emphatic examples of energy services found in the literature. For example, when Lovins [34] mentions, 'such desired energy services as hot showers and cold beer' (p4), cold beer would (according to the proposed definition) be the end service or state provided by the energy service of refrigeration. A 'hot shower' would be the end service associated with the energy services of water heating and movement, or 'showering'. Likewise, when Haas et al. [13] state that the ability 'to reach the shop where I can buy a certain product ... [is] the actual energy service' in the mobility sector, this would here be viewed as the energy service 'transport' (or 'mobility') leading to the end service or state of being at the shop. The definition also deliberately excludes any mention of combination with devices or conversion of energy. This decision admits

'natural' processes such as sunlight for illumination as energy services, thereby putting them on a level playing field with delivered energy services as a way of delivering end services or states. Of course, the distinction 'delivered' or 'naturally occurring' can be used as a clarification, should this distinction need to be made.

7.1. Limitations

In closing this discussion, it is important to acknowledge several limitations associated with the approach taken here. While the CA sample was expected to include broad coverage of different kinds of energy research, it is not claimed to be representative. For example, because of the focus of the journals included, it should be expected to capture more social and policy perspectives on energy services than engineering ones. Other definitions or examples of energy services may have been encountered if other sources had been included. However, because the purposive searching conducted for the review did allow a broader range of literature to be captured, yet did not reveal substantially different definitions or examples, this is considered unlikely. Even if other definitions or examples do exist, this would not be expected to undermine the reasoning of the foregoing discussion. It is also possible that because all coding was done by a single coder, certain examples may have been missed that would have been picked up by a second coder, or interpreted differently. Again, however, because the coding in this case required relatively little subjective interpretation (i.e. it mainly consisted of recording words and phrases) it is not considered likely that this would significantly affect the conclusions reached.

Finally, while best efforts were made to identify those key works that engage deeply with the concept of energy services, a full systematic search was not conducted due to resource constraints and it is possible that some have been missed. If such documents make observations that undermine the conclusions presented here, responses are welcomed in the form of communications. It is also acknowledged that certain documents concerning international development or Energy Service Companies give extensive attention to the concept of energy services but have not been discussed in detail here. This is because they are principally concerned with operationalizing the energy services concept for use within these specific fields and are less useful in helping to inform a more general understanding of the concept.

8. Conclusion and implications

This paper has presented the results of content analysis (CA) and literature review focusing on the question, 'what are energy services'? The CA included all articles from the journals *Energy Policy* and *Energy Research and Social Science* which contained the term "energy service*" in the title, abstract or keywords. The literature review supplemented this through hand-searching of key references and focused online searches. Definitions and examples of energy services were recorded and then subject to thematic analysis.

Only 10% of the sources in the CA included a definition of energy services, although it was more often explained simply through reference to examples. A total of 27 distinct definitions were recorded. Common themes identified in these definitions were the provision of 'useful work/energy' and 'benefits' to people, amongst others. In total, 173 separate terms were identified as examples of energy services in the CA sample. Their usage was characterised by common usage of certain examples ('lighting', 'cooking', 'heating', 'space heating', 'water heating' and 'refrigeration'), followed by a long tail of terms used a few times or just once. Many of the examples in the long tail suggest that there is substantial variation between researchers' understandings of what energy services actually are.

⁸ As defined in previous section: 'Activity; action in general' [33].

Much of the previous research that engaged deeply with the concept of energy services agreed that there was some distinction between the end service or state which is actually desired, and the energy service used to provide it. Through a process of reasoning, and with reference to the identified definition themes and examples, a new definition of energy services was proposed that make this distinction explicit. This definition is: *Energy services are those functions performed using energy which are means to obtain or facilitate desired end services or states.*

Clearly this definition will not be suitable in all contexts. For example, in literature dealing with ESCOs the EU definition will be more relevant, and likewise for work discussing modern energy services in the context of development, the ‘wellbeing’ element may be important to emphasize. However, it is put forward in the hope that it will contribute to researchers’ conceptualization of what energy services are, and promote greater consistency and precision in how the concept is used. This is important within energy research for at least two reasons. Firstly, it makes communication easier and lessens potential for confusion when there is agreement around the precise meaning of terms. Secondly, this precision can be important in framing actual research challenges. For example, there is a real temporal difference between the energy service of ‘cooking’ and the end service of ‘cooked food’ which is important to appreciate when considering questions around the time of electricity use and what this means for networks and generation.

Finally, it is hoped that making a clearer distinction between the energy service and the end service or state may be useful from a policy perspective. This is because it emphasizes that the end service is the ultimate goal, rather than a specific energy service. The end service or state may be able to be achieved via other (lower energy) energy services which policy could incentivize. Alternatively, while reduction may be observed on a proxy measure of energy service (e.g. temperature for ‘heating’), a measure of end service or state (e.g. satisfaction with the thermal environment for ‘thermal comfort’, perhaps described in terms of utility) may remain stable – again saving energy. A policy designed to deliver homes that people find warm enough should therefore ideally be evaluated on the basis of thermal comfort assessment rather than temperature (acknowledging the different practical challenges associated with each approach). Determining the most useful metrics for such assessments would be an appropriate subject for future consideration and research.

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Appendix A.

	Definition	Source
1	The consumer is interested in (and gets wellbeing from) energy service	([9], p426)
2	Energy services include a variety of activities, such as energy analysis and audits, energy management, project design and implementation, maintenance and operation, monitoring and evaluation of savings, property management, and energy and equipment supply (see CTI, 2003; ECS, 2003)	([15], p1820)
3	ES [energy services] are defined as “the benefits that energy carriers produce for human well-being” [30,31] [NB This is actually the Modi et al. [11] definition cited by Sovacool and included elsewhere in this table] or more concretely, the wellbeing dimension attained from transforming energy in the form of end-uses.	([35], p111)
4	An energy service is a measure of the service actually provided to ultimate consumers by their own use of energy, quantified, for example, using units of work or of heat at various temperatures.	([12], vi)
5	‘Energy services’ discussed throughout this book relate to services that traditionally required large amounts of energy for provision. Many services, from hairdressing to financial management, have required relatively small amounts of energy. To provide them, however, the availability and cost of energy has little impact upon the price of the service. For heat, power (stationary or mobile, that is, transport) and lighting, energy has been important in its provision and a major expense. Goods and services in economics have most commonly been distinguished by the latter being immaterial. So, energy and energy-using equipment are non-durable and durable goods respectively and heating, power, transport and lighting are the immaterial services that drive demand.	([36], p8)
6	Energy services refer to the services that are generated from consuming energy combined with appliances.	[37]
7	Energy services refer to the commodity, which is actually used or demanded, i.e., refrigeration, hot water, and process heat.	([38], p389)
8	... what people need and purchase thus is not the commercial energy itself, but rather energy services provided by the energy system that converts energy sources and flows from nature into these services [examples given] ... There are several possible definitions of energy services in various sectors. E.g. in the mobility sector the actual energy service is to reach the shop where I can buy a certain product or to reach my office, etc. In a system of short distances (provided e.g. by corresponding spatial planning and infrastructure) this may be possible with very low-energy input. However, a common and more technical definition of transport energy services are distances travelled. In this paper we will use this definition, keeping in mind that an important additional aspect of efficient mobility is to keep distances as short as possible.	([13], p4012)
9	People do not use energy but obtain benefits from the services provided by energy. The term energy services is used to describe these benefits, such as illumination or cooked meals [18] [NB This appears to be a paraphrasing of general points raised by Pachauri and Spreng, rather than a specific definition proposed by them, and also resembles the UNDP [39] definition below.]	([17], p7513)
10	As Sorrell [40] stated, we define energy service as the useful work obtained by energy consuming.	([41], p590)
11	While the demand for energy service (useful energy) is projected to increase ...	([42], p3329) (a similar construction – i.e. parenthetical ‘useful energy’ – is employed by Kesicki & Anandarajah [43] and elsewhere)

- 12 Energy services are the benefits that energy carriers produce for human well being. ([11], p9), also quoted in Sovacool [30,31] and, via Sovacool [30,31], Cravioto et al. [35] and, in paraphrased form, in Nissing & von Blottnitz [44]
- 13 ... the services that energy and energy appliances provide ... lighting, heating for cooking and ([11], p1), also quoted in Brew-Hammond [45]
- 14 ... the services that energy and energy appliances provide ... lighting, heating for cooking and space heating, power for transport, water pumping, grinding, and numerous other services that fuels, electricity, and mechanical power make possible.
- 15 The elements of the tier 'energy services' represent the useful services delivered by end-user devices (e.g. space heating, heat for cooking, motive power) ... Energy services are being consumed for the satisfaction of end-user needs. ([24], p2375)
- 16 An energy service may be defined as a measure of the service provided to ultimate consumers by their own use of energy in any of its forms. ([22], p305)
- 17 Useful energy is the energy form which is really demanded by the consumer for heat, light or mechanical motion. The amount of useful energy delivered from a given amount of final energy that is available to the consumer depends on the efficiency of the end-use technology. *Useful energy reaches the consumer by providing some types of energy services.* ([46], p1167)
- 18 [emphasis added]
- 19 'Energy services' are the combination of energy with other inputs, usually capital, to produce the desired service. ([47], p1303)
- 20 We define 'energy services' as area heated, distance travelled by mode, etc., real manufacturing output by branch, etc. ([48], p382)
- 21 In its broadest sense, the term 'energy services' could refer to any service that requires the use of energy: for example, heating, motive power, transportation and computing. But this is unhelpful since practically all services require energy in some form. For example, energy is required for hairdressing and information technology, but here the energy inputs are secondary to labour and capital. Hence, the term 'energy services' is best applied to those services where energy is a 'dominant' input in financial terms and when dedicated conversion equipment is required. This definition is imprecise, but clearly includes services such as space heating, lighting, refrigeration, motive power and high and low temperature process heat. ([14], p7)
- 22 Energy services are provided through a combination of capital equipment, labour, materials and energy. An essential feature of an energy service is the useful work obtained which ... may be measured by a variety of ways. ([49], p20)
- 23 Yet energy is a peculiar kind of good. Strictly speaking, it is not a good, but a means by which we acquire other goods. This understanding of energy is captured in a phrase used by energy analysts: "energy services. Energy does work for us – it provides us with services such as lighting, heating, and mobility. We are not interested in energy itself, but with the abundant benefits it provides. ([50], p23)
- 24 Energy services refer to what those energy users actually want: a cooked meal, a well lit room, a fast computer with an internet connection, a cold beer, a warm bed, mechanical power for pumping or grinding. Energy services can thus be regarded as the [here quotes Modi et al. [11] definition] ([31], p218)
- 25 "Useful energy," "useful energy demands," and "energy services" are what we are most interested with in this study, and refer to what "end-use energy" is transformed into: heat for a stove or mechanical energy for air circulation [51] [NB The Howells citation is for the examples – heat for a stove, etc. – not the text preceding the colon. This article also quotes the [11] definition – see elsewhere in table]. ([30], p1660) and also used in adapted but very similar form, excluding the actual citation to Howells and Modi, in [50]
- 26 The object of the energy system is to deliver to consumers the benefits that energy offers. The term energy services is used to describe these benefits, which in households include illumination, cooked food, comfortable indoor temperatures, refrigeration, and transportation. ([39], p4)
- 27 The term 'energy services' is used to describe the benefits that energy use offers. ([16], p2), cited by Nissing and von Blottnitz [44]
- 28 End-use demands (i.e. energy services) in the base case are based on socio-economic assumptions ([52], p2298)
- 29 ...
- 30 'energy service': the physical benefit, utility or good derived from a combination of energy with energy efficient technology and/or with action, which may 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 lead to verifiable and measurable or estimable energy efficiency improvement and/or primary energy savings; DIRECTIVE 2006/32/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC, also quoted in [53], paraphrased in [54] and [55]

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.erss.2017.02.010>.

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