IMPROVING THE ROBUSTNESS OF SOCIETAL EXERGY ACCOUNTING: FROM PRIMARY ENERGY TO ENERGY SERVICES

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Abstract

Results of useful exergy accounting at the societal (i.e. national or global) level are potentially important for policy purposes, such as the development of energy or GHG emission scenarios, and the determination of the major energy inefficiencies (and thus improvement potentials) within a country. However, useful exergy societal studies commonly differ in their accounting methodology, which affect the results. Such differences include the starting point (primary or final energy), the method used to compute primary exergy, the classes of useful exergy categories considered, the definition of second law efficiencies, the inclusion (or not) of exergy inputs related with non-energy uses, and the inclusion or not of muscle (and human) work. To help bring a more consistent approach to useful exergy accounting at the societal level, we review the methodologies of past studies, highlighting the differences and discussing their advantages and disadvantages in each case. Based on this, we select our preferred options, leading to a proposed common methodology that can be used to build national and international series of useful exergy.

1 Introduction

1.1 From primary energy to useful energy and useful exergy

Modern societies use vast amounts of primary energy in the form of fossil fuels, uranium and renewable energy. Whereas in the past this energy might have been used directly, for example by burning fuels for heat or using wind to provide work, today energy is commonly upgraded into more concentrated and transportable forms through a complex network of conversion process in the energy supply chain. Figure 1 shows these conversion processes, from primary energy (fossil fuels, nuclear, renewables), to final energy (refined fuels and electricity) to useful energy (heat, cooling, mechanical work, light). Useful energy is the useful part of energy that remains at the end the energy supply chain, at the final point of energy use, i.e. when it is exchanged for energy services. It is the energy that people actually engage with everyday: the heat that is delivered from an electric radiator, the mechanical work delivered to the tyres of a car, or the electro-magnetic radiation coming from a light bulb.

The penalty for upgrading the energy quality is a ‘loss’ at each stage of the conversion process device (e.g. electricity engine, motor, light bulb). Useful energy is then delivered into ‘passive systems’ (buildings, cars) where it is mostly lost as unwanted heat, in exchange for energy services such as thermal comfort, illumination and transport (see Cullen and Allwood [1] for more information on passive systems).

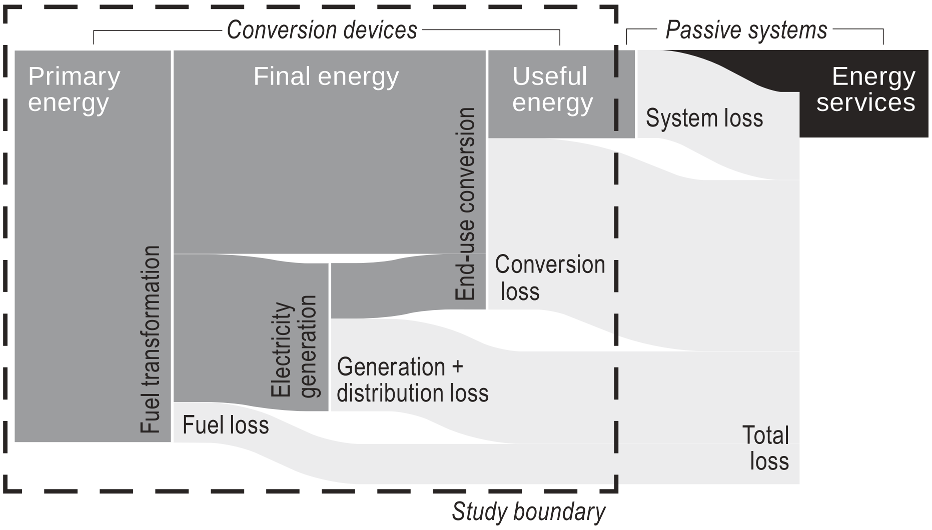

Figure 1: Energy supply chain: from primary energy to final energy services (adapted from Cullen and Allwood in [2]).

The scale and efficiency with which useful energy is delivered in a society is important, as this determines the amount of primary energy required. Using an energy approach, based on the first law of thermodynamics, one can calculate the energy flows quantities, the efficiency of each conversion and energy ‘lost’ (degraded), along the specific energy chains. Yet, this approach ignores the quality of different energy carriers. An exergy approach, based on the second law of thermodynamics, takes into account the potential of each energy carrier to do work and matches it more consistently to the end-use work need to accomplish at task. The maximum exergy efficiency of the process is always 100% and can be used to evaluate the improvement potential of each conversion process and compare between processes. For example, heating a house with an electric radiator has energy efficiency (first law) of 100%, with all electricity being converted to heat, and yet this is an inefficient process, because low temperature heat is a lower quality form of energy compared with electricity. Using a second law approach, the exergy efficiency of the same process is only 10% reflecting the potential to deliver heat more efficiently; for example, more heat per unit electricity could be delivered using a heat pump. Quantifying useful exergy, rather than useful energy, reveals a much richer picture of an energy system.

1.2 The background of societal exergy studies

The concept of useful exergy is not new, having been discussed and debated amongst academics for nearly fifty years, and many attempts have been made to quantify the amount of useful exergy delivered at a sector, national or global level. A good review and synthesis of past useful exergy studies for several societies is provided by Ertesvag [3]

Useful exergy has been referred in past studies using different names. Carnahan et al. in [4] has used the term “useful work” to refer to useful exergy. This term “useful work” was first used by Cook [5] but as a synonymous of useful energy in an assessment of the energy flows in the US for 1970. Reistad [6] uses “useful available energy” to refer to useful exergy while Schaeffer [7] and Rosen et al. [8] and [9] already use the term useful exergy in a national analysis. Afterwards, Ayres et al. [10] return to the use of “useful work” as a synonymous of “useful exergy”.

Useful exergy analyses have been used for different applications within the field of societal exergy analysis. The initial focus of societal exergy analyses has been the analysis of energy systems to show major inefficiencies and improvement potentials. The first accounting of useful exergy at the national scale that the authors know of is the work by Reistad [6] focused on the United States whose aim was to identify the sectors that used more resources in the least efficient way. Cullen and Allwood [11] provide an updated global second law efficiency analysis for 2008 giving an overall 11% efficiency providing for the first time a detailed breakdown of the global exergy losses from energy conversion [2]. In studies [6], [8] and [9] energy is compared with exergy analysis to show that exergy analysis provides a different and better picture on which are the sectors that have the highest potential for improvement. Hammond and Stapleton [12] obtain the exergetic improvement potential for each type of energy end-use in absolute values. Then, Ayres et al. [10] analysing results by end-uses, concluded that in energy systems technical progress has moved from exergy conversion efficiency to end-use efficiency. Warr et al. [13] made the important introduction of muscle work as an end-use associating with it food and feed as a form of final energy.

Extending country level studies to look into the past is also important (e.g., [10], [14], [15] and [16]) to explore long-term energy and societal transitions and the long-term evolution of the energy use performance. For the last century, Warr et al. [17] found that aggregated primary to useful exergy efficiencies increased tremendously stabilizing after the first oil crisis in the early 1970s while long-run primary energy intensities exhibited a secular decline and useful exergy intensities increased in all economies until the oil crisis, and declined thereafter. These findings together imply either that structural changes have occurred in the economy and that the role of energy in terms of boosting economic growth has changed.

These long-run historical societal studies on useful exergy can be used to address deeper debates, for example to explore the importance of exergy, in its useful form, as a source of long-run economic growth ([18], [19], [20]). Warr et al. in [17] claim a unidirectional causality from exergy and useful exergy to GDP in the second half of the 20th century for the USA. Later, Serrenho et al., [14], [15], [16] have explored the long term patterns on the useful exergy economic intensity, concluding that useful exergy intensity year-on-year variation depends only on the variation of high temperature heat and residential uses.

Another current debate concerns the drivers of long-run energy intensity change, specifically the role of technical efficiency as opposed to other types of technological or structural changes in the patterns of production and international trade.

Useful exergy accounting has also been used for future projections of energy use or economic growth. Ayres et al. [21] developed an energy-economic forecast tool - REXES - based on growth accounting methods. Brockway et al. [22] develop a useful exergy based method for projecting China's primary energy demand to 2030, and also test implications of potential future declines in the rate of exergy efficiency improvement. Their analysis suggests that due to structural change and declining efficiency gains, significantly more primary energy will be required by 2030 (versus mainstream projections), in order to deliver the required energetic inputs (useful exergy) needed for the forecast economic growth.

1.3 Rationale and aim for this paper

Whilst societal exergy accounting studies have the common aim to trace the flow of exergy as it moves along the supply chain, their methodological approaches vary greatly. Some typical differences in approach include: the starting point (either primary or final energy); the method used to compute the primary exergy of renewable electricity; the classes of useful exergy categories considered; how second law-efficiency is defined for different conversion processes; the inclusion (or not) of non-energy exergy inputs; how to treat muscle work (human and animal). These and other barriers - such as a lack of understanding and familiarity with 'exergy'

- have frustrated attempts to define a common methodology for useful exergy analysis. The creation of a common accounting system would provide a more consistent basis for research into energy (e.g. prioritising action to improve energy efficiency, assist the development of improved scenarios of future energy and GHG emissions) and economics (e.g. allow the tracking of exergy intensity changes between nations to explain economic growth trends).

This paper sets out to review the different approaches taken for calculating useful exergy and suggest possible options for resolving methodological discrepancies, with the aim to provide understanding and clarity to those undertaking future useful exergy studies. In section 2, we systematize methodological differences in past studies of useful exergy, discussing the advantages and disadvantages of each approach. Based on this, we have a discussion and recommendations for a consistent methodology for future useful exergy studies, in section 3, before concluding the paper.

2 Methodological issues

In this section we explore the methodological differences of the societal useful exergy studies that we have collected (see Table 1).

Year	Author	Country	Time-span
1975	Reistad	USA	1970
1987	Wall	Sweden	1980
1990	Wall	Japan	1985
1992	Rosen	Canada	1986
1992	Schaeffer	Brazil	1987
1994	Wall	Italy	1990
1996	Nakicenovic	World	1990
1997	Rosen	Turkey	1993
2001	Hammond & Strapleton	UK	1965-1995
2003	Ayres	USA	1900-1998
2005	Ertsvag		
2008	Warr	UK	1900-2000
2010	Warr	UK, Austria, Japan and US	1900-2000
2014	Brockway	UK, US	1960-2010
2014	Serrenho	Eu 14	1960-2009
2014	De Stercke	World	1900-2010
2015	Serrenho	Portugal	1860-2009
	Guevara et al.	Mexico	1960-2009

Table 1 – Summary of selected societal useful exergy studies

2.1 Which flows should be considered?

There are two different approaches to societal exergy accounting: the first focusses on resource accounting (e.g. [23], [24] and [25]), and takes into account the exergy in material flows such as iron ore, whilst the second focus on 'energy carriers' for either energy services (e.g. [10], [16] and [26]) or energy efficiency (e.g. [6] and [7]).

The first approach is based on the fact that exergy can be used as a common metric for measuring both energy and material flows, on the same scale. Useful exergy can be extracted as the material returns to the average reference state, normally taken as the concentration in the earth's crust. For example, the process of steel oxidising to iron ore releases energy which could theoretically be recovered as work. The maximum recoverable work for the material is equal to the minimum theoretical energy required for the reduction reaction needed for making steel from iron ore which is approximately 6.7GJ/tonne [27]. This is the energy embedded (not embodied[1]) in the steel. Steel, and other recyclable materials, can also be used as input partially replacing the need for energy, e.g., a high efficiency virgin steel plant uses twice as much input energy in GJ for each tonne of steel produced compared to an electric recycled steel plant.

The distinction between energy resources and other resources is sometimes difficult to make, [25]. For example, metallurgical coke is used in steel-making for three functions: as a heating fuel; as a reducing agent in the iron ore to iron reaction; as a 'feedstock' embedded in the iron and the steel. The small fraction of carbon (3.5–4.5%) embedded in iron is considered a material input, but about half of this is later oxidised to as a fuel to CO2, to meet the final carbon content specification for steel (0.12–2.0%). Using exergy as a common metric for energy and materials allows energy feedstocks (also called non-energy) to be treated more consistently as they are transformed along the supply chain from materials to energy fuels.

Although the first approach has the advantages of treating feedstocks and recycling processes more consistently, it is much more data intensive. Also, it does not provide a good description of energy end-uses. Consider again the case of metallurgical coke used for steel production; if the exergy embedded in the steel is the useful exergy that is accounted for then the useful exergy of the high temperature heat used to produce the steel cannot be considered because a fraction of it is embedded in the steel.

A middle approach would be to take into account energy carriers related to non-energy use (such as oil used to produce asphalt) which currently represent around 5% of normal TPES,

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[1] Embodied energy calculations capture the entire upstream energy input, and allocate this to the material flow, but this bears no resemblance to the physical energy embedded in the material.

but growing as discussed in [28] [16]. This might be a good approach if the focus of the study is forecasting the demand for energy carriers.

2.2 Which are the Input Data Sources?

For studies that use primary or final energy from 1960 onwards one of the best sources of data is the International Energy Agency database, as illustrated by [16], which used this dataset to obtain useful exergy for 15 European countries between 1960 and 2009. This database disaggregates final energy uses per energy carrier into fourteen individual industrial sectors, agriculture, services, transportation and households. To be able to do useful energy/exergy calculations using this dataset, an allocation between values of final energy uses and end-uses is needed (e.g. [28] and [16]). The most problematic energy carrier regarding the specification of end-uses is electricity, because of its ubiquity and the way it has been used has been changing in time.

For long timespans it is much easier to find data on primary energy because with a few exceptions ([29], [15] and [17]), the great majority of the national long-run energy studies focus only on primary energy use ([30]; [31]; [32]; [33]; [34]; [35]; [36]; [37]). Many of these studies also include, besides fossil fuels and primary electricity, complex and laborious historical estimates of traditional forms of energy, such as firewood and peat, direct water and wind and muscle energy[2]. However, to be able to calculate useful exergy from this data, we also need to collect information on their distribution end-uses and historical efficiencies.

Most of the data that would help to allocate energy by end-uses lies buried in national sources such as industrial census, utilities reports, household surveys or transport and agriculture statistics. The time consuming process of collecting these data has so far prevented the development of a comprehensive set of national studies. Nevertheless, there are some international statistics compilations that might be useful in the allocation of end-uses. For example, Mitchell ((see [38]; [39]; [40]; [41]) includes historical output series for almost all countries in the world for some key industries, such as iron and steel, aluminium, mining or chemicals and electricity, transport data such as tonnage of ships and railway freight and numbers for livestock and the labour force. These data, coupled with some knowledge about the evolution of historical energy efficiencies ([42], [29], [43], [34]) could be used imaginatively to construct proxies for missing energy data.

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[2] Estimates for traditional energy carriers are difficult, since many energy sources were not directly recorded. Firewood and peat are usually estimated from household surveys, forest fellings or taxation records. Wind and water power rely on windmill and watermill figures and estimations of their power, time of use and efficiency and animal power relies on livestock numbers and their estimated feed requirements.

An example of how these historical figures can be used is given by, De Sterck [44], who estimated useful energy and useful exergy (from 1900 onwards) for a group of large-sized countries, responsible for 80% of the world's energy consumption. The author used World Primary Energy Statistics on coal, oil and hydro-power ([39]; [41]; [40]; [45]; [46]) and available historical estimations of firewood use ([37]; [47] and [34]) and electricity production to estimate a final aggregate energy series. Due to lack of data on sectoral final energy uses, De Stercke had to estimate the allocation of energy uses to three consumer categories (industry, transportation and other) applying the sectoral proportions by energy carrier reported by the IEA for 1960 to the entire period 1900-59. The final energy data is converted to useful energy by compiling information on first-law efficiencies by sector and energy carriers end-uses and constructing a model of the final to useful energy conversion efficiencies as a function of income per capita. Then, De Stercke computes useful exergy by applying the exergy to energy ratio factors described in Nakicénovic [48] for the whole period. De Sterke's approach is ambitious in scope, but the data limitations over the time period forced the use of proxy data and broad assumptions to complete the study.

2.3 How to quantify primary energy associated with primary electricity?

Studies differ in the way they take into account primary energy associated with renewable and nuclear electricity. An example that illustrates this is the primary energy associated with hydroelectricity which is the coal equivalent for [6] and [10]; the change in kinetic and potential energy of a mass of flowing water for [8], [9] and [17] and the electricity produced for [48], [7] and [12]. The rationale for using the change in kinetic and potential energy of the water as a measure of primary energy is to consider primary energy as it is found in nature. This is easily expanded to other renewable resources and the conversion factors from electricity to primary energy will depend on the technology used.

The rationale that supports the use of primary electricity produced as a measure of primary energy is that renewable electricity is the first form of commercial available energy (electricity for hydro, photovoltaic and wind, heat for geothermal and nuclear electricity). This is called Physical Content Method and is used by the IEA.

The coal equivalent as a measure of primary energy is the fuel that would be needed to produce the same amount of electricity in conventional power plants. This is the method used by the EIA and is called the Partial Substitution Method. Small variations of this method are used by BP and other statistical offices.

Other possibility would be to quantify primary electricity as corresponding to a null amount of primary energy if primary energy is understood as fossil energy.

These methods yield very different results and the choice of method should depend on the aim of the study. To illustrate this imagine a country in two consecutive years that only uses electricity as a final energy carrier and whose energetic sector consists only of coal power plants, dams and wind farms. Consider also that the first year is very rainy with all electricity being produced in dams and windfarms while the following year is very dry with all electricity being produced in windfarms (30%) and the rest in coal power plants. In these consecutive years consider that the total amount of electricity consumed, the economic structure of the country and the GDP had no significant changes. Primary energy computed would depend on the method chosen: it would remain the same with the Partial Substitution Method and it would increase significantly but differently with the Physical Content Method and the other two methods referred. The change in primary energy intensity, which is often used as a measure of efficiency of the economy, computed using the different methods would yield different results.

2.4 Computing efficiencies – the devil is in the detail

Exergy (or second law) efficiency can be defined as [49]:

$$\boldsymbol{\epsilon = \frac{w_{min}}{w_{max}}}$$

Eq. 1

where the numerator represents the minimum amount of work in the output and the denominator represents the theoretical maximum amount of work that could be produced with the energy input .

Table 2 specifies exergy efficiencies for several pairs of energy inputs (source) and end-uses. Energy inputs include work (electricity), fuel (coal, natural gas, oil, biomass among others) and added heat while the end-uses include work (mechanical and muscle work) and added or extracted heat. All these efficiencies depend on first law efficiencies (that depend on technology); for devices that convert one form of mechanical energy to another the exergy efficiency is equal to the first law efficiency while for devices that have heat as an input or output then heat must be downgraded into equivalent units of mechanical work [2].

End Use \ Source		Work W_{in}	Fuel Heat of combustion $\lvert \Delta H \rvert$	Exergy B Heat Q_1 from hot resevoir at T_1
		$W_{max} = W_{in}$	$W_{max} = B$	$W_{max} = Q_1\left(1-\frac{T_0}{T_1}\right)$
Work W_{out}	$W_{min} = W_{out}$	$\epsilon = \eta = \frac{W_{out}}{W_{in}}$	$\epsilon = \frac{W_{out}}{B} \approx \eta$	$\epsilon = \frac{W_{out}}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \frac{\eta}{1-\frac{T_0}{T_1}}$

Heat Q_2 added to warm reservoir at T_2	$W_{min} = Q_2\left(1-\frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{W_{in}}\left(1-\frac{T_0}{T_2}\right) = \eta\left(1-\frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2}{B}\left(1-\frac{T_0}{T_2}\right) \approx \eta\left(1-\frac{T_0}{T_2}\right)$	$\epsilon = \frac{Q_2\left(1-\frac{T_0}{T_2}\right)}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \eta\frac{1-\frac{T_0}{T_2}}{1-\frac{T_0}{T_1}}$
Heat Q_3 extracted from cool reservoir at T_3	$W_{min} = Q_3\left(\frac{T_0}{T_3}-1\right)$	$\epsilon = \frac{Q_3}{W_{in}}\left(\frac{T_0}{T_3}-1\right) = \eta\left(\frac{T_0}{T_3}-1\right)$	$\epsilon = \frac{Q_3}{B}\left(\frac{T_0}{T_3}-1\right) \approx \eta\left(\frac{T_0}{T_3}-1\right)$	$\epsilon = \frac{Q_3\left(\frac{T_0}{T_3}-1\right)}{Q_1\left(1-\frac{T_0}{T_1}\right)} = \eta\frac{\frac{T_0}{T_3}-1}{1-\frac{T_0}{T_1}}$

Table 2 – Adapted from [49] by [15]

Table 2 does not synthesize all second law efficiencies. There are cases where an expression in this table could be used but for some reason (e.g. lack of data or meaningfulness of the boundary on useful exergy), it is not. In these cases a proxy for the exergy efficiency is used and the useful exergy is computed as the product between this proxy and final exergy. The proxy is computed using Eq. 1 where but the numerator is the minimum amount of exergy needed to produce the useful output (e.g. minimum exergy needed to produce 1 tonne of steel). Also, expressions in this table cannot be directly applied to the conversion of electricity into light, sound and information because the useful output cannot or is not typically measured in energy units. For these cases Eq. 1 also applies but the numerator is the minimum amount of exergy needed to produce the output:

$$\boldsymbol{\epsilon = \frac{W_{min}}{W_{max}} = \frac{Electricity_{min,light}}{Electricity_{input}} = \frac{Output/Electricity_{input}}{Output/Electricity_{min,light}} = \frac{\eta}{\eta_{ideal}}}$$

Eq. 2

To compute second law efficiencies at an aggregated level we need to allocate final energy carriers to energy end-uses (see [28] and [16]) for an allocation for the IEA datasets) and to know the first law-efficiencies of the energy transformation devices (dependent on the technology level).

If the second law efficiencies are computed only between the final and useful stages of energy use (e.g [16]) then care as to be taken when comparing the energy carrier (thermo)electricity with other fuels because it has a much lower primary to final efficiency. To deal with this issue [26] consider that for all second law efficiencies the exergy of electricity is the primary exergy and that the conversion has a 40% efficiency.

There are differences in the studies in Table 1 regarding the detail used to compute second law-efficiencies, namely, the level of disaggregation in the allocation of energy-carriers to end-uses. However, most of these studies do not specify the process and the data used to estimate second law efficiencies with enough detail so that readers can have an informed opinion on the accuracy of the estimations.

Reistad [6] provides first and second law efficiencies for energy conversion devices; for some electrical devices the author provides two values of second law efficiencies where the second takes into account the inefficiencies in electrical generation and transmission losses. The author uses aggregated 2nd law efficiencies for each sector that depend on the relative weight of each energy vector (fuel and electricity) and the respective transformation devices and that were estimated in a very pragmatic manner. Rosen [8] and Rosen and Dincer [9] follow generally the same approach but estimate a mean 2nd law efficiency for the industry sector by considering the 5 most important industries and the uses of heating (at different temperatures for electricity and fuels) and mechanical drive. Hammond and Stapleton [12] also use aggregated 2nd law efficiencies for each sector that depend on the relative weight of each energy vector (fuel or electricity) and the respective uses. Nakićenović et al. [48] provide first and second law efficiencies for 1995 in pairs of energy vector (coal, renewable fuel, oil, gas, heat and electricity) and respective uses (residential/commercial: cooking, washer and dishwasher, space heating and TV among others; industry: L&M temperature, HHT, mechanical drive and other uses; Transport: bus, car, airplanes among others and shares of different energy carriers for different energy services). Cullen and Allwood update their efficiencies to the year 2005 using IEA trend data for energy intensity in each sector.

Wall [24] [23] and [25] computes aggregated second law efficiencies for Wood, Pulp & Paper, Food, Lighting, Mechanical Work, Ores & Steel, Chemicals (oil and oil product), Transports, Heating and Space Heating to discuss the efficiency of natural resources use. Wall [24] [23] and [25] use a second law efficiency for fuel conversion to mechanical work in transport of 10%. Probably this author also considers second law efficiencies for heating at low temperature, at high temperature and for electricity conversion for lighting and mechanical work but these efficiency values are not specified in the papers.

2.5 Computing efficiencies - how to define the boundary between useful exergy and energy services?

Much confusion has arisen in useful exergy studies over definition of useful exergy, and in particular, at what exact point useful exergy should be calculated. The 'efficiency' of many end-use devices are commonly measured in hybrid units (called intensities) where the device output is measured in non-energy units. For example, vehicles are compared on a mile-per-gallon basis, building heat on a kilowatt-hour per square metre, and light bulbs as lumens per watt. In each case the units of miles, square metres and lumens are not measures of energy or exergy, so extend beyond the useful exergy boundary.

Cullen and Allwood in [2] provided clarity on boundary for useful exergy by dividing the energy supply chain into conversion devices and passive systems, as seen in Figure 1. Conversion devices are defined as technical devices that 'transform or upgrade energy into more useful forms' and include oil refineries, electricity generation facilities, engines, motors and light bulbs. The energy supply chain consists of many conversion devices linked together in chains, which transform primary exergy through to the useful exergy forms of heat, cooling, motion, light and sound. Passive systems, are the last technical component at end of each energy chain, and act as a reservoir for useful exergy. For example, heat and light are delivered into buildings or kinetic energy into vehicles. Useful exergy is eventually 'lost' or dissipated from the passive system (as unwanted heat) in exchange for a final energy service, such as thermal comfort, illumination or transport (which cannot be measured in energy or exergy units). The term passive is used because the loss of exergy is not desired, or actively pursued; instead good energy management seeks to hold or trap the useful energy for longer periods of time, for example by insulating buildings or reducing drag forces on vehicles.

Defining the boundary between conversion devices and passive system, is not always easy, and careful attention is required to maintain a consistent approach. The key skill is to isolate the last conversion point in the energy chain, just before the remaining useful exergy is all dissipated as unwanted heat. Discrepancies between approaches often surface where no data is available to quantify the useful exergy at the correct boundary point. In these cases, hybrid proxies are used to compute second law efficiencies that are then used to compute useful exergy. Care must be taken when using such approaches, as the real changes in the final to useful conversion efficiency can be masked by efficiency changes in the passive system (e.g. the mass or shape of the vehicle when using miles-per-gallon as a proxy for transport efficiency). Similarly, for refrigeration, cooling is delivered into an insulated 'cold-box', and for lighting, electro-magnetic radiation is delivered into an illuminated space, where good reflectors and light colour surfaces help 'trap' the light for longer.

Additionally, there are cases where there is a two stage final conversion, for example, a residential diesel-fuelled generator where diesel is converted to electricity and then electricity is converted to an end-use, e.g., light. In these cases, the final to useful aggregated efficiency should consider the final energy carrier (diesel) and the end-use (light).

Some studies ([10], [28], [13]) have recently proposed that useful exergy for the industrial sector should be measured not as the delivered heat, motion and light in the factory, but instead the much smaller amount of embedded exergy in the material, which the consumer uses. There is debate over whether this approach measures the 'final energy service' or some 'material service' alternative, and the additional data required to calculate the embedded exergy in complex multi-material products in not trivial. This particular area of research requires further methodological development and exploration if it is to become standard for exergy accounting.

2.6 Transport efficiencies

There are differences among the different studies regarding the way second law efficiencies are computed for transport. For transport (mechanical work) the second law efficiencies are equal to first law efficiencies independently of the energy carrier (see Table 2).

For vehicles, energy is transformed along the energy chain, from crude oil, to refined fuel, to heat and pressure in the engine, to mechanical rotational work, through the gearbox and driveshaft to the tyres. Losses occur at each stage of conversion stage, but it is at the tyres (where 'rubber meets the road') that the final loss of exergy occurs, and where we define the boundary for useful exergy. Here the thrust force delivered to the vehicle (passive system) is resisted by rolling and aerodynamic drag forces, and dissipated a low-grade heat. This approach serves us well when considering the provision of the final transport energy service, however it fails to account for other energy services provided by the vehicle such as cooling from the air-conditioning system or music from the radio. Although, if warranted, that useful exergy could also be calculated for these secondary services.

The standard approach, provided by Carnahan et al [4], uses compression ratios and other loss factors. This approach that has been used by [11] and [16] is consistent with our definition of useful exergy boundary efficiencies although the loss factors have not been updated for 40 years.

Other studies [10] and [26] used a different approach, these authors used data on mpg (fuel economy) vs. road transport efficiency to estimate a linear relationship, obtaining that efficiency is mpg x 0.52. Brockway et al. [28] took a similar but asymptotic approach - since mpg x 0.52 would give exergy efficiency above first law device (engine) efficiency at high (future) fuel economies. Actually, the values obtained by [28] for the historical analyses 1960-2010 had little real difference from the linear approach of [10] and [26].

The approach of using mpg as a proxy for exergy efficiency can be justified due to lack of recent data on loss factors used by the standard approach but it does not differentiate between improvements in the conversion device and the passive system.

2.7 Heating Efficiencies

There are also differences regarding the methodology used to compute second law efficiencies for heating processes, i.e., whenever heat is provided from electricity, a fuel combustion process, or a CHP facility. The standard approach ([6], [48], [8], [9] and [16]) computes second law efficiencies as a function of first law efficiencies and the Carnot ratio that depends on the environment reference temperature (T_0) and the temperature at which heat delivery occurs (T_2) (see Table 2). Results obtained improve if they take into account different temperatures for different industries as shown by [50] in a sensitivity analysis.

A different approach ([10], [26] and [28]) considers that second law efficiencies for heat purposes (at least HTH) are defined as the ratio between current exergy use and minimum exergy use needed to produce a certain product. For example second law efficiency in industries, e.g., nitrogen fixation, is defined as the ratio between minimum exergy and exergy used to produce 1 ton of product (this does not separate between the different energy carriers used in the same process for heat purposes). For high temperature heat [10] and [26] use the steel industry as a model for efficiency gains while [28] takes the 2 largest heat consuming industries e.g. steel and ammonia and then apply their weighted efficiency as a proxy for all industry.

This method of computing second law efficiencies of heating processes is extended to low temperature heat in houses taking into account insulation to compute the minimum exergy by Warr et al. [26]. However, according to our discussion on the boundary of useful exergy, in buildings the useful exergy is the heat delivered into some confined space (passive system), which is typically insulated to trap the heat for longer and thus second law efficiencies up to the useful energy boundary should not take into account insulation.

The standard method of computing second law efficiencies is more consistent with the way of obtaining second law efficiencies for other uses and with our definition for the boundary on useful exergy (see section 2.5). The other methods referred also have a consistency problem because it is difficult to extend them for other heat uses and the choice of method to compute heating efficiencies should at least be extendable for all sub-sectors of industry, e.g. agriculture, food, light manufacturing etc.

2.8 Muscle work

Manual labour and draught animals have become almost irrelevant as sources of useful exergy in post-industrialized societies, but they continue to have considerable importance in most developing countries and agricultural communities.

For draught animals, a measure of their primary energy or exergy requirements can be extracted from the gross calorific value[3] of their feed intake ([15]). Historical values for primary energy are usually calculated from recommended digestible feed intake, draught animals' headcount and from quantitative and qualitative information on average weight and working effort[4]. These figures can then be used to get approximations of gross exergy requirements.

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[3] The **gross energy (GE)** value of a given feed is the amount of **heat** released when it is burned in a bomb calorimeter and represents the maximum available work of the feed. Serrenho et al. [15], using data from [64], calculated that gross energy is 1.54 times higher than metabolized energy. This relation can change, depending on the composition of the feed. For example, hay has a lower digestible content than grain.

[4] See Kander and Warde ([65]) and Smil ([52]).

To derive primary exergy to useful exergy efficiencies, we need information on the typical power and utilization time of working animals. According to Stout [51] and Smil [52], draught animals can produce a power output of 0.3-0.8 KW, depending on their type and weight. Hours of use depend on the region and historical time-period, but it is safe to assume that they cannot sustain this level of power for more than 4 or 5 hours per day over the year [53][5]. The range for the efficiencies of draught animals given in historical studies varies between 4 and 13% ([42]; [14])[6].

Draught animals exist almost solely to provide energy services[7]. Therefore, it is widely accepted that their total intake of feed should be accounted for as primary energy, whether it's used for work or for just keeping the animal alive at all times. There is greater controversy about the inclusion of food for humans as an input to physical work, and a variety of approaches have been proposed in the literature ([54]). Some have suggested including as an energy input only the increase in food intake that occurs due to working activity, that is, excluding energy requirements for body survival and for small activities such as hygiene, eating and standing ([52]) or even leisure activities. Others have suggested considering the proportion of food that is consumed by the organism, both for doing work and staying alive, but only during working hours (see [55]). These two approaches argue that it's important to distinguish the food needed for doing work from the caloric intake that is used for other types of needs. Finally, many studies include all the consumed food as primary energy, either considering only the working population ([56]) or the whole population ([34]). They argue that even if not all the food is consumed while working, it is indispensable for the labour force to receive nutrition to be kept alive between working hours; and that even if a share of the population is not economically active, they occupy positions in society that are necessary for it to function ([57]). In terms of work output, the power of physical human labour is estimated at 75 W for the entire working day ([51]). The calculated efficiencies will, of course, depend on which approach is adopted[8].

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[5] Manual work usually did not exceed 2000 hours/per capita/year in traditional agriculture and draught animals put in even less hours. For example, a study of Danish agriculture indicates that horses were used 1220 h per year on average in 1938, see Schroll [66].

[6] For illustration purposes, we describe a typical way of calculating efficiencies: A 500 kg horse working with average effort needs about 35 GJ of digestible feed per year or about 54 GJ gross energy. Assuming a power of 0.75 KW and 1500 hours of work per year gives a work output of 3.78 GJ and an overall efficiency of 7%.

[7] Some draught animals such as cows provide also dairy products, but adjustments on feed intake can be made to take that into account.

2.9 The need for cooling and which end-uses should be considered

Reistad [6] and Rosen [8] and Rosen and Dincer [9] compute aggregated first and second law efficiencies for sectors including the utility sector but do not analyse results by end-uses. End-uses (and only heating and mechanical power) are only referred to compute mean efficiencies. Hammond and Stapleton [12] compute second law efficiencies for pairs sectors-end use considering for the domestic and service sectors the uses of space heating, water heating, lights and appliances and cooking; for the industry sector the uses of low, medium and high temperature heat and mechanical drives obtaining the exergetic improvement potential for each type of end-use in absolute values. Ayres et al. [10] analyse results by end-uses considering mechanical work, HTH, MTH and LTH while Warr et al. [13] analyse results by end-uses considering heat, light, mechanical work, muscle work (from animals and humans) and electricity introducing for the first time the muscle work as an end-use and associated with it food and feed as a form of final energy. This end-use (or the food/feed) is especially important relatively to other end-uses (or final energy forms) in the past. Serrenho et al. [14], [15] and [16] and Brockway et al. [28] have also used muscle work as an end-use. Cooling was introduced by Brockway et al. [28] to improve the overall second law efficiency of mechanical work and by Palma [50] as a differentiated end-use. Palma [50] showed that the introduction of cooling had a relevant impact on overall second law efficiencies because its efficiency is low.

3 Results and discussion

The focus of the study and the availability of data should define the flows that are taken into account. If the focus is (1) on forecasting energy needed for energy services or (2) the efficiency in energy use or (3) the links between economic growth and energy use, then only the energy carriers that are used to provide an energy service should be considered. If the focus is on forecasting the amount of final or primary energy carriers then energy carriers related to non-energy uses should also be taken into account. If the focus of the study is on resource accounting then materials flows other than energy carriers should also be taken into account.

The method chosen to compute primary energy associated with primary electricity should depend on the aim of the study and the importance of the energetic sector for that purpose. For example, if the focus is on the efficiency of energy use in the economy, measured with the ratio of primary energy to GDP, then the Partial Substitution Method makes more sense because it ignores changes in the energetic system. If the focus is on the sustainability of the energy sector or on the transition from fossil to renewable energies, then the Partial Substitution method is not a good option. The Physical Content method is a better option in these cases but it taxes geothermal electricity and biomass derived electricity more than fossil energies because they have lower efficiencies. A detailed discussion on these methods that could help in choosing the best option is presented in [58], [59] and [60].

Computation of second-law efficiencies has issues regarding accuracy and consistency. The main factors controlling the accuracy of the estimates of second law-efficiencies are the existence and quality of data on: the allocation of energy carriers to sectors and then to end-uses, the time-dependent allocation of the pair electricity-sector to end-uses, time-dependent first-law efficiencies and process temperatures for different industries. From 1960 onwards one of the best sources of data is the International Energy Agency databases that can be used with the allocation provided by [28] or [16]. Also, second-law efficiencies are not consistent among different uses because some useful outputs such as light, computers and TV's are not typically measured in energy units. For the sake of consistency and accuracy, second law efficiencies should take into account intended secondary exergy services associated such as the air conditioning in a car.

Intimately related with the computation of second law efficiencies is the definition of the boundary for useful exergy that separates the transformations from final to useful exergy and useful exergy to energy services. Clarity on this issue is provided by the distinction between conversion devices (final to useful) and passive systems (useful to services) made by Cullen and Alwood, [2]. The definition of this boundary is important to assess whether overall increases in efficiency from final energy to energy services (litres per passenger.km) are due to increases in the thermodynamic efficiency of conversion devices (e.g. more efficient engines) or in the passive systems (e.g. better aerodynamics and less rolling resistance).

Examples that illustrate an increased energy service despite second law energy efficiencies in converting final to useful exergy are: the same amount of heat at low temperature is more effective in a well-insulated house (higher indoor T) and the same amount of fuel in a light car is more effective (more km). This increased efficiency appears in the step of converting useful exergy to energy services and that should be clear.

Categories used for useful exergy used in exergy studies include: mechanical work, heating (HTH, MTH and LTH), light, cooling, other electric uses and muscle work. This choice should depend on the aim of the study and on the availability of data and a decision must be made about whether or not to include animal and/or human muscle work and whether or not to include cooling. It might be considered controversial to include physical human labour as a measure of useful exergy if we want to econometrically test the importance of exergy for growth, since standard economic models already account for labour in different ways. On the other hand, if the study aims at understanding long-run transitions in energy use or the importance of energy in agriculture, then the energy consumed and provided by working animals and humans should be accounted for. Regarding cooling, its impact might become more and more important as countries that need more cooling become richer and the decision on whether to isolate cooling should depend on the difficulties of gathering information regarding this energy use.

4 Conclusions

Researchers that are going to do societal exergy studies should be careful to specify and justify the methodological options chosen. Special care should be given to the specification of the data used to compute second law efficiencies. This would make the studies more comparable and easier to use for other purposes. The methodological options taken have an impact on the results and policymakers should be aware of those differences.

To improve societal exergy studies that include the useful level of energy use there is the need to collect and systematize data regarding efficiencies and the allocation of final energy carriers to end-uses at the national level. The lack of this data has prevented national statistical offices and international organizations from producing consistent annual datasets for useful exergy. The creation of such datasets, spanning several decades, would provide a more consistent basis for prioritising action to improve energy efficiency, assist the development of improved scenarios of future energy and GHG emissions, and allow the tracking of exergy intensity changes between nations to explain economic growth trends.

Acknowledgements

We gratefully acknowledge the support of Engineering and Physical Sciences Research Council (EPSRC) and Arup for contributing to the PhD CASE (Collaborative Award in Science and Engineering) scholarship of Paul Brockway and the Portuguese Science Foundation for the sabbatical scholarships provided to Tiago Domingos and Tânia Sousa. The support of the Economic and Social Research Council (ESRC) is also gratefully acknowledged. Sofia Henriques acknowledges the generous support of Jan Wallanders and Tom Hedelius foundation and Tore Brodwaldhs foundation. The work contributes to the programme of the ESRC Centre for Climate Change Economics and Policy. We gratefully acknowledge the discussions and comments that we had with Julia Steinberger, Steve Sorrel, Peter Taylor, Timothy Foxon and Jack Miller.

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