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An estimation of different minimum exergy return ratios required for society

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Abstract

This article shows that several minimum exergy return ratios (ExRRs) can be computed in relation to different aggregate exergy conversion efficiencies. Through the exploitation of available data on exergy conversion efficiency for several countries, our results suggest that as technical change enhances the conversion efficiency of primary-to-final and final-to-useful exergy processes, the minimum ExRR required for society decreases, irrespective of the boundary under consideration. Therefore, the gains in exergy conversion efficiency that mostly occurred between the 1940s and the 1970s have compensated for the concurrent decrease of exergy surpluses of the fossil energy system. However, while the minimum ExRRs required for modern societies have been quite stable, actual ExRRs prevailing for energy systems have continue to decrease. Effectively the increased difficulty in improving exergy conversion efficiency since the mid-1970s has resulted in a tightening exergy constraint on economic growth; this could partially explain the global economic slowdown of the last forty years. Further work is needed to estimate actual exergy return ratios that prevailed in the past decades and compare their distance relatively to the minimum levels estimated in the present article, and hence have a more precise idea of the exergy constraint's magnitude acting on economic growth.

Keywords: Minimum ERR; Exergy; Thermodynamic efficiency; Growth constraint.

JEL Classification: N50, Q43, Q55, Q57.

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1 Introduction

The concept of energy-return-on-energy-investment (EROEI, or more simply EROI) of human societies has been the subject of much research since its formulation in the 1970s (Brockway et al., 2018; Court and Fizaine, 2017; Hall, 2017; King and van den Bergh, 2018; Masnadi et al., 2018). The EROI is the ratio of the quantity of energy delivered by a given process to the quantity of energy consumed in that same process. Hence, the EROI is a measure of the accessibility of a resource; the higher the EROI, the greater the amount of net energy delivered to society that can support tasks other than energy extraction necessary for economic growth (Hall et al., 2014). Several scholars, such as King (2014) and Brandt et al. (2013), point out that this definition is rather 'loose' and that a clear distinction should rather be made between gross energy return ratio (GERR, i.e., the gross energy output divided by the energy consumed due to supply of final invested energy) and net energy return ratios (NERR, i.e., the energy that only goes to final consumption divided by the energy consumed due to supply of final invested energy).[1] For the remainder of this article, we avoid the term EROI, and use ERR only when the distinction between GERR and NERR is either unnecessary or unclear when citing other studies that do not precise this distinction.

1.1 What is the minimum energy return ratio that a society must have?

A literature review reveals only four studies that discuss potential values for minimum societal ERR. Hall et al. (2009) offer a technical minimum ERR of 3 for oil at the well-head. They also theorised that a higher value of 5 would be necessary to just support our current complex societies, and that a minimum ERR around 12–15 for primary energy is likely necessary to sustain modern forms of culture and leisure. Weißbach et al. (2013) give a minimum ERR of 7 required for OECD countries although they did not clearly explain the underlying calculation. The study of Lambert et al. (2014), based on nonlinear correlations between ERR and the Human Development Index (HDI) in cross sectional data, claim that contemporary human societies require a societal minimum ERR of 15 for primary energy in order to reach an HDI of at least 0.7. Finally, Fizaine and Court (2016) used an indirect approach based on energy expenditures to show that the USA required its primary energy to be supplied with a (yearly) GERR above 11 to have a positive economic growth. This econometric result indicates that a GERR of around 12–15 for primary energy seems necessary to support a growing modern economy.

As we can see, all these studies concern primary energy, and there is seemingly no study that seeks to estimate the minimum return ratio of final energy required for society. However, two recent articles assessing the return ratio of final energy at the point of use for two different countries can provide some answers on this subject. Feng et al. (2018) estimate that the NERR of China's final energy production sector declined from 11 to 5.5 between 1987 and 2012. At the global level, Brockway et al. (2018) estimate that between 1995 and 2011, the NERR of fossil fuels at the final stage has slightly declined from 6 to 5.4. According to these results, it may be speculated that a minimum ERR between approximately 4 and 5 is required for the final energy supply of industrialized societies.

1.2 A link between the minimum energy return ratio of society and its energy conversion efficiency

Debeir et al. (2013) describe a simple link between the minimum ERR required for society and its aggre-

[1] Moreover, King et al. (2015) show that another crucial distinction should be made between the 'yearly ERR' of an energy system (i.e., annual energy production divided by annual invested energy) and the 'full ERR' of the entire life cycle of an energy system (i.e., cumulated energy production divided by total life cycle invested energy). Understandably, the 'full ERR' represents the entire life cycle integral of all 'yearly ERRs' for a given energy system.These controversies surrounding ERR calculations are the subject of other articles (Arvesen and Hertwich, 2015; Brandt et al., 2013; King, 2014; Modahl et al., 2013; Murphy et al., 2011; Zhang and Colosi, 2013).

gate energy conversion efficiency.

> "In terms of energy, society 'invests' a certain energy quantity and 'harvests' a given food-energy quantity, obviously greater than the initially invested energy. Hence, the ratio
>
> $$P = \frac{Harvested\ energy}{Invested\ energy},$$
>
> measures the energy productivity of society. For its part, the population returns to the biosphere a fraction of this consumed food-energy in the form of work. The efficiency of such a conversion is measured by the following ratio:
>
> $$E = \frac{Returned\ energy}{Consumed\ energy}$$
>
> [...] Every society must comply with the following: the energy conversion efficiency must be at least the inverse of the energy productivity of the food production system. If we take the cycle: subsistence $\rightarrow$ human energy $\rightarrow$ subsistence, and with the example of a society in which the conversion efficiency would be $E = 5/100$, meaning that, when this society has 100 kilocalories of subsistence, it cannot re-invest more than 5 kilocalories in its predatory or productive activities. To enable this society to at least simply reproduce, the energetic productivity P must be greater than $5/100$, otherwise the energy potentially re-invested in the next cycle will not be capable of supplying enough subsistence for the needs of society. This reproduction condition is expressed by the following general inequality:
>
> $$P > \frac{1}{E}."$$

One might argue for the unclear definition of the different concepts used in the above quotation of Debeir et al. (2013, pp. 51–52). Indeed, as shown in Figure 1, 'harvested' and 'consumed' energy correspond to final food energy generated by the photosynthetic conversion of primary solar energy; whereas 'invested' and 'returned' energy correspond to useful muscle energy resulting from the human body conversion of final food energy.[2] So, to be clear, the 'energy productivity P', described by Debeir et al. (2013, pp. 51–52) in the context of an agrarian society, corresponds to the gross quantity of final food energy that society is able to generate per unit of invested useful muscle energy; in other words, it corresponds to the $GERR_{F/U} = \frac{F_{tot}}{U_{in}}$ of society.[3] Moreover, in the context of agrarian societies, the energy 'conversion efficiency E' of Debeir et al. (2013, pp. 51–52) corresponds to the aggregate efficiency of humans and draft animals to convert final food energy into muscle useful work, i.e., $E = \frac{U_{tot}}{F_{tot}} = \frac{U_{else}+U_{in}}{F_{tot}}$. By convention (see Appendix B), this final-to-useful energy conversion efficiency is noted η_2, while, as shown in Figure 1, η_1 would designate the primary-to-final efficiency of the sun-to-food energy conversion process. Finally, one can reformulate the last relation of the above quotation of Debeir et al. (2013, pp. 51–52) as follows: *the minimum gross energy return ratio of an agrarian society is equal to the inverse of its final-to-useful energy conversion efficiency, i.e.,* $GERR_{min,F/U} \equiv \left(\frac{F_{tot}}{U_{in}}\right)_{min} = \frac{1}{\eta_2}$.

[2]In the quotation of Debeir et al. (2013, pp. 51–52), it is unclear if the quantity of 'consumed' food energy is lower than the 'harvested' quantity because of losses during food processing. In the absence of greater precision, we assume in Figure 1 that these processing losses are not taken into account and that, consequently, harvested and consumed food quantities are strictly equal.

[3]For the purpose of consistency, it is noted that the useful energy invested in food production, U_{in}, includes not only to the muscle work directly exerted to complete agricultural duties, but also the muscle energy used to produce the different tools and physical assets necessary for food production. In other words, U_{in} is the sum of the direct and indirectly embodied energy investments in food production.

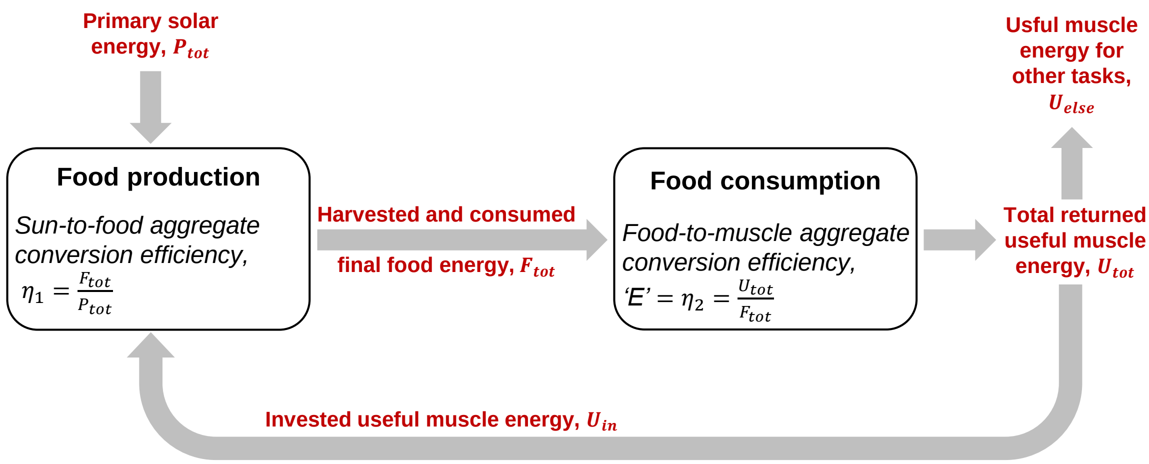

Figure 1: Representation of the agrarian society described by Debeir et al. (2013, pp. 51–52). For graphical convenience, losses at each stage are not represented.

1.3 Goal and organization of the paper

It appears that the minimum ERR required for society has been neither defined nor estimated using Debeir et al.'s (2013, pp. 51–52) analysis. At first, this might be surprising given the apparent simplicity of this relation. But as always, the devil is in the details, and distinguishing conversion efficiency at different stages (primary, final, and useful) mean that different minimum ERR required for society can be defined according to the system boundary under consideration. Moreover, the *exergy* concept has received recent attention because it is a more appropriate concept than energy for assessing the biophysical dynamics of society (see Appendix A) (Ayres, 1998; Miller et al., 2016; Serrenho et al., 2016). Accordingly, in exergy terms, primary-to-final, final-to-useful, and primary-to-useful conversion efficiency are respectively designated by ε_1, ε_2, and ε (see Appendix B). Taking stock of this literature, the goal of the present paper is to reformulate the intuition of Debeir et al. (2013, pp. 51–52) in a more pragmatic way.

Section 2 shows that several minimum exergy return ratios (ExRR) can be computed in relation to different exergy conversion efficiencies. Data availability presented at the end of this methodological section restrict the possibilities of estimations for the different minimum exergy returns ratios. Nevertheless, Section 3 presents and discusses the long-run estimates of the minimum exergy return ratios of the European Union(EU)-15 countries, the USA, Japan and the world. Finally, a summary of the contributions of this article is given in Section 4, along with recommendations for future research.

2 Methods

2.1 Analytical approach

Taking stock of the literature related to exergy (see Appendix A and B), it is possible to systematize the analysis developed by Debeir et al. (2013, pp. 51–52) for the special case of agrarian societies. Figure 2 is a graphical generalisation of Figure 1 in exergy terms.

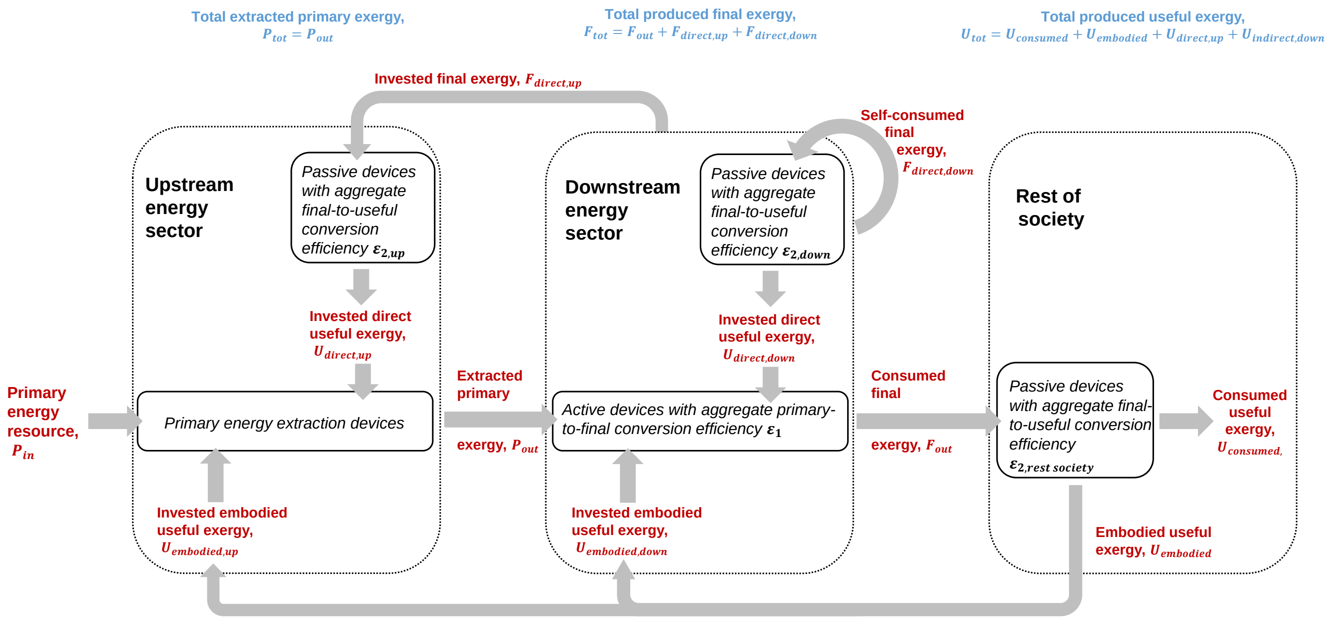

Figure 2: Exergy flows between the (upstream and dowstream) energy sector and the rest of society. For graphical convenience, losses at each stage are not represented, nor is the primary energy self-consumed by the upstream sector.

Using Figure 2, one can theoretically compute three minimum gross exergy return ratios, $GExRR_{min}$, required for society, namely

$$GExRR_{min,P/F} = \left(\frac{P_{tot}}{F_{direct,up}}\right)_{min} = \frac{1}{\varepsilon_1}, \tag{1}$$

$$GExRR_{min,F/U} = \left(\frac{F_{tot}}{U_{direct,up} + U_{embodied,up} + U_{direct,down} + U_{embodied,down}}\right)_{min} = \frac{1}{\varepsilon_2}, \tag{2}$$

$$GExRR_{min,P/U} = \left(\frac{P_{tot}}{U_{direct,up} + U_{embodied,up} + U_{direct,down} + U_{embodied,down}}\right)_{min} = \frac{1}{\varepsilon}. \tag{3}$$

Where $GExRR_{min,P/F}$ gives the minimum number of primary exergy that the upstream energy sector must generate per unit of invested (direct) final exergy, whereas $GExRR_{min,F/U}$ gives the minimum number of final exergy that the energy sector must return per unit of direct invested (direct+embodied) useful exergy, and $GExRRR_{min,P/U}$ gives the minimum number of primary exergy that the upstream energy sector must yield per unit of invested (direct+embodied) useful exergy.

With the definition of these various minimum GExRR required for society, two elements are worth exploring. Firstly, what has been commonly called the minimum EROI required for society at the primary level in previous studies (Fizaine and Court, 2016; Hall et al., 2009; Lambert et al., 2014; Weißbach et al., 2013), corresponds to an ERR in which indirect embodied energy invested in the form of capital is accounted for. This is not the case with the $GERR_{min,P/F} = 1/\varepsilon_1$ of Eq. (1). Accordingly, the $GERR_{min,P/F} = 1/\varepsilon_1$ is more likely to be higher than other estimates of minimum ERR found in the literature. Secondly, with the present methodology, it is not possible to calculate a minimum ERR at the final output level that would correspond to the boundary of Feng et al. and Brockway et al. (2018) analyses. Both, Feng et al. and Brockway et al. (2018) estimated final energy return per final energy input unit, whereas in Eq. (2), the exergy output is also at the final stage but the exergy inputs at the denominator correspond to useful exergy.

2.2 Data

Several time series shown in Figure 3 have been computed for exergy conversion efficiency.[4] Serrenho et al. (2014) estimate the aggregate final-to-useful exergy efficiency (ε_2) of the European Union(EU)–15 countries from 1960 to 2009, and these authors have extended this analysis up to 1856 for Portugal (Serrenho et al., 2016).

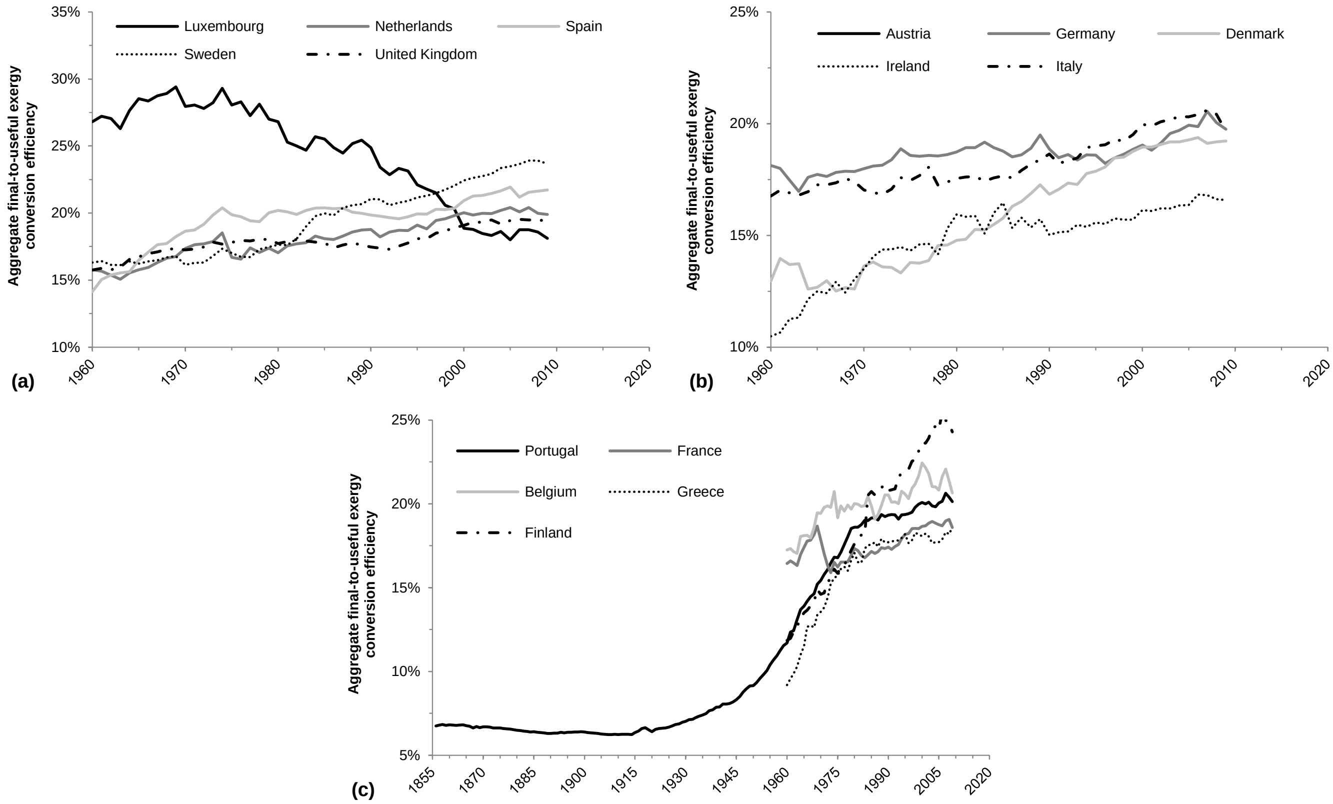

Figure 3: Aggregate final-to-useful exergy conversion efficiency (ε_2) of the EU-15 countries (1856–2009 for Portugal, 1960–2009 for all others). Source: Serrenho et al. (2014), Serrenho et al. (2016).

In addition, Warr et al. (2010) estimated of the aggregate primary-to-useful exergy conversion efficiency (ε) for the USA, UK, Austria, and Japan from 1900 to 2000, with updated values proposed for Austria from 1900 to 2012 in Eisenmenger et al. (2017). Brockway et al. (2014) also proposed updated values for the US and UK primary-to-useful exergy conversion efficiency (ε) from 1960 to 2010. Despite several differences in methodologies,[5] we used Brockway et al. (2014)'s trends to extend Warr et al. (2010)'s data for the USA and UK from 2000 to 2010. De Stercke (2014) performed the same assessment of the aggregate primary-to-useful exergy conversion efficiency (ε) for the world economy from 1900 to 2014 (Figure 4).[6]

[4]On the contrary, as far as we know, even though energy is a more familiar concept than exergy, time series have never been estimated for energy conversion efficiency.

[5]Differences correspond to (i) the fact that Brockway et al. (2014) only take into account the above-basal-need food intake needed for heavy labor, while Warr et al. (2010) consider the entire food intake of people; (ii) a higher assumption for food conversion efficiency into muscle work in Brockway et al. (2014) compared to Warr et al. (2010); (iii) a higher mechanical drive efficiency in Brockway et al. (2014) compared to that from Warr et al. (2010) (e.g. 11% versus 8% respectively in 1960); and (iv) a higher heat efficiency in Brockway et al. (2014) as more heat is allocated to Low Temperature Heat end-use in Warr et al. (2010)'s analysis (e.g. 12% versus 7% respectively in 1960).

[6]An estimate of the primary-to-useful exergy conversion efficiency (ε) of China from 1971 to 2010 is performed in Brockway

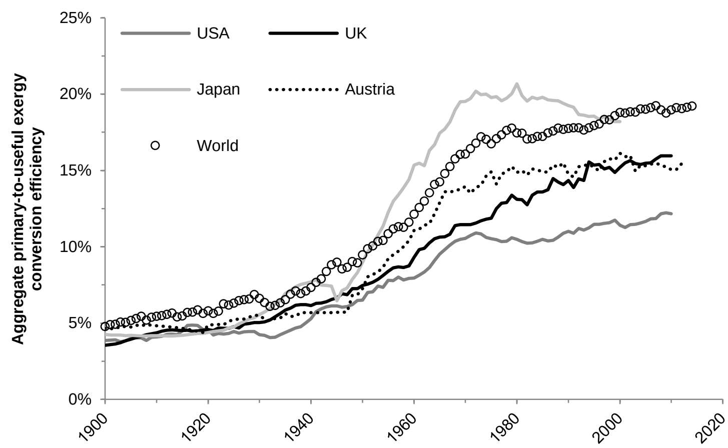

Figure 4: Aggregate primary-to-useful exergy conversion efficiency (ε) of the USA (1900–2010), UK (1900–2010), Austria (1900–2012), Japan (1900–2000), and the world (1900–2014). Source: Warr et al. (2010), Brockway et al. (2014), De Stercke (2014), Eisenmenger et al. (2017).

3 Results and discussion

3.1 Estimates of the $GExRR_{min,F/U}$ of the EU–15 countries

We can easily compute the $GExRR_{min,F/U}$ of the EU-15 countries by applying Eq.(2) to the available data presented in Figure 3. Considering the long-span availability of Portugal's data, this country delivers the most interesting insight. Figure 5c shows that the $GExRR_{min,F/U}$ of Portugal was stable from the 1850s to the 1920s at approximately 15–16. From then, it follows a decreasing sigmoid shape and gradually declined towards a value of 5. In addition, results show that, except for the peculiar case of Luxembourg, other countries roughly follow this pattern from 1960 to 2009. More precisely, one can observe consistently decreasing trends converging towards a minimum final exergy quantity of around 5 units that the energy sector of these countries must yield per unit of invested useful exergy.

3.2 Estimates of the $GExRR_{min,P/U}$ of the USA, UK, Austria, Japan, and the world

Similarly, combining Eq. (3) and available data presented in Figure 4, we can easily compute the $GExRR_{min,P/U}$ of the USA (1900–2010), UK (1900–2010), Austria (1900–2012), Japan (1900–2000), and the world (1900–2014). Figure 6 shows that between 1900 and 2010s, the minimum primary exergy that the USA, UK, Austria, and Japan had to yield per unit of invested useful exergy has declined from about 25 to 6 following following decreasing sigmoid-shape trends. The $GExRR_{min,P/U}$ of the world economy has pursued a very similar sigmoid-shape declining trend.

et al. (2015) with a methodology similar to that of Brockway et al. (2014). We chose not to show this data on Figure 4 for the sake of methodological consistency. One can also find primary-to-final exergy conversion efficiency (ε_1) for Portugal (1856–2009) in Serrenho et al. (2016) and for the world economy (1900–2014) in De Stercke (2014). Nevertheless, up to recent decades, these estimates are really close to unity because of the relative importance of food and feed (i.e., fodder for draft animals) whose primary energy estimates are conventionally equated entirely to final energy, meaning that the conversion efficiency of solar primary energy into final chemical energy of photosynthetic plants of around 4% is not accounted for. Hence, estimates of primary-to-final exergy conversion efficiency only make sense when non-food energy forms are dominant.

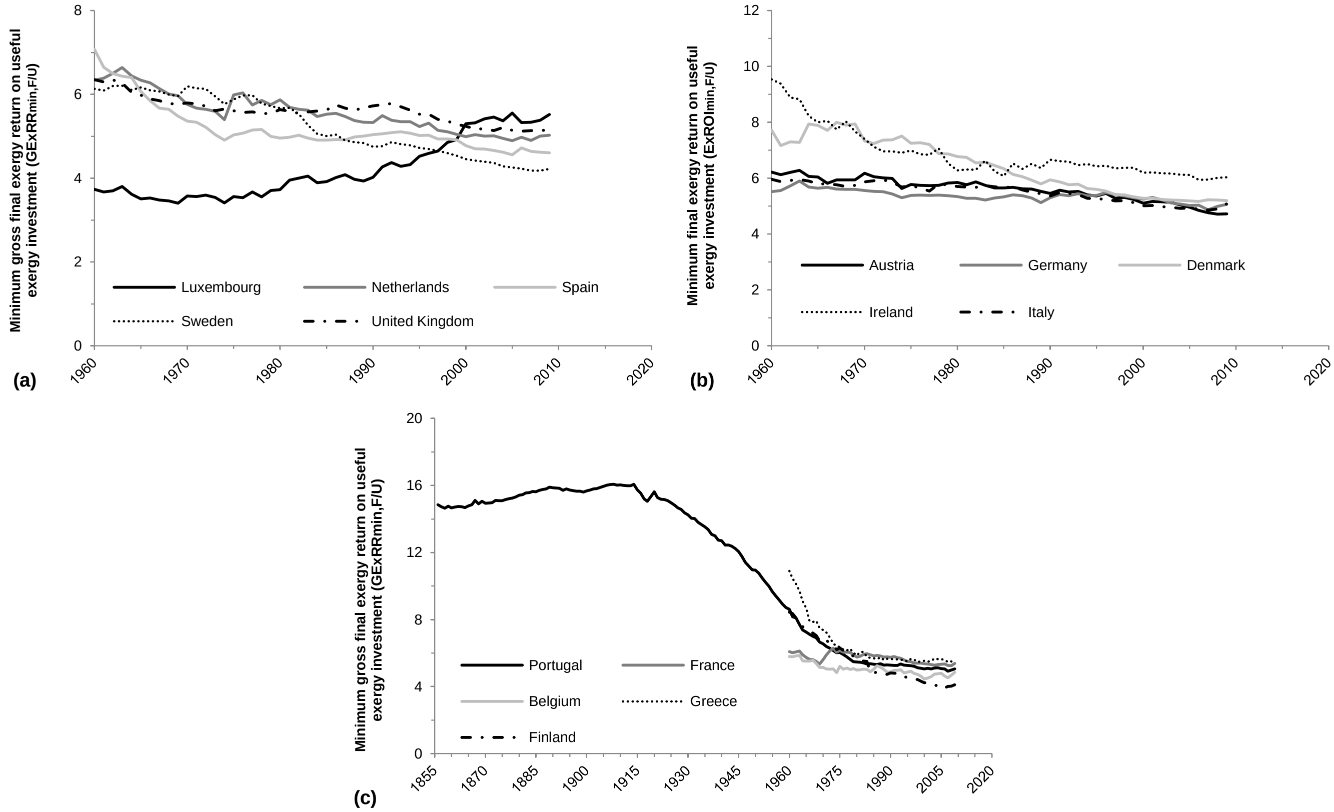

Figure 5: Minimum final exergy return on useful exergy investment ($GExRR_{min,F/U}$) of the EU-15 countries (1856–2009 for Portugal, 1960–2009 for all others).

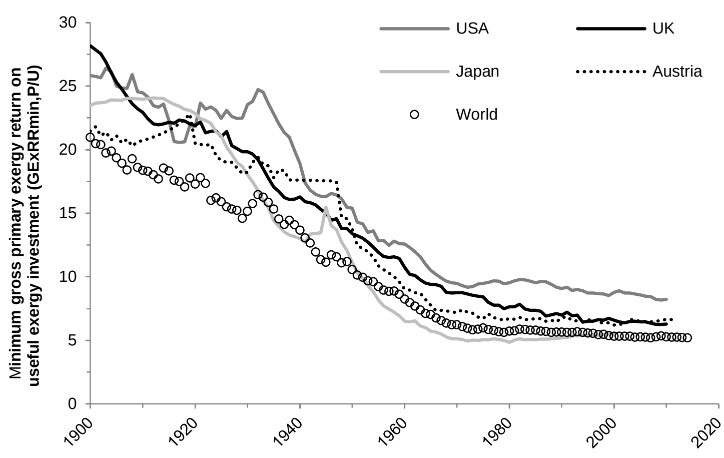

Figure 6: Minimum primary exergy return on useful exergy investment ($GExRR_{min,P/U}$) of the USA (1900–2010), UK (1900–2010), Austria (1900–2012), Japan (1900–2000), and the world (1900–2014).

3.3 Contribution to previous discussions on ERR dynamics and economic growth

There has been no attempt so far to calculate the exergy return ratio that 'actually prevailed' in the past for a given energy system or society. Moreover, the two minimum exergy return ratios, $GExRR_{min,P/F}$ and $GExRR_{min,P/U}$, that we estimated for primary exergy outputs have different inputs boundaries than the usual minimum primary energy return on final energy investment estimated in previous studies (Fizaine and Court, 2016; Hall et al., 2009; Lambert et al., 2014; Weißbach et al., 2013). Accordingly, we cannot directly compare the 'minimum required' GExRR estimated in the previous section with real GExRR to compute their relative distance and thus assess the extent of the exergy constraint on society. Nevertheless, the results of the present article lead to the simple idea that, as technical change enhances the conversion efficiency of primary-to-final and final-to-useful en/exergy processes, the minimum E/ExRR required for society decreases irrespective of the boundary under consideration (Figure 5 and 6).[7] This could explain that the declining GERR of oil and gas global productions since the 1940s assessed by Court and Fizaine (2017) have not resulted in a drastic economic degrowth. In others words, improvements in en/exergy conversion efficiency that mostly occurred between the 1940s and the 1970s (Figure 3 and 4) have compensated the decreasing en/exergy surpluses of the fossil energy system that occurred over the same period.

However, as shown in Figure 7, the rate of global economic growth slowed down after the 1970s. Some may see this slowdown over the past 40 years as a deficiency compared to the 1950–1970s time period. But others may argue that we are reverting to the previous low growth trend, therefore the 1950–1970s period should be seen as an anomalous period. Either way, there is no consensus among economists on the causes of this macroeconomic dynamic that is more apparent in more economically developed countries compared to less economically developed countries (Gordon, 2015; Summers, 2015). The fact that further improvements in en/exergy conversion efficiency have been harder to get since the mid-1970s (see Figure 3 and 4) could partially explain this global economic slowdown. Indeed, since the mid-1970s, while the minimum E/ExRR required for modern societies have been quite stable (Figure 5 and 6), actual E/ExRR prevailing for energy systems have decreased worldwide (Court and Fizaine, 2017; Masnadi et al., 2018), which might have caused in a tightening exergy constraint on economic growth. To confirm this hypothesis, further work is needed to estimate actual exergy return ratios that prevailed in the past decades. Confirming whether actual ExRRs have decreased in the last decades would give credibility to the high level of correlation between annual gains in the UK and Ghana's aggregate exergy conversion efficiency and economic growth recently uncovered by Heun and Brockway (2018).

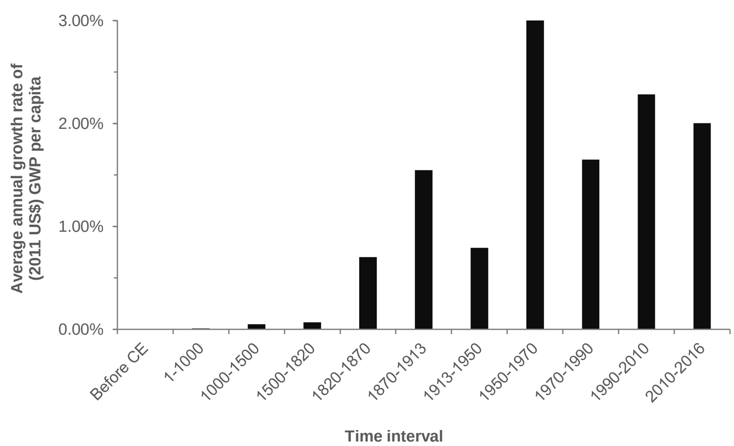

Figure 7: Average annual growth rate of real (2011 US$) GWP per capita, 1–2016 CE. Data source: Bolt et al. (2018).

[7]The term E/ExRR is used in this section and in the conclusion when speaking about a return ratio without any distinction between energy and exergy. Accordingly, I'll also use the term $E/ExRR_{min}$ when speaking about the minimum E/ExRR required for society.

3.4 A possible correlation between the $ExRR_{U/U}$ of society and levels of economic development

Return ratios analyses based on exergy might also overcome the problem posed by the absence of a correlation between the aggregate ERR of society and its level of economic development when comparing foraging, agrarian, and industrial societies. It is indeed clear that one cannot directly relate higher levels of economic development with higher ERR because foraging and traditional farming societies can present ERR values that are quite similar to modern industrial societies. For instance, Smil (2017, pp. 36–37) claims that in foraging societies, typical gathering returns are around 10–20 final food-energy units per useful muscle-energy unit invested, similar to those of hunting large animals. Similarly, Smil (2017, pp. 44–45) reports that many early agricultural societies were able to yield 15–20 final food-energy units per unit of useful muscle-energy invested. However, as illustrated in Figure 8, we postulate that the overall level of economic development of a society is correlated with the discrepancy between the 'actually prevailing' and 'minimum required' useful exergy return on useful exergy investment of its energy system. The available surplus of useful exergy per invested unit of useful exergy should be a good proxy for the level of economic development of society. Further research is still needed to confirm this proposition.

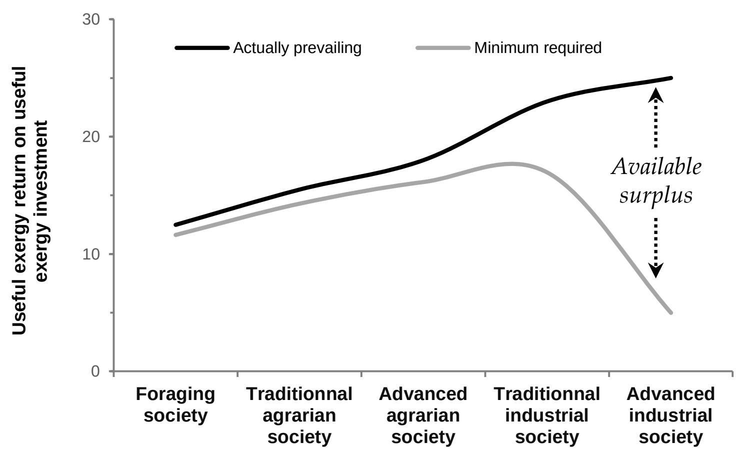

Figure 8: Hypothetical evolutions of actually prevailing and minimum required useful exergy return on useful exergy investment.

4 Conclusion and perspectives

Starting with a concept devised by (Debeir et al., 2013, pp. 51–52), this article showed that several minimum exergy returns ratios can be computed in relation to different levels of exergy conversion efficiency. Currently, data availability restricts estimation possibilities to the $GExRR_{min,F/U}$ of the European Union(EU)–15 countries, and the $GExRR_{min,P/U}$ of the USA, UK, Austria, Japan, and the world. Our results consistently indicate declining sigmoid-shaped trends for all these minimum gross ExRR. In summary, the methodology presented in this article and the resulting $GE/ExRR_{min}$ estimates suggest that, as technical change enhances the conversion efficiency of primary-to-final and final-to-useful exergy processes, the minimum ExRR required for society decreases irrespective of the boundary under consideration.

Then, we discussed those estimates in relation to previous ERR studies. It appears that improvements in exergy conversion efficiency that mostly occurred between the 1940s and the 1970s compensated for concurrent decreasing exergy surpluses of the fossil energy system. However, since the mid-1970s, while the minimum ExRRs required for modern societies have been quite stable, actual ExRRs prevailing for energy systems have continue to globally decrease. This decrease in the rate of exergy conversion efficiency improvements since the mid-1970s could have created a constraint on economic growth, which could partially explain the global economic slowdown of the last forty years.

This article demonstrates that analyses of return ratios based on exergy, and not energy, might deliver more insightful outcomes when compared with standard economic indicators such as GDP growth rates (or investment levels and prices). Therefore, greater attention and investment should be directed toward work seeking to estimate the final or even useful exergy returns on useful exergy investment of energy systems. Calculating such exergy return ratios is needed to assess their distance relatively to the minimum levels estimated in the present article, and hence have a more precise idea of the exergy constraint's magnitude acting on economic growth.

Overall, this article indicates that analyses of return ratios based on exergy, and not energy, might deliver more insightful outcomes compared to standard economic indicators such as GDP growth rates (or investment levels and prices). Therefore, greater attention and investment should be directed toward work seeking to estimate the final or even useful exergy returns on useful exergy investment of energy systems. Calculating such exergy return ratios is needed to assess the ratio of this figure to the minimum levels estimated in the present article, and hence have a more precise idea of the exergy constraint's magnitude acting on economic growth.

Appendices

Appendix A: Energy vs. exergy

Energy, measured in joule (J) is a prime concept of thermodynamics that is formally defined as the ability of a system to cause change.[8] In practice, energy is rarely considered in terms of its 'content' but rather in terms of its 'flow': thermal energy flows from a body to another, this is also the case for chemical energy, mechanical energy, electrical energy, and so on (Sciubba, 2011).

However, energy is not sufficient to understand real processes because, as well as varying in quantity, real processes also vary in quality. Indeed, from the beginning of the Industrial Revolution, scientists and entrepreneurs noticed that the fraction of energy that can be converted into mechanical work is not the same from one process to another. Scientists introduced the concept of *exergy* to account for the capacity of a given quantity of energy to be converted into mechanical work. Formally, exergy (also measured in joule) is the maximum amount of work that can theoretically be recovered from a system as it approaches equilibrium with its surroundings reversibly, that is, infinitely slowly (Ayres, 1998).[9] It is important to remember that the physical quality of a given quantity of energy changes according to its relative exergy content.

Exergy derives from the second law of thermodynamics, which (in one form) states that every transformation process involves the loss of some measure of quality of the system because of irreversibilities at the microscale, which are visible as frictions and heat losses at the macroscale. In other words, in any conversion process, exergy is destroyed as energy flows lose their ability to perform work (Kümmel, 2011, p.114). On the other hand, energy is always conserved in every transformation process and cannot be destroyed, as stipulated by the first law of thermodynamics (Miller et al., 2016).

[8] One joule (J) is defined as the quantity of work transferred to an object by moving it a distance of one meter (m) against a force of one newton (N), i.e. 1 J = 1 Nm. One newton is the force needed to accelerate one kilogram (kg) of mass at the rate of one meter per second (s) squared in the direction of the applied force, i.e. 1 N = 1 kg ms^{-2}. In the context of energy transfer as heat, 1 J = 0.2389 calorie, and one calorie represents the energy needed to raise the temperature of one gram of water by one degree Celsius at a pressure of one standard atmosphere (corresponding to 101,325 Pascal).

[9] Earlier equivalent terms to name exergy are available work, available energy (or even availability), and free energy. For the sake of completeness and clarity, "Gibbs free energy" represents exergy in a particular process performed at constant temperature and pressure, whereas "Helmholtz free energy" represents exergy in a particular process performed at constant temperature and volume.

Therefore, calculating an exergy value from an energy value depends on the intrinsic ability that the energy form under consideration has to deliver work. In most energy calculations, energy is displayed in one of the following forms: fuel, electricity, mechanical work, heat and non-energy products. As summarized in Table 1, for each form, the exergy content is different (Serrenho et al., 2016). Fuels have exergy factors (the ratio of exergy to energy) marginally superior to 1 because their theoretical maximum work content correspond to their standard enthalpy of combustion (ΔH) plus the additional contribution of the post-combustion water vapor (lower heating value) and the flue-gas components (Table 2, row 1). Mechanical (both kinetic and potential) and electric energy flows can be theoretically completely converted to useful work. Thus, they have an exergy factor of 1, while in the case of work that produces some sort of waste such as heat, the exergy factor is smaller than 1. Therefore, an electric energy flow can be completely converted to work and its exergy content equals its energy (Table 2, row 2),[10] while heat cannot be completely converted into work. In this case, the maximum work extractable from a sub-system connected to a thermal reservoir at T_0 is the work obtained by an ideal Carnot engine (Table 2, row 4).

Table 1: Exergy factor for primary and final energy carriers. Source: adapted from Serrenho et al. (2016).

Primary energy source or final carrier	Primary (Φ_P) or final (Φ_F) exergy factor
Coal and coal products	1.06
Oil and oil products	1.06
Natural gas and gas products	1.04
Renewable combustibles (biomass)	1.11
Food and feed	1.00
Other non-conventional	1.00
Electricity	1.00
Heat from Combined Heat & Power (CHP) plant	0.60

Table 2: Exergy content of different energy flows (T_0 is the environment temperature and T is the temperature of the reservoir from which heat is added). Source: adapted from Serrenho et al. (2016).

Energy flow (E)	Exergy content (Ex)	Observations
Fuel	$Ex = -\Delta G =\mid \Delta H \mid - T_0 \Delta S$	The maximum work done by a fuel is the chemical work of its combustion corresponding to the released Gibbs free energy, $-\Delta G$, equals to: the enthalpy of combustion, ΔH, minus the heat, $T_0 \Delta S$, rejected as a consequence of the entropy received.
Electricity	$Ex = E$	Electricity can be completely converted to work.
Work	$Ex = E$	Available work is exergy by definition.
Heat	$Ex = E(1 - \frac{T_0}{T})$	The maximum work done by a heat flow is the work that would be done by a Carnot cycle working between T and T_0.

Appendix B: Energy vs. exergy conversion efficiency

Primary, P, energy and exergy are present in the environment in the form of i natural stocks (coal, oil, gas, uranium) or flows (sun, water, wind, geothermal source, wave and tide). As such, primary en/exergy (a term used from now on when speaking without distinction of energy and exergy) forms are of no use for humans so that conversions of those primary resources into $j \geq i$ secondary en/exergy types are

[10] In practice there are heat losses when converting, for example, kinetic energy into mechanical work, but they are unknown *a priori*. Thus, one can decide to consider an efficiency of 1 which is the theoretical maximum given by the first law of thermodynamics, which means that there is no theoretical thermodynamic result that sets a maximum conversion efficiency in this case. Therefore, we consider electricity as 'pure work' (Serrenho et al., 2016).

required. Such final, F, en/exergy carriers consist in refined products of solid, liquid or gaseous forms, electricity, and heat flows. A number of $k \geq j \geq i$ end-use devices allow the conversion of final carriers into useful, U, en/exergy in the form of motion (i.e., mechanical drive), heat, and light, and electricity for information processing.[11] Accordingly, to compare the performance of individual processes, one can considers their conversion efficiency through energy or exergy approaches (Figure 9).

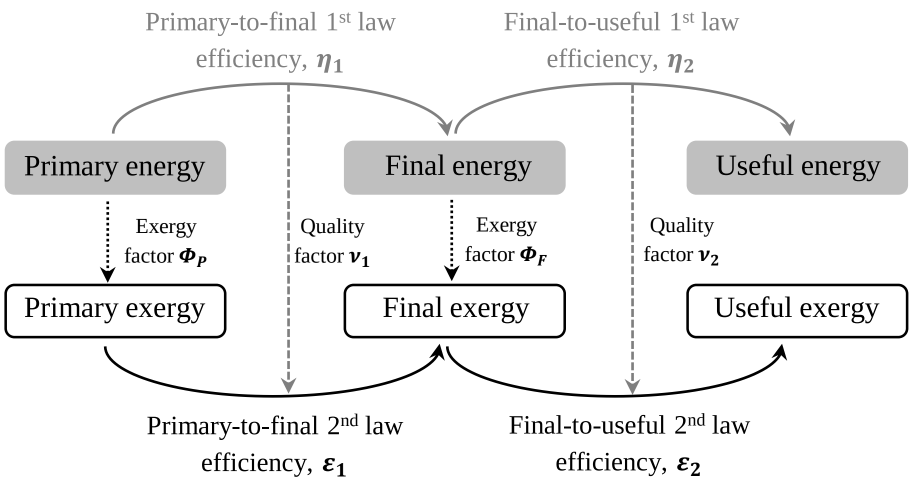

Figure 9: Energy vs. exergy conversion efficiency. Source: adapted from Palma et al. (2016).

Energy conversion efficiency, also called fist-law efficiency, expresses the fraction of energy of a desired kind that is transferred in a process. Hence, for any j primary-to-final process, and any k final-to-useful device, one can respectively define:

$$\eta_{1,j} = \frac{final\ energy\ output, j}{primary\ energy\ input, i} = \frac{E_{out,F,j}}{E_{in,P,i}} \tag{4}$$

and,

$$\eta_{2,k} = \frac{useful\ energy\ output, k}{final\ energy\ input, j} = \frac{E_{out,U,k}}{E_{in,F,j}}. \tag{5}$$

For example, when assessing a power cycle, the first-law efficiency is the quotient of the net work done by the cycle and the heat input to the cycle. As a consequence of the first law of thermodynamics, we usually get $0 < \eta_1 < 1$ (e.g. a natural gas power plant operating at 40% efficiency), and $0 < \eta_2 < 1$ (e.g. an electric motor that is 95% efficient). However, energy efficiency does not behave this way for all energy uses and devices, so in theory nothing prevent first-law efficiencies to be greater than unity (Serrenho et al., 2016). For instance, a typical heat pump has a Coefficient of Performance, corresponding to η_2, of 3 and under ideal conditions it can approaches 10. This is because the relevant energy input does not include the heat input from the environment (the cold reservoir). Since the domain of η is any positive real number, this example demonstrates that the first-law efficiency does not provide a comparable figure of merit across energy uses because it does not take into account the quality of energy flows—electricity and mechanical work are more valuable energy carriers than low temperature heat (Cullen and Allwood, 2010).

[11] It is important not to confuse useful energy with energy services. As put by Cullen and Allwood (2010), energy services (transport of passengers and goods, space heating, and illumination) are the outcomes of the interaction of useful energies (mechanical drive, heat, and light) with passive devices/infrastructures. Hence, all useful energy flows are measured in joules, whereas energy services take different units of measurement such as passenger-km or tonne-km for transport, and lumen for illumination.

In contrast, exergy efficiency, also called second-law conversion efficiency, provides a more equitable measure of conversion efficiency. It uses mechanical work rather than energy as the basis for comparing devices with each other and their thermodynamic ideal. For any j primary-to-final process, and any k final-to-useful device, exergy efficiencies are respectively defined as:

$$\varepsilon_{1,j} = \frac{final\ exergy\ output, j}{primary\ exergy\ input, i} = \frac{Ex_{out,F,j}}{Ex_{in,P,i}} \tag{6}$$

and,

$$\varepsilon_{2,k} = \frac{useful\ exergy\ output, k}{final\ exergy\ input, j} = \frac{Ex_{out,U,k}}{Ex_{in,F,j}}. \tag{7}$$

As a consequence of the second law of thermodynamics, exergy efficiency is always bounded by unity, meaning that the theoretical maximum exergy efficiency of a process is, by definition, always 100% (Sousa et al., 2017). Therefore the second-law efficiency expresses a figure of the quality and closeness to an ideal process for a given energy use. Exergy efficiency can be calculated directly, by finding the ratio of the output to input exergy flows through the device; in practice this is a much more complicated process. Instead, (dropping indexes j and k for convenience) if the conventional energy efficiency η_1 (respectively η_2) is known, then the exergy efficiency ε_1 (respectively ε_2) can be estimated using:

$$\varepsilon_1 = \eta_1 \times \nu_1 \tag{8}$$

and,

$$\varepsilon_2 = \eta_2 \times \nu_2. \tag{9}$$

Where a dimensionless quality factor ν_1 (respectively ν_2) is used to correct for the loss of energy quality (i.e. exergy destruction) in the conversion process (Cullen and Allwood, 2010). Even though they logically evolves over times thanks to technical change, Table 3 give typical values for η_1, ν_1, and ε_1 of primary-to-useful processes, whereas Table 4 give typical values for η_2, ν_2, and ε_2 of end-use conversion devices. Figure 9 summarizes the interrelations of all variables defined in the present section.

Finally, considering that j final carriers deliver end-use services through k devices, one can computes the quantity-weighted average energy and exergy efficiency of all j primary-to-final processes (η_1, respectively ε_1), and the quantity-weighted average energy and exergy efficiency of all k final-to-useful devices (η_2, respectively ε_2), and finally obtain the energy and exergy aggregate efficiency for the whole economy (η, respectively ε):

$$\eta = \eta_1\eta_2 = \frac{\sum_j \eta_{1,j} E_{out,F,j}}{\sum_j E_{out,F,j}} \frac{\sum_k \eta_{2,k} E_{out,U,k}}{\sum_k E_{out,U,k}} \tag{10}$$

and,

$$\varepsilon = \varepsilon_1\varepsilon_2 = \frac{\sum_j \varepsilon_{1,j} Ex_{out,F,j}}{\sum_j Ex_{out,F,j}} \frac{\sum_k \varepsilon_{2,k} Ex_{out,U,k}}{\sum_k Ex_{out,U,k}}. \tag{11}$$

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Table 3: Energy and exergy efficiency of primary-to-final conversion processes. Source: Cullen and Allwood (2010).

P-to-F process	Description	η_1 (%)	ν_1 (%)	ε_1 (%)
Electricity generation from:				
Coal	Hard coal, lignite and derived fuels (e.g. coke, blast furnace gas)	34	94	32
Oil	Crude oil and petroleum products	37	94	35
Gas	Natural gas and gas works	40	96	38
Nuclear	Nuclear fission (heat equivalent of electricity)	33	100	33
Biomass	Combustible plant/animal products and municipal/industrial waste	25	90	23
Renewable	Hydro, geothermal, solar, wind, tide, and wave energy	80	100	93
Fuel transformation	In petroleum refineries, gas works, coal preparation, liquefaction, distribution and own-use	93	100	93
CHP	Combined heat and power plants (all fuels)	56	62	35
Heat	Utility heat plants (all fuels)	85	24	20

Table 4: Energy and exergy efficiency of final-to-useful conversion devices. Source: Cullen and Allwood (2010).

F-to-U device	Description	η_2 (%)	ν_2 (%)	ε_2 (%)
Motion:				
Diesel engine	Compression ignition diesel engine: truck, car, ship, train, generator	22	95	21
Petrol engine	Spark ignition petrol engine: car, generator, garden machinery	13	99	12
Aircraft engine	Turbofan, turboprop engine	28	99	27
Other engine	Steam or natural gas powered engine	47	53	25
Electric motor	AC/DC induction motor (e.g. refrigeration)	60	93	56
Heat:				
Oil burner	Boiler, petrochemical cracker, chemical reactor	61	25	15
Biomass burner	Open fire/stove, boiler	34	20	7
Gas burner	Open fire/stove, boiler, chemical reactor	64	21	13
Coal burner	Open fire/stove, boiler, blast furnace, chemical reactor	59	31	19
Electric heater	Electric resistance heater, electric arc furnace	80	30	24
Heat exchanger	District heat, heat from CHP	87	15	24
Other:				
Cooler	Refrigeration, air con: industry, commercial, residential	104	6	7
Light device	Lighting: tungsten, fluorescent, halogen	13	90	12
Electronic	Computers, televisions, portable devices	20	30	6

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