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Illumination as a material service: A comparison between Ancient Rome and early 19th century London

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Abstract

Specific combinations of energy flows, material flows and stocks are responsible for those services that support societal function and development. In this paper, we develop the concept and accounting method for material services, which we define as "those functions that materials contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a material flow or stock is supplied by the market". In this respect, material services are an intermediate step that incorporates stock to bridge the gap between resource consumption, accumulation and aspects of wellbeing. We provide a material service case study, which identifies the level of lighting experienced by urban Ancient Romans relative to that enjoyed by inhabitants of 1820s London (the Georgians). Our results show that the average Roman experienced 41,102 lm-hour/year, which is more lighting than the Georgian value per capita (at 35,698 lm-hour/year). In terms of fuel consumption, Georgians were four times more efficient than their Roman counterparts, but there was a trade-off between materials and energy, given that stock efficiency was 53 times lower than that of the Romans. This trend of improving fuel efficiency at the expense of materials appears to have continued into the 21st century, which holds important implications for sustainable development. Further research needs to be undertaken to ascertain whether this holds true for other material services such as heating, transport and shelter.

Key words: MFA, Roman lighting, Georgian lighting, energy services, stock efficiency, material efficiency, sustainable materials

1. Introduction

Economic growth and, perhaps more importantly, aspects of human wellbeing depend on the continuous throughput and transformation of energy and materials (Krausmann et al., 2017). Yet, resource efficiency analysis has traditionally centred on energy efficiency and not materials per se (Allwood et al., 2012; Dusastre and Martiradonna, 2017; Goeller and Weinberg, 1978; Smil, 2017). Furthermore, the delivery of services such as transport, lighting or heating, depends on a combination of energy flows, and materials flows and stocks (Haberl et al., 2017). It is insightful to follow the production chain into services because energy and materials are not usually something that people desire in and of their own right, or perceive as critical to their wellbeing (Day et al., 2016).

Examining socioeconomic development, through the lens of ecological economics is helpful because it provides a framework within which to measure the rate and efficiency that society converts natural resources into products and services (Daly, 2005; Gerber and Scheidel, 2018; Haberl et al., 2019). Within this discipline, there has been considerable research which traces energy sources into services and onto wellbeing, as indicated by Fell's (2017) and Kalt et al. (2019)'s respective reviews of the "energy services" concept. The same cannot be said for materials, which are used by society as both stocks and flows, and which can be extracted, harvested or mixed into an almost infinite number of compounds. In addition, materials provide a greater number of services, such as shelter and packaging, that energy alone cannot. All these issues combine to make material accounting much more difficult than its energy counterpart and the "material services" concept much more difficult to test and evaluate.

This paper develops the material services concept and categories, as explored by Carmona et al. (2017). This is done to demonstrate the use of material services in the evaluation of both stocks and flows, as an intermediate step between material consumption, accumulation and aspects of societal wellbeing. We propose an updated definition of "material services" to make it more widely measurable, implementable and to complement Fell's (2017) definition of "energy services". By extension, we explore the implications of measuring the transformation of materials into societal services in physical units (such as lumens-hour or kcal). In this respect, we build on what has already been done by Fouquet (2008), when he connected energy flows to illumination, as an energy service. We extend the scope of his analysis by including material stocks because whilst energy flows activate stock, they do not offer service provision without material consumption (e.g. modern lighting works with electricity and the devices that transport and transform that electricity into light).

Upon establishing the conceptual framework, we propose a method for measuring the resource efficiency at which energy and material units are supplied. We test the method in a case study, which compares the lighting stock and flows of two historical periods, Roman Pompeii (and Herculaneum) with Georgian London (circa 1820). Through this methodology, we are able to identify a trade-off between energy and material efficiency, with gains in one achieved at the expense of the other. This is something which is frequently overlooked when analysis is restricted to energy services, given that the latter concept only accounts for flows whilst material services account for both energy flows and material flows and stocks. Finally, we discuss the potential link between wellbeing and illumination as a material service and propose future directions for research including further investigation into the trade-off between energy and materials.

2. Material services

2.1. Rationale: where material services fit in MFA (material flow accounting)

Given the importance of material flows for economic growth and social progress, some authors have begun to evaluate resource consumption and its link to wellbeing (Pauliuk, 2018; Steinberger and Roberts, 2010; Vita et al., 2018). In addition, various quantitative tools have been developed for the assessment of certain aspects of sustainability with regards to material consumption. One of the most important is the economy-wide material flow accounting (which we refer to as MFA). MFA quantifies, in tonnes, all flows of physical matter (with the exception of air and water) which occur within an economic system in a given year (Mayer et al., 2017; Schaffartzik et al., 2014).

MFA has addressed various issues linked to material production and consumption and reached a level of maturity (Fischer-Kowalski et al., 2011; Schandl et al., 2017). It enables the quantitative measurement of socioeconomic activity, including trade, and can be used to allocate impact on a consumption rather than production basis (Behrens et al., 2007; Giljum et al., 2011).

MFA, when linked to input-output analysis, has resulted in more accurate depictions of consumer environmental impact, as captured in the material footprint (Wiedmann et al., 2015). MFA also highlights stock variation, which gives an indication of the importance of material accumulation in socioeconomic development. In addition, the tool holds widespread acceptance amongst policymakers involved in sustainable development and sustainable resource use. Many of its indicators have been, according to Krausmann et al. (2017, p. 652), referred to *in policy documents in the context of improving resource productivity, decoupling resource use and economic growth, dematerialisation, and circular economy strategies*. One criticism regarding how the MFA is applied is that flows and stocks are often linked to GDP (e.g. OECD, 2008; Schandl et al., 2017; UN, 2015), but not all societal activities create GDP and therefore neither does all material consumption. Subsequently, both Haberl et al. (2017) and Carmona et al. (2017) have called for the development of service indicators *as complementary concepts of socioeconomic wellbeing*.

The introduction of material (and energy) services is helpful, because of the concept's ability to bridge the gap, as an intermediate step, between resource consumption and the personal/societal benefits that such consumption may provide (Figure 1). This step addresses some (although certainly not all) of the complexities faced by those who are using the MFA methodology to link material use with societal wellbeing (e.g. Mayer et al., 2017; Schandl et al., 2017; Schaubroeck and Rugani, 2017).

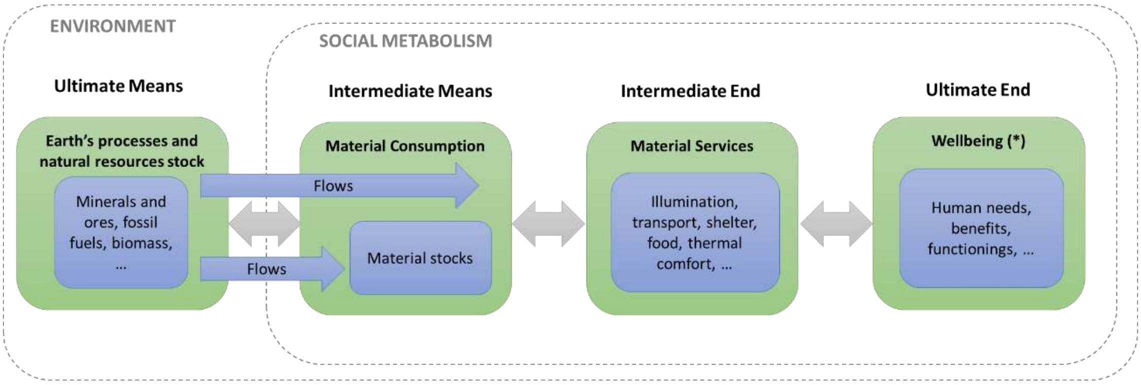

Figure 1. Material consumption chain. Adapted from (Daly, 1991) ends-means spectrum. Note: (*) These are components that contribute to aspects of wellbeing, which alone may not result in a holistic sense of happiness.

2.2. Establishing a definition

The concept of material services was built upon and borrows heavily from energy services, which was first mentioned by Lovins (1976) and Haefele (1977), and later developed by Nakićenović et al. (1993). The energy service concept identifies and accounts for society's dependence on energy to support the functioning of complex systems, through the conversion of energy into desired end uses (services). The concept of energy services had already been mapped by various authors (including Cullen and Allwood, 2010; Heun et al., 2018; Knoeri et al., 2016; Nakićenović et al., 1996, 1993; Schaeffer and Wirtshafter, 1992), and Fell (2017, p. 137) came up with the following definition he derived via a systematic literature review:

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

Using a similar concept, Carmona et al. (2017) defined material services as, "*those benefits that materials contribute to societal wellbeing, through fuels and products (regardless of whether or not they are supplied by the market) when they are put to proper use*". In our opinion, this definition correctly identified that, as material services do not necessarily come from the market, it is possible to separate economic activity from the need to provide societal services. It thus opens the concept to traditional or alternative forms of community and trade, including those existing historically or prehistorically, which did require material services but did not have a market mechanism for their provision.

However, and due to the inclusion of the term "wellbeing" in this definition, as it stands, "material services" incorrectly supports the idea that they directly translate into wellbeing. In reality, the perception of what exactly constitutes societal wellbeing or how to achieve it may change over time and between regions (Brown and Vergragt, 2016; Carlisle et al., 2009). This is because the notion depends on the underlying belief system or the perspective of the person doing the defining. The same is true for the term "proper", as different people will have a different view on what that constitutes.

That said, we believe that a significant added value of material services lies in the concept's ability to measure across spatial-temporal barriers and cultural differences. This is because in consistently assessing the societal function provided by a given material service (which may or may not be transformed into actual or perceived societal or personal aspects of wellbeing), one can identify how an average inhabitant of a given space at a given time, experienced material stocks and flows. One can then compare their experience to that of an average individual with a different set of norms and values. This doesn't mean that the latter two are not important. On the contrary, they exist because a set of beliefs has been instilled to secure the distribution and use of resources (Baccini and Brunner, 2012; Lent, 2017; Lewis and Maslin, 2018). Therefore, governmental structures, religion and education, whilst embodying cultural principles and responsible for material allocation, are not in and of themselves flows or stocks.

Consequently, we propose an updated definition for material services, which builds on that of Fell (2017):

Those functions that materials contribute to personal or societal activity with the purpose of obtaining or facilitating desired end goals or states, regardless of whether or not a material flow or stock is supplied by the market.

In this definition, the term "function" refers to the overall characteristic that society requires in order to do something (e.g. the living space that shelter offers). It should not be confused with material properties or technical attributes such as steel's tensile strength or a motor's RPM. Based on this definition, and using artificial lighting as an example, we know that for human beings to undertake certain activities (e.g. reading, writing or simply navigating a room) a certain amount of illumination is required (which could be measured in lumen-hour, lux or candela per square metre). In this respect, a Roman citizen reading a papyrus would require the same (or a similar) amount of light to someone reading a letter written today. Therefore, their lighting requirements are analogous, although the technology used to meet them may have changed. This is significant because lumens-hour and other physical units are directly comparable. This is in effect what we do in the case study when we contrast the lumen-hours experienced by the average Roman inhabitant of Pompeii/Herculaneum with that of the average person living in Georgian London (see Section 4).

All material services are provided by flows (or stocks) but not all flows (or stocks) provide material services. The distinction between them comes down to whether material consumption or accumulation contributes to a societal function measurable in physical units (such as lumen-hour or joules) or simply social status, financial wealth, obsolete stock or waste. An extreme case to illustrate the difference between the two is the introduction of fake "lifejackets", which openly state that the wearer will not be saved in the event of drowning. Given that such lifejackets do not keep the wearer warm and that since they actually increase the likelihood of dying, should one fall into the water (Miliband, 2017; Tzafalias, 2016), they evidently do not fulfil their objective as either thermal comfort or as a health aid. Instead, they represent a clear case of where material consumption does not transform into a material service. In other words, national GDP was added and personal wealth accumulated but no noticeable increase in material service units occurred. A more mundane example would be where packaging is used for promotional purposes or to make a brand look more luxurious rather than protect, preserve or communicate an integral characteristic of a product. Perfume and food packaging provide two very common examples, see Rundh (2009) and Van Rompay et al. (2012). Likewise, given that for a flow or stock to form a service an interaction between the user and the system is required, a light bulb left on accidently in an empty room (that does not increase a real or perceived sense of security) also fulfils these criteria because the lumen-hour provided does not fulfil the purpose of obtaining or facilitating desired end goals or states. One should also clearly distinguish between material services and the immaterial aspects that support societal end goals such as increased social participation. Education and job creation are two such examples which depend on a number of material services for their delivery but are not material services in their own right (see Section 2.4. for more details).

In some cases, the actual or perceived obtaining or facilitating desired end goals is not directly linked to efficient material service delivery. On a national or regional level, governments may prioritise increased employment rates, as a means to achieve policy targets, over more efficient ways of providing services (Schaffartzik, 2019a). An example of this includes the opening of new car manufacturing sites, even when cars are not the most material efficient form of transport, nor the most sustainable when one considers environmental impacts (Carmona et al., 2019a; Schaffartzik, 2019b).

2.3. Material service categories

The full list of material services is shown in Figure 2. These were developed and amended from those published in Carmona et al. (2017). They are grouped into one of five categories (essential, interconnection, regulating, cultural and provisioning), to simplify their identification and primary function. However, we do acknowledge that some material services do belong to more than one category. Appendix 1 provides the complete list, unit examples and a detailed description of each. The provision category (which accounts for the production side of goods and utilities) should only be calculated if the scope of the analysis does not extend to the consumption side, because otherwise there will be double counting.

There have been other authors, such as Baccini and Brunner (2012); Brand-Correa and Steinberger (2017); Cullen and Allwood (2010); Knoeri et al. (2016) and Rao and Min (2018), who have proposed services categories. The most relevant of these are mapped onto our categories in Appendix 2.

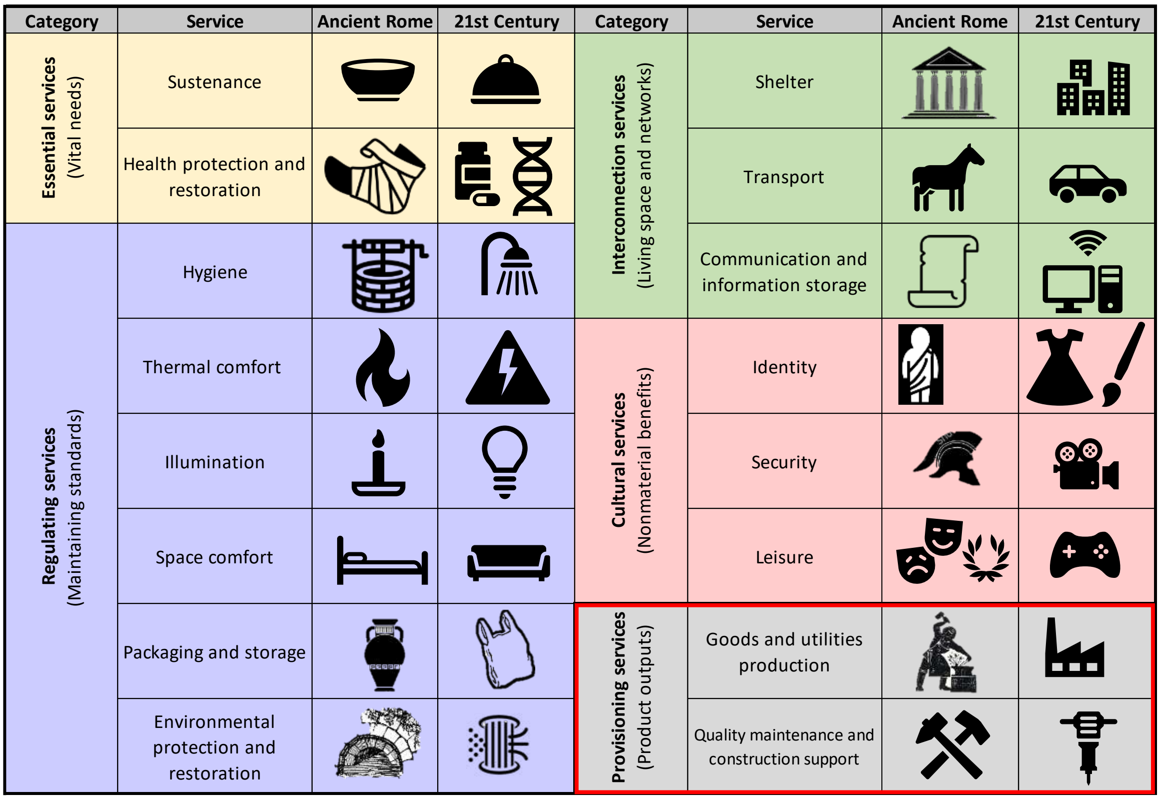

Figure 2. Material service categories. Adapted from Whiting et al. (2018). Note: the provisioning services represents the production side of social metabolism. It is useful to calculate them when consumption data is scarce.

2.4. Scope

Having defined the concept and presented the categories, the scope and some of the peculiarities of material services can be identified and presented with greater clarity:

1) **Flows and Stocks**: Like in the conventional MFA, one should clearly differentiate material flows and stocks. The former corresponds to energy or material units moved or transformed within a defined period of time. Examples include diesel, detergents, fertiliser, lubricants and salt. Stocks constitute those materials that have accumulated over a specified period of time and typically include boilers, buildings ovens, roads and vehicles. Consequently, flows measured in tonne/year, for example and stocks simply in tonnes are incommensurable. The link between flows and stocks within the material services concept can be ascertained through the material service efficiency indicators (see Section 3.2).

2) **Distinction between material services and desired end goals or states**: Some societal functions are not considered within the scope of material services because the material aspects of their provision are covered elsewhere, and their inclusion would lead to double counting. Two examples of that are education and job creation. The reasons why education is not a material service is because the physical institution where teaching and learning takes place comes under the function of “shelter”. In the case of a web-based online institution reliant on “the cloud”, the material aspects are considered under the service “communication and information storage.” This is also true for the whiteboards, paper, pencils, computer hardware or software employed in the process of sharing or receiving information. The light bulbs or other lighting technologies are measured under

"illumination". The chairs and tables in the classroom (or indeed at home) come under "space comfort". Additional extracurricular activities such as sports programmes will likewise be accounted for under "cultural services" or "health protection and restoration" (if specific personal protective equipment is required). Likewise, the football and goal posts come under "cultural services". Consequently, the societal service of institutionalised education can occur precisely because materials have met the other needs and thus facilitate learning. Similarly, one can follow the same logic through for job creation.

3) **Differences between material services and energy services:** All energy services are material services but only some material services are energy services (Figure 3). The distinction between the two relates to whether stocks or flows provide the primary function of a given service. For example, heating is both an energy and material service because it is predominantly provided by a continuous flow of a combustible material (fuel), whilst shelter is only a material service because it is primarily supplied by the accumulation of material stock. By extension, units of material will be assigned to a service based on the primary properties used in that service's provision. Wood, for example, will provide heating when society makes use of its high calorific value upon burning but will offer shelter when its structural integrity delivers the service.

Energy service accounting only considers energy flows, even though it is not just energy that is involved in the provision of a service. Using lighting as an example, in energy service accounting one would restrict the calculation to those fuels or electricity that provide the illumination. Material services accounting extends such calculations to also include light bulbs, cables, switches, lamppost, electricity pylons and gas turbines. All of these pieces of equipment constitute material stocks. Under the material service concept most energy carriers are considered material flows. The energy service and material service calculation for energy carriers are the same, unless other non-fuel flows also support service provision e.g. when salt is added to olive oil to cause a lamp to burn brighter.

It is important to note that electricity and some forms of renewable energy are exceptions within material service accounting because they are pure energy flows and thus immaterial. However, the harnessing of these energy flows does depend on materials (e.g. fossil fuels or biomass flows and solar panels, wind turbines or hydroelectric dams). To account for such flows one can use a method that can place both material and pure energy flows under the same unit (e.g. exergy, as demonstrated by Ayres et al., 2006; Carmona et al., 2019b; Whiting et al., 2017). Alternatively, one can choose to ignore them and only calculate the stocks responsible for renewable energy transformation or use both energy and material services in a complementary approach.

4) **All material services indirectly benefit from ecosystem services:** Nature provides all the raw materials that are transformed and incorporated into material services. The boundary between ecosystem services and material services occurs on the incorporation, processing and transformation of Nature into the flows and stocks that constitute aspects of social metabolism. Whilst "sustenance", "environmental protection and restoration" and "cultural" services are typically calculated within the scope of ecosystem services, other material services such as "shelter", "packaging and storage" and "space comfort", which also rely on what Nature provides, are not accounted for. This is where material services can bridge the gap between natural processes (particularly biosphere) and social metabolism.

Figure 3 shows a conceptualisation of the material service concept scope and interconnections between material services, energy services and ecosystem services.

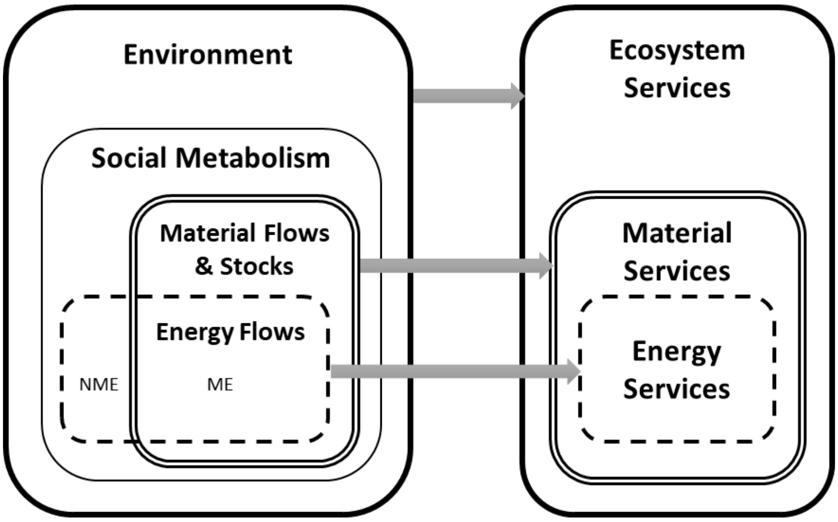

Figure 3. The relationship between energy, material and ecosystem services. Material flows are classified as "biomass", "fossil fuels", "metal ores" and "mineral ores" (Fischer-Kowalski et al., 2011; Krausmann et al., 2018). Note: ME: Material energy flows (biomass and fossil fuels), NME: Non-material energy flows (solar, hydro, wind)

5) **Material services do not necessarily contribute to GDP** and can account for those materials that are traded between people without the legal recognition of monetary exchange i.e. in transactional agreements that are not formally recognised by the State such as bartering, black market activity or cryptocurrencies such as Bitcoin. The concept of material services overcomes this issue because it is robust enough to consider subsistence farming or fishing, for instance, under "sustenance" as a material service. This property is particularly helpful where artisanal mining (which in many countries is illegal but not necessarily criminal) provides a noticeable quantity of a given ore.

6) **Material services can be used for present and historical analysis:** Given the quantifiability of material service units, one can compare the number of lumens per hour, kcal of sustenance or m^2 of shelter accessed across nations, industries and individual factories in the present, or distant past, without determining whether such differences have (or had) a positive or negative effect on society. It is important to point out higher quantities of a given set of material service units does not necessarily mean that the service provided is "better". This is because a single unit does not capture all aspects deemed important in the provision of a service. For example, a greater number of m^2 tends to provide a greater flexibility of space arrangement. However, a local authority interested in meeting national sustainability targets might consider metrics linked to equity/fairness, accessibility and occupancy. This is why it is good practice to measure a service with more than one set of units.

7) **Exclusions and limitations:** The material services concept does not primarily measure environmental impact or wellbeing. Neither does it provide value judgements regarding whether or not one unit of service (e.g. kcal, passenger-km) is to be preferred over another. For example, it does not distinguish between the kcal provided by a doughnut or a lettuce leaf, except in terms of how efficiently that kcal was produced. In other words, material services cannot be used to state whether an individual should prefer (because it is healthier or for ethical concerns) to ingest a kcal from one food type or another. Nor does the concept state societal level preferences i.e. whether there is a desire for more or less lighting than what is available to a given community. However, one could

infer that larger numbers of lumen-hour per capita, for example, mean that society values night-life and the ability to work or socialise after dusk. It could also mean that a small elite group has invested heavily in lighting and enjoy it whilst a large number have no (or very limited) access to lighting. In this case, the average would become skewed and not represent the “average user” at all. This is why contextualised analysis is essential and why assumptions must be clearly stated.

In order to overcome certain elements of this limitation, a practitioner should measure the service in a number of ways that incorporate various characteristics and/or dimensions. The set of indicators selected should be fit for purpose and supported by a thorough contextual analysis with detailed assumptions. For example, in addition to lumens-hour, lighting quantity could be measured in lux or candela per square metre. Artificial lighting can also be considered in terms of quality. Comprehensive reviews of possible units of measure for technical aspects of lighting can be found in Kruisselbrink et al. (2018). One could also look at the number and size of windows to gauge quality of natural light, as this will impact lighting levels in buildings and the dependency a person has on artificial lighting as a material service. For public lighting, one could consider metrics such as “distance from the nearest streetlight”, the distance between those lights or perceptions, preferences and feelings towards the artificial lighting provided (Beute and de Kort, 2013; Rankel, 2014).

Lastly, the scope of “material services” does not include elements linked to human labour, knowledge, know-how or immaterial assets, although each of these factors influences the level/quality of any given service. The scope is restricted in this way because the primary function of the concept is to analyse the relationship between service provision, energy flows, and materials flows and stocks, as well as their various trade-offs.

3. Methodology

3.1. Quantifying Flows and Stocks

Material flows and/or stocks accounting in material services uses the same methodology as that presented by Fischer-Kowalski et al. (2011). For flows, Equation 1 applies.

$$Material\ consumption = Extraction + Imports - Exports + Recycling \qquad (1)$$

For stocks, the equation depends on whether an inflow-driven or stock-driven approach is taken, a selection which is subject to the quality of information available and the complexity of the system being analysed. Equation 2 applies to an inflow-driven model:

$$M_{Stock[i,N]} = \underbrace{M_{Stock[i,0]}}_{Initial\ stock} + \underbrace{\sum_{n=1}^{N} M_{Inflow[i,n]}}_{Inflow} - \underbrace{\sum_{n=1}^{N} M_{Inflow[i,n]} \cdot f_{[n]}}_{Outflow\ (End\ of\ Life)(or\ M_{Outflow})} \qquad (2)$$

In this equation, $M_{Stock[i,N]}$ represents the in-use stock at time *N* and *i* may be a sector or specific material. $M_{Stock[i,0]}$ refers to the in-use stock at time 0 and $M_{Inflow[i,0]}$ is the material inflows for year *n*. The outflows are derived from a residence time model. They are calculated relative to the inflows via the convolution integral (Müller et al., 2014); whereby $f_{[n]}$ is the probability density of the lifetime distribution function. Key examples include Krausmann et al. (2018) and Wiedenhofer et al. (2019).

Equation 3 shows the application for a stock-driven model, where $M_{p[i,N]}$ is the material embodied in all products and infrastructure p for year N, while c_i refers to the concentration or fraction of a material contained within a given product (if applicable). Key examples include Cabrera Serrenho and Allwood (2016) and Pauliuk and Müller (2014).

$$M_{Stock[i,N]} = \sum_{p=1}^{P} M_{p[i,N]} \cdot c_{i,N} \quad (3)$$

For both flows and stocks, where a material has more than one primary use, allocation is necessary and practitioners would need to justify their decision.

3.2. Material service accounting and efficiency

The exact unit measured depends on the purpose of the study. For example, if a government or urban planning authority were interested in housing, they might consider the number of inhabitants per household and the living area of that household in terms of floor area (m^2). They also might, if checking for safety compliance, measure tensile strength (MPa or kN) of the steel contained within high rise buildings. Ideally, they would use more than one unit of measurement in order to obtain a more holistic understanding of the nature of service delivery. More information regarding possible accounting units is in Appendix 1.

To calculate how efficiently material services are provided one needs to calculate the ratio of flows or stocks relative to the service, as shown in Table 1. Intensity indicators are used as proxies because services are measured relative to societal functions whilst flows and stocks are measured in mass. The last column presents the specific indicators used in our case study.

Table 1. Material service efficiency indicators

Indicator	Description	General Equations	Case study application
Material stock efficiency	The amount of stock required to provide a unit of service	$\frac{S}{M_{Stock}}$ (4)	$\frac{Service\ (lumen{-}hour/cap/year)}{lighting\ device\ stock\ (kt/cap)}$ (5)
Material flow efficiency	The amount of material flow that is consumed to provide a unit of service	$\frac{S}{M_{Inflow(consumables)}}$ (6)	$\frac{Service\ (lumen{-}hour/cap/year)}{Fuels\ used\ for\ lighting\ (kt/cap/year)}$ (7)

Note: Where, S: Material Service, M_{Stock}: Material stock, M_{Inflow}: Material flow.

4. Case study: illumination as a material service

For illumination, one must account for fuels (flows) and associated production and distribution systems, including lighting devices (stocks). Specifically, in this case study, we compare Roman Pompeii/Herculaneum (79 CE) with Georgian London (circa 1820). These historical time periods and locations were selected because they represent two key empires that had access to some of the most advanced technologies amongst their peers. Pompeii/Herculaneum was selected due to the unusual circumstances linked to the Vesuvius eruption and the remarkable preservation of urban Roman life around the Bay of Naples. Georgian London was selected because this was the capital of the most industrialised nation. In both cases, a sufficient level of data and primary sources are available, so as to reduce the number of assumptions.

We evaluate the use of three types of lighting technology and their respective fuel for each period: candles, oil lamps and coal gas production and distribution. We followed the generic process below:

1) Identification of key authors and primary/secondary source material to provide contextual information including the type and the pace of lighting innovation. This involved the obtaining of demographic information and the number of buildings per category.

2) Calculation or identification from primary sources of the number of lighting devices, the type of fuel (e.g. oil, tallow, coal gas), their corresponding stock (e.g. candlestick or lamp post) and the material from which the stock is made (e.g. iron, bronze or clay).

3) Ascertain the fuel consumption per hour and per capita device use. For coal gas, calculate the materials used in production.

4) Measure the service of lighting, i.e. the number of lumens per hour per capita.

5) Validation and/or comparison of results with those of modern authors.

6) Provide Sankey diagrams to illustrate the relationship between stocks, flows and services.

Key primary sources for the Georgian period were Ure (1840), Accum (1820), Peckston (1819) and Clegg (1841, 1866). Key sources of data and contextual information for the Ancient Rome, Pompeii and Herculaneum comes from Wallace-Hadrill (1994), Griffiths (2016), Kaiser (2011a, 2011b), Beard (2015, 2010), Rowan (2017), and Peña (2007). More detailed information regarding the use of units, including the modern standardisation of disused units, data collection and cross-referencing for contextual analysis and calculations can be found in the Supplementary Information.

One limitation of this study, which will have led to the overestimation of lighting efficiency is the limited accounting of those upstream material flows that produced the energy sources and the upstream energy flows that supported the extraction of mineral and metal ores. Unfortunately, the sources of information linked to the energy and material flow/stock requirement for mining and processing were incomplete or unavailable. Lastly, we do not include the role of human labour involved in the provision of services, although undoubtedly this played a part.

4.1. Material service efficiency of illumination

The per capita breakdown of lighting fuel and stock use for the Roman and Georgian period is shown in Table 2. Stock per capita in Georgian London was, in absolute terms, 47 times that of Roman Pompeii/Herculaneum. For fuels, the results are reversed, with the average urban Roman consuming almost five times more than their Georgian counterpart. The main user of lighting, as a material service in urban Rome was “households”, which accounted for 60 percent of the total. For circa 1820 London, it was “industry” that represented the largest user at 56 percent. That said, one should be careful when comparing “industry” across the two cultures because what exactly constituted this category changed between the two periods, as did the predominant workplace locations and the extent of the formal relative to the informal work sector.

The difference between the use of lighting in the "households" reflects the variations between the Roman and Georgian workday, labour and societal/personal expectations and values, and/or the ease of access to lighting amongst the poor. In 1820s London, for example, there was a Candle Tax that was later repealed because of its detrimental impact on the working class who lived in squalid conditions and had little access to fuels, let alone lighting devices (see Supplementary Information for details). Consequently, the level of artificial illumination, as a material service, was higher for Herculaneum and Pompeii than it was for London almost 2000 years later.

Table 2. Per capita lighting stock and fuel consumption.

Period	**Urban Roman 79 CE**			**London 1820s**		
Sector	Stock (kg/cap)	Flow (kg/cap/year)	Service (lumen-hour/ cap/year)	Stock kg/ cap)	Flow (kg/ cap/year)	Service (lumen-hour/cap/year)
Households	0.6	14.4	24368	5.7	1.8	5667
Industry and commercial	0.05	5.0	7743	29.9	1.7	20020
Cultural	0.1	5.1	8991	2.2	1.8	10011
Total	0.8	24.5	41102	37.8	5.3	35698

Note: Assuming 50% of devices are lit. The categories represent primary functions. Ancient Rome industry and commercial considers bar/restaurant (coupon, popina, thermopolium), brothel (lupinar), shop (taberna), bakery, forge, kiln, workshop, basilica, senate-house (curia) buildings. Georgian London industry and commercial encompasses mills and factories. The "cultural" category covers temples, churches and theatres. Households lighting takes into consideration both interior and public streetlights.

Table 3 shows the level of artificial illumination in terms of efficiency i.e. how effectively a unit of stock or fuel provided a certain quantity of lumen-hour. In Georgian London the lighting device stock was 53 times less efficient than the stock available to the average Roman living in the Bay of Naples. However, one must be careful when interpreting Roman stock efficiency because the clay used to produce the majority of oil lamps (their primary technology) is lighter than the iron that supported the provision of Georgian lighting. The scarcity of stock per capita in the Roman period (as shown in Table 2) also positively skews the results and may make the Romans appear more efficient than they actually were. There may also have been more stock than that found by archaeologists, given that it is highly probable that those subject to the eruption of Vesuvius took a lamp with them upon escaping the city.

Fuel efficiency, as indicated by material flow efficiency indicator in Table 3, was four times higher in Georgian London than it was in Roman Pompeii/Herculaneum. This is due to a number of factors, including technological advancements in candle moulds, fuel quality, and differences in a fuel's physicochemical properties. The introduction of coal gas, for example, drove fuel efficiency in the Georgian industrial sector.

Table 3. Material service efficiency

Period	**Urban Roman 79 CE**		**London 1820s**	
Sector	Stock efficiency (lumen-hour/kg/year)	Flow efficiency (lumen-hour/kg)	Stock efficiency (lumen-hour/kg/year)	Flow efficiency (lumen-hour/kg)
Households	39173	1695	988	3195
Industry	160190	1540	670	11611
Cultural	61568	1780	4586	5568
Total	50344	1681	944	6741

Note: Assuming 50% of devices are lit. Category breakdown is mention in the notes accompanying Table 2.

4.2. Stock-flow Sankey diagrams

Figures 4a and 4b provide a static snapshot of per capita material consumption (flows and stocks) and artificial illumination provided over an average year within the respective periods studied. They are not traditional Sankey diagrams, because they show stocks, not just flows. In addition, the balance between inputs and outputs is not equal to zero, as stock accumulates for decades. The lines on each diagram represent the flows. Since stocks and flows are expressed in different units, the width of the lines is proportional to the annual quantity of material that provides the illumination, whilst the area of the blocks represents the weight of the lighting devices and is indicative of stock accumulation. The ratio between the material services and the material flows and/or stocks identifies the efficiency at which illumination was achieved. For example, if household fuel consumption is high but the conversion efficiency into illumination is low then the yellow line will be thicker than the orange one.

With regard to this specific case study, Figure 4a shows that ancient urban Roman illumination was predominantly supported by fuels (i.e. olive oil and animal fats). Stock was minimal and used efficiently, but the Roman trade-off was to burn more fuel to compensate for the less efficient lighting technologies. For Georgian London, one can see that the dependency of fuels reduced as lighting stock increased. In other words, the efficiency of fuel conversion into illumination, as a material service, is higher but stock efficiency is lower, which demonstrates their trade-off. In terms of improving our understanding of ancient Roman and Georgian day to day activities, the Sankey diagrams reflect a greater emphasis on the workplace, as we approach the Industrial Revolution and a move away from more domestic based tasks. One can certainly suggest that Roman life in Pompeii/Herculaneum was much more home centred.

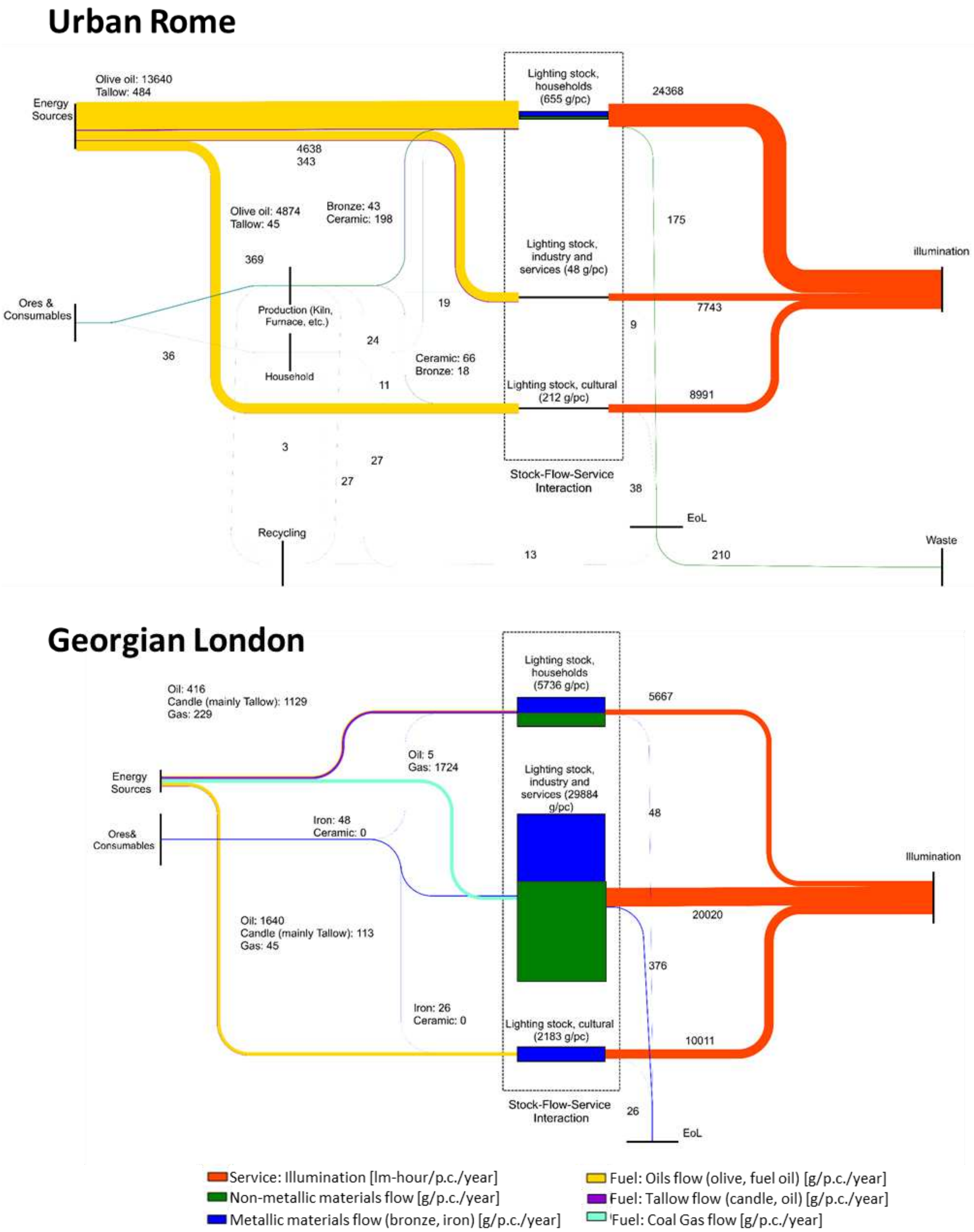

Figure 4. Sankey diagrams representing the annual per capita (p.c.) stocks- flows-service for illumination. 4a: Ancient Rome. 4b: Georgian London.

5. Discussion

Through the material services concept, we have demonstrated that stocks play a significant role in the intermediate step that exists between resource consumption and certain aspects of human wellbeing. Using a case study, we have shown that a specific combination of flows and stocks supplied illumination and that the combination used in the Bay of Naples in 79 CE provided the average person living in Pompeii/Herculaneum with more artificial light than their Georgian counterpart living in London. Whilst we cannot necessarily take this to mean that the average Roman felt happier than the average Georgian, we can hypothesise about their quality of life. We may for instance infer, should we take Sen and Nussbaum's (Nussbaum, 2003; Sen, 1985, 1994) framing of wellbeing (as discussed in Whiting et al., 2018), that the Pompeiian was more capable of freely succeeding in doing what they chose to do, being who they choose to be and pursuing what he or she could have done, according to their own idiosyncrasies, during the hours of darkness or inside a dark room.

Of course, lumens-hours is only one potential unit of measurement, a proxy which does not capture all relevant aspects of service provision. Furthermore, higher quantities of lumens-seconds do not *necessarily* give an indication of overall service quality because, for instance, the devices might be poorly distributed (either too concentrated or too spread) so as not to optimise artificial levels in all rooms of a house, all areas of a street or all parts of a neighbourhood. This is why it is important to have more than one unit of measurement when assessing service provision (e.g. distance from nearest streetlight). Furthermore, lighting is only one aspect of daily life, and arguably to be able to experience Sen's "good life" or meet what Doyal and Gough (1991) refer to as the universal basic needs of physical health and autonomy, one would also need to have a certain degree of space and thermal comfort, be free from hunger and so on. This point demonstrates the value of identifying, accounting and evaluating material services without going into more existential matters. After all, the concept of material services does not state that emphasising flow efficiency over stock efficiency is good or bad. Neither does it indicate how one should provide or distribute lighting, or whether that provision is environmentally sustainable or its allocation just. For answers to such questions, we would have to look into morality and ethics, specifically what we ought to do and why we ought to do it, or whether there exists anything at all that we ought to do (as discussed by Harris, 2011; Sandel, 2010). That said, material services could at the very least facilitate a debate on how to design and manage the product lifecycle and resource distribution.

For one thing, our results indicate that artificial lighting requires a trade-off between energy and materials. In other words, stock efficiency appears to be sacrificed to reduce fuel consumption. This trend has been observed in the 21st century whereby energy saving devices have been manufactured via the introduction of composite materials, many of which are scarce (Carmona et al 2017, Valero and Valero 2014). This trade-off is thus an important consideration for the discourse around sustainability and policy development into the coming decades. That said, further research needs to be done to establish whether the trade-off between energy and materials is equally apparent for other services. It would certainly be worth calculating the extent at which a trade-off increases or diminishes relative to the exact service provided. Other research could be undertaken to look more closely at the relationship between GDP and material services, including, for example, artificial lighting provision and GDP per capita. One way to do this might be though the consumer surplus approach, something which Fouquet (2018) has already done for energy services. To better connect material services to other aspects of wellbeing, a more in depth analysis of the relationship between material consumption, material services and the meeting of human needs should be undertaken to properly evaluate the role of the material service concept in a wellbeing framework, such as that proposed by Doyal and Gough (1991).

Lastly, the introduction and integration of material services alongside the MFA is not without its challenges. All three are subject to issues linked to intensive data collection and processing. In the case study presented here, an extensive and laborious literature review was required with many missing gaps needing to be filled by contextual historical analysis. There may also be some aversion to learning yet another set of metrics and there is always the problem of whether one really measured what they set out to do in the first place i.e. demonstrating a link between material consumption and access to lighting, then inferring that we can in fact understand something new about someone's way and quality of life. Of course, whilst there are challenges, as with any concept or metric, it can be refined as system complexity is better understood.

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References

Accum, F.C., 1820. Description of the Process of Manufacturing Coal Gas, for the Lighting of Streets, Houses, and Public Buildings. with Elevations, Sections, and Plans of the Most Improved Sorts of Apparatus Now Employed at The Gas Works in London, and the Principal Towns of Great Britain; Accompanied with Comparative Estimates, Exhibiting the Most Economical Mode of Procuring this Species of Light, 2nd ed. Thomas Boys, London, UK.
Allwood, J.M., Cullen, J.M., Carruth, M. A., Cooper, D. R., McBrien, M., Milford, R. L., Patel, A. C., 2012. Sustainable materials: with both eyes open, 1st ed. UIT Cambridge, Cambridge, UK.
Ayres, R.U., Ayres, L.W., Masini, A., 2006. An application of exergy accounting to five basic metal industries, in: Sustainable Metals Management. Springer, pp. 141–194.
Baccini, P., Brunner, P.H., 2012. Metabolism of the anthroposphere: analysis, evaluation, design. MIT Press, Cambridge, US.
Beard, M., 2015. SPQR: A history of ancient Rome. Liveright, New York, NY, USA.
Beard, M., 2010. Pompeii: The life of a Roman town. Profile books, London, UK.
Behrens, A., Giljum, S., Kovanda, J., Niza, S., 2007. The material basis of the global economy: Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. Ecol. Econ. 64, 444–453.
Beute, F., de Kort, Y.A., 2013. Let the sun shine! Measuring explicit and implicit preference for environments differing in naturalness, weather type and brightness. J. Environ. Psychol. 36, 162–178.

Brand-Correa, L.I., Steinberger, J.K., 2017. A Framework for Decoupling Human Need Satisfaction From Energy Use. Ecol. Econ. 141, 43–52.

Brown, H.S., Vergragt, P.J., 2016. From consumerism to wellbeing: toward a cultural transition? J. Clean. Prod. 132, 308–317.

Cabrera Serrenho, A., Allwood, J.M., 2016. Material stock demographics: cars in Great Britain. Environ. Sci. Technol. 50, 3002–3009.

Carlisle, S., Henderson, G., Hanlon, P.W., 2009. 'Wellbeing': A collateral casualty of modernity? Soc. Sci. Med. 69, 1556–1560.

Carmona, L.G., Whiting, K., Carrasco, A., Sousa, T., Domingos, T., 2017. Material Services with Both Eyes Wide Open. Sustainability 9, 1508.

Carmona, L.G., Whiting, K., Haberl, H., Sousa, T., 2019a. The use of steel in the United Kingdom's transport sector: a material stock-flow-service nexus case study. J. Ind. Ecol. In review.

Carmona, L.G., Whiting, K., Sousa, T., Carrasco, A., 2019b. The evolution of resource efficiency in the United Kingdom's steel sector: An exergy approach. Energy Convers. Manag. 196, 891–905.

Clegg, S., 1866. A Practical Treatise on the Manufacture and Distribution of Coal-gas: Its Introduction and Progressive Improvement, 4th ed. Jhon Weale, London, UK.

Clegg, S., 1841. A Practical Treatise on the Manufacture and Distribution of Coal-gas: Its Introduction and Progressive Improvement, 1st ed. Jhon Weale, London, UK.

Cullen, J.M., Allwood, J.M., 2010. The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy 38, 75–81.

Daly, H.E., 2005. Economics in a full world. Sci. Am. 293, 100–107.

Daly, H.E., 1991. Steady-state economics: Second edition with new essays. Island Press, Washington D.C.

Day, R., Walker, G., Simcock, N., 2016. Conceptualising energy use and energy poverty using a capabilities framework. Energy Policy 93, 255–264.

Doyal, L., Gough, I., 1991. A theory of human need. Palgrave Macmillan, New York, US.

Dusastre, V., Martiradonna, L., 2017. Materials for sustainable energy. Nature Publishing Group.

Fell, M.J., 2017. Energy services: A conceptual review. Energy Res. Soc. Sci. 27, 129–140.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. J. Ind. Ecol. 15, 855–876.

Fouquet, R., 2008. Heat, power and light: revolutions in energy services. Edward Elgar Publishing.

Fouquet, R., 2018. Consumer surplus from energy transitions. Energy Journal 39 (3). doi:10.5547/01956574.39.3.rfou.

Gerber, J.-F., Scheidel, A., 2018. In search of substantive economics: comparing today's two major socio-metabolic approaches to the economy–MEFA and MuSIASEM. Ecol. Econ. 144, 186–194.

Giljum, S., Burger, E., Hinterberger, F., Lutter, S., Bruckner, M., 2011. A comprehensive set of resource use indicators from the micro to the macro level. Resour. Conserv. Recycl. 55, 300–308.

Goeller, H.E., Weinberg, A.M., 1978. The age of substitutability. Am. Econ. Rev. 1–11.

Griffiths, D.G., 2016. The Social and Economic Impact of Artificial Light at Pompeii. School of Archaeology and Ancient History, University of Leicester.

Haberl, H., Wiedenhofer, D., Erb, K.H., Görg, C., Krausmann, F., 2017. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. Sustainability 9.

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustain. 1.

Haefele, W., 1977. On energy demand. IAEA Bull. 19, 21–37.

Harris, S., 2011. The moral landscape: How science can determine human values. Simon and Schuster.

Heun, M.K., Owen, A., Brockway, P.E., 2018. A physical supply-use table framework for energy analysis on the energy conversion chain. Appl. Energy 226, 1134–1162.
Kaiser, A., 2011a. Roman urban street networks: Streets and the organization of space in four cities. Routledge, New York, NY, USA.
Kaiser, A., 2011b. What was a via? An integrated archaeological and textual approach, in: Poehler, E., Flohr, M., Cole, K. (Eds.), Pompeii. Art, Industry and Infrastructure. Oxbow Books, Oxford, UK, pp. 115–130.
Kalt, G., Wiedenhofer, D., Görg, C., Haberl, H., 2019. Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade. Energy Res. Soc. Sci. 53, 47–58.
Knoeri, C., Steinberger, J.K., Roelich, K., 2016. End-user centred infrastructure operation: towards integrated end-use service delivery. J. Clean. Prod. 132, 229–239.
Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, D., 2018. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. Glob. Environ. Change 52, 131–140.
Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T., 2017. Material Flow Accounting: Measuring Global Material Use for Sustainable Development. Annu. Rev. Environ. Resour.
Kruisselbrink, T., Dangol, R., Rosemann, A., 2018. Photometric measurements of lighting quality: An overview. Build. Environ. 138, 42–52.
Lent, J.R., 2017. The Patterning Instinct: A Cultural History of Humanity's Search for Meaning. Prometheus Books, New York, US.
Lewis, S., Maslin, M., 2018. The human planet: How we created the anthropocene. Penguin, London, UK.
Lovins, A.B., 1976. Energy strategy: the road not taken. Foreign Aff 55, 65.
Mayer, A., Haas, W., Wiedenhofer, D., 2017. How Countries' Resource Use History Matters for Human Well-being–An Investigation of Global Patterns in Cumulative Material Flows from 1950 to 2010. Ecol. Econ. 134, 1–10.
Miliband, D., 2017. The Refugee Crisis is a Test of Our Character.
Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: A review of dynamic material flow analysis methods. Environ. Sci. Technol. 48, 2102–2113.
Nakićenović, N., Gilli, P.V., Kurz, R., 1996. Regional and global exergy and energy efficiencies. Energy 21, 223–237.
Nakićenović, N., Grübler, A., Inaba, A., Messner, S., Nilsson, S., Nishimura, Y., Rogner, H.-H., Schäfer, A., Schrattenholzer, L., Strubegger, M., 1993. Long-term strategies for mitigating global warming. Energy 18, 401.
Nussbaum, M., 2003. Capabilities as fundamental entitlements: Sen and social justice. Fem. Econ. 9, 33–59.
OECD, 2008. Measuring material flows and resource productivity: Volume II. The accounting framework. Organization for Economic Cooperation and Development, Paris, France.
Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001: 2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92.
Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Change 24, 132–142.
Peckston, T.S., 1819. The Theory and Practice of Gas-lighting: In which is Exhibited an Historical Sketch of the Rise and Progress of the Science, and the Theories of Light, Combustion, and Formation of Coal, with Descriptions of the Most Approved Apparatus for Generating, Collecting, and Distributing, Coal-gas for Illuminating Purposes. Thomas and George Underwood, London, UK.
Peña, J.T., 2007. Roman pottery in the archaeological record. Cambridge University Press, Cambridge, UK.
Rankel, S., 2014. Future lighting and the appearance of cities at night: A case study. Urbani Izziv.

Rao, N.D., Min, J., 2018. Decent living standards: material prerequisites for human wellbeing. Soc. Indic. Res. 138, 225–244.

Rowan, E., 2017. Personal correspondence.

Rundh, B., 2009. Packaging design: creating competitive advantage with product packaging. Br. Food J. 111, 988–1002.

Sandel, M.J., 2010. Justice: What's the right thing to do? Macmillan.

Schaeffer, R., Wirtshafter, R.M., 1992. An exergy analysis of the Brazilian economy: from energy production to final energy use. Energy 17, 841–855.

Schaffartzik, A., 2019a. International metabolic inequalities mediated by the distribution of stocks.

Schaffartzik, A., 2019b. Personal correspondence.

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014. The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010. Glob. Environ. Change 26, 87–97.

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., 2017. Global Material Flows and Resource Productivity: Forty Years of Evidence. J. Ind. Ecol.

Schaubroeck, T., Rugani, B., 2017. A Revision of What Life Cycle Sustainability Assessment Should Entail: Towards Modeling the Net Impact on Human Well-Being. J. Ind. Ecol. 21, 1464–1477.

Sen, A., 1985. Well-being, agency and freedom: The Dewey lectures 1984. J. Philos. 82, 169–221.

Sen, A.K., 1994. Well-being, capability and public policy. G. Degli Econ. E Ann. Econ. 333–347.

Smil, V., 2017. Energy and Civilization: A History. MIT Press, Cambridge, US.

Steinberger, J.K., Roberts, J.T., 2010. From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. Ecol. Econ. 70, 425–433.

Tzafalias, M., 2016. Fake lifejackets play a role in drowning of refugees. Bull. World Health Organ. 94, 411–412.

UN, 2015. Transforming our world: The 2030 agenda for sustainable. Resolution adopted by the General Assembly on 25 September 2015.

Ure, A., 1840. A Dictinary of Arts, Manufactures and Mines: : containing a clear exposition of their principles and practice. Longman, Orme, Brown, Green and Longmans, London, UK.

Van Rompay, T.J., De Vries, P.W., Bontekoe, F., Tanja-Dijkstra, K., 2012. Embodied product perception: Effects of verticality cues in advertising and packaging design on consumer impressions and price expectations. Psychol. Mark. 29, 919–928.

Vita, G., Hertwich, E., Stadler, K., Wood, R., 2018. Connecting global emissions to fundamental human needs and their satisfaction. Environ. Res. Lett.

Wallace-Hadrill, A., 1994. Houses and society in Pompeii and Herculaneum. Princeton University Press, New Jersey.

Whiting, K., Carmona, L.G., Sousa, T., 2017. A review of the use of exergy to evaluate the sustainability of fossil fuels and non-fuel mineral depletion. Renew. Sustain. Energy Rev. 76, 202–211.

Whiting, K., Konstantakos, L., Carrasco, A., Carmona, L.G., 2018. Sustainable Development, Wellbeing and Material Consumption: A Stoic Perspective. Sustainability 10, 474.

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., Krausmann, F., 2019. Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and Global Application for 1900–2050. Ecol. Econ. 156, 121–133.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112, 6271–6276.

Appendix 1: Material services categories and description

Material Service	Service Description	Material flows and stocks	Suggested Units or indicator*
Essential services			
Sustenance	Removal of hunger and thirst	Products that can be consumed for nutritional purposes without immediate risk to a person's health or wellbeing. It also includes kitchen utensils, microwaves, ovens, plates and cutlery etc. In addition, the fuels used to cook prepare (e.g. butane gas, electricity etc). It also includes those materials required to provide access to drinking water.	kcal kJ kg Shannon Entropy Modified Functional Attribute
Health Protection and Restoration	The non-nutritional reinstating or enhancing of wellness/health.	It includes prescriptive measures such as pills, cough syrups, lotions, nasal sprays, vitamins and minerals etc. It does not include soaps, floor disinfectant etc which are covered under "Hygiene and Access to Water". It also extends to walking sticks, wheelchairs, glasses and bandages. It also includes personal protective equipment such as ear protectors, face mask, harnesses etc. Armour used in combat is also included here. Life support machines and x-rays would be accounted for here. Medical tools such as the scalpel and the stereoscope are likewise included.	Number of… Reduction in dB Reduction in days needed to recover Life expectancy increase Quality of Life Inventory
Regulating Services			
Hygiene	The maintenance of hygienic standards at the desired temperature.	This includes include pipes, taps, aqueduct, water fountain. It also includes fuels, thermostat and thermal solar technology. It considers those products used for predominately non-medical purposes such as soaps, shower gel, window cleaner, detergent etc. It also includes the materials used in the broom, mop, bucket, washing machine, dishwasher etc.	m^3 m^3 at 60 ºC kg
Illumination	The artificial support of vision in the absence of sufficient natural light.	It includes all materials used in artificial lighting e.g. candles, light bulbs, lanterns and floodlights. It also includes batteries and associated equipment such as cables, switches. Fires are not included as they predominately provide heating, which is address under "Thermal Comfort".	Lumen-hour Lux Candela per square metre
Packaging and Storage	The preservation and protection of material goods.	Examples include cardboard boxes, plastic food and drink packaging, aluminium cans, liquid nitrogen, etc. Historically it would include amphorae. It also includes the materials employed in buildings that are used to store goods such as warehouses, fridges and freezers. *Please note that the material service unit does not measure for the packaging, but rather pertains to the good being protected (e.g. wine inside the glass bottle, but not the glass bottle itself).*	tonne or m^3 of goods storage
Space Comfort	The physical comfort of a person operating in a given space, and which do not provide heat or cooling as a primary function.	Household and office furniture.	tonne Multifunctionality Modularity
Thermal Comfort	Temperature regulation through space heating or cooling.	Air conditioning units, radiators, the equipment, biomass or fuel used to create and maintain a fire etc. They also account for the equipment required to "house" the fire. It includes the thermal comfort undertaken in vehicles.	m^3 at 20ºC Environmental (comfort) index for temperature and humidity.
Environmental protection and restoration	The protection, maintenance or rejuvenation of land, sea or air quality outside of human dwellings.	Examples include materials used to remediate land, preventing leachate from leaking into aqueducts via geotextile membranes, catalytic converters to reduce excessive air pollutants from entering the atmosphere and wastewater treatment plants and products.	Removed pollutant load (tonne) or reduced concentration (ppm, mg/L)
Interconnection Services			
Communication and Information Storage	That which allows people to communicate information in some documented form (physical or virtual).	Personal stationary, books, computer hardware and software, microphones, internet infrastructures, radio antennae, and communication satellites are all included.	Bytes m^2 hours

Shelter	The sheltering for people or those animals (e.g. pets) that are not reared for food or clothing.	Those materials that constitute finished buildings. They include houses and offices.	m^2 Homelessness per 1000 inhabitants Vacancy rate
Transport	The movement of people, animals or goods.	Includes cars, buses, trams, planes, bicycles, articulated lorries, boats, trains etc. It may also include muscle power (horses, oxen etc). Transport infrastructure such as airports, roads and bicycle lanes.	Passenger-km Tonne-km Average waiting time
Cultural Services**			
Identity	The facilitation of creating and promoting aspects of one's inner being.	This includes and is not restricted to clothing, religious buildings and artisanal tools for artistic forms of creativity.	Likert scale Human freedom index Press freedom index
Leisure	The opportunity for rest and relaxation	Examples include musical instruments, board games, game consoles, balls and bats. It also includes sport stadiums, monuments, etc. Protective equipment used in sport, such as helmets and mouth guards, comes under "Medical Appliances and Health Aids".	Hours Number of users
Security	The physical and emotional integrity of the self or the group.	This includes outdoor fences, military equipment, personal weapons, security cameras.	Reduction in the number of homicides, thefts.
Provisioning services			
Goods and utility production***	The intermediate step between natural resource extraction and goods provision to the end user.	These include the materials involved in the production of iron bars, aluminium sheets, cement etc. They include the iron furnace, the cement mixer etc. They also include energy infrastructure such as electricity pylons, hydropower dams and gas turbines.	tonne kWh Technical properties such as tensile strength (MPa)
Quality Maintenance and Construction Support	The reparation and upgrading of material stock.	It includes construction tools, scaffolding or 'Temporary works' (large, usually steel or timber, structures to support construction that are removed when the actual building/structure is stable).	Extended longevity (e.g. hours, years) Number of uses

*** The exact unit applied will depend on the nature of the material product and its material service category. There is flexibility in unit choice, although any selection made by a practitioner should be justified within the context it is used. The units can be converted into per capita terms or remain in total amount.*

*** Those materials that support non-material benefits as their primary function and which do not also provide shelter or any other material service in their own right. Please note that cultural aspects are fluid and there may be more than one primary reason for being involved in a given activity e.g. a person may play an instrument as a means of being at one with their identity or simply entertainment, or for both reason at the same time.*

**** Goods and utility production as a material service, will often be measured in terms of kg_{sr} (service) relative to kg_{in} (inflow). This is an exception within the general concept, but makes sense given that it is a supporting material services which provides kilograms of material to other industries (e.g. steel bars destined for the construction sector). This material is then placed into the final goods that provide a different service, such as shelter. Please note that other forms of measurements such as average unit life expectancy or tensile strength are units linked to material properties rather than service provision per se.*

Appendix 2: Comparison with other proposed energy/material services categories

Service categories	Material Service (this paper)	Cullen and Allwood (2010)		Baccini and Brunner (2012)		Knoeri et al (2015)		Rao and Min (2018)	
		ES category	Service metric	MS category	Service description	ES/MS category	Service metric	MS category	Service metric
Essential services (Required for vital needs)	Sustenance	Sustenance	Joules food	To nourish	Production and distribution of food (including food conservation and storage) Food consumption (including cooking)	Sustenance	Food conservation: kg of food cooled and frozen Cooking: number of meals, times of hob, oven, microwave, kettle, tap uses	Nutrition: Food and cold storage	Total calories, protein, micronutrients; Fridge (or other technology)
	Health protection and restauration	-	-	-	-	-	-	Health care: Accessible and adequate health care facilities***	Minimum health expenditure per capita
Interconnection services (Large structural services)	Shelter	Structure	Deflection: MPa^2/3m3	To reside and work	Residential units, work and recreation facilities	-	-	Shelter	Solid walls and roof
	Transport	Passenger transport Freight transport	Passenger-km Tonne-km	To transport and communicate	Transport persons and goods (including road construction)	Mobility	Work, business & education trips Shopping, escort & personal trips Leisure trips	Mobility	Access to public transport, or vehicle, if essential Public transport and road infrastructure
	Communication and information storage	Communications	Bytes	To transport and communicate	Transport information (including education)	Communication	Entertainment: hours of use Home computing: hours of use Internet: hours of use Telephone: hours of use	Communication Information access	Phone (1 per adult) Television/internet device ICT infrastructure
Regulating services (Maintaining standards)	Hygiene	Hygiene	Hot water: m3K Mechanical work: Nm	To clean	Hygiene/Cleaning	Hygiene/ cleanliness	Textile cleaning (laundry): number of weekly cycles Personal hygiene: number of showers, baths, sink, & tap uses Food cleaning**: number of dish washing cycles, sink use volume Gardening**: tap uses & water volume	Living conditions: Hygiene Clothing	Minimum, accessible water supply In-house improved toilets Water and sanitation infrastructure Washing machines per 1000 persons

	Thermal comfort	-		-		Thermal comfort	Usable floor area (UFA) at average temperature	Living conditions: Basic comfort (bounded temperature/ humidity) Clothing	Modern heating/cooling equipment Electricity infrastructure Minimum clothing materials
	Illumination	Illumination	lm-s	-	-	Illumination	Lumen perceived by the user (in the lit environment calculated as 1/3 of the emitted source-lumen)	-	-
	Space comfort	-	-	To reside and work	Equipment needed to run home and work facilities.	-	-	Living conditions: Sufficient, safe space	Minimum floor space
	Environmental protection and restoration	-	-	To nourish To clean	Waste disposal Environmental protection (waste treatment and management)	Cleanliness	Human waste disposal: number of toilet flushes	Air quality: Maximum ambient particulate matter (PM2.5)	Clean cook stoves Restricted transport infrastructure
	Packaging and storage	-	-	-	-	-	-	-	-
Cultural services (Nonmaterial benefits)	Identity	-	-	-	-	-	-	Freedom to gather/dissent	Public space, sq. m. per 1000 persons
	Security	-	-	-	-	-	-	-	-
	Leisure							Freedom to gather/dissent	Public space, sq. m. per 1000 persons
Provisioning services (Product outputs)	Goods and utilities production	-	-	-	-	-	-	-	-
	Quality maintenance and construction support	-	-	To clean	Maintain the quality (aesthetics and functioning)	-	-	-	-

ES: Energy service, MS: Material service.

**Food cleaning and gardening was originally allocated to sustenance.

*** Only include the material (non-human) requirement