Citation for published version:
Cooper, S, Hammond, G & Norman, J 2017, 'An empirical assessment of sector level exergy analysis', Energy Procedia, vol. 142, pp. 4050-4055. https://doi.org/10.1016/j.egypro.2017.12.324

DOI:
10.1016/j.egypro.2017.12.324

Publication date:
2017

Document Version
Peer reviewed version

Link to publication

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2017) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

An empirical assessment of sector-level exergy analysis

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Abstract

By relating to both the quality and quantity of energy flows, exergy analysis can be used to assess the improvement potential of thermodynamic systems. Exergy analysis has previously been applied at the economy level in order to provide a measure of the scope for efficiency improvement. While this approach can help to guide progress, meaningful analysis that takes full advantage of the insights of exergy, at this scale, retains some challenges. This study explores three relevant considerations to the interpretation and use of exergetic improvement potential applied at the macro (economy) scale. Specifically: (i) the nature of the relationship between improvement potential and the changes in efficiency that occur, (ii) the relative significance of exergy embodied in flows and (iii) the sensitivity of efficiency calculations to the definition of systems outputs. The nature of these considerations is evaluated empirically, using historic data. It is shown that exergy can provide useful information but that there is a complementary role for energy analysis. The scope for savings outside of direct "improvement potential" is also noted. It is hoped that appreciation of these considerations will lead to more effective exergy analysis at the economy scale, with its advantages and also limitations properly understood.

Keywords: exergy; exergo-economics; improvement potential; industrial sector; energy analysis

1. Introduction

Exergy is a thermodynamic measure that depends upon the quantity and quality of energy. It can enable the quantification of improvement potential that is inherent in the supply or conversion of an energy carrier. The firm theoretical basis for this improvement potential means that it has found increasing use in the analysis of such systems; aiding in the identification of processes for which development is most likely to be productive when conventional energy analysis might draw inappropriate conclusions. The prospect of exploiting this advantage to provide additional

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insights in the analysis of larger systems such as economic sectors makes it an attractive metric for such studies [1]–[6].

However, when comparing the exergetic improvement potential of economic sectors, there are several factors that may compromise the analysis or limit its enhanced usefulness relative to a more conventional energy analysis [7]–[9]. In this paper, an empirical approach is applied to the exploration of three broad considerations:

1. The relationship between exergetic improvement potential and efficiency improvements
2. The significance of embodied exergy inputs when assessing the scope for energy savings
3. The sensitivity of the calculation of improvement potentials to the selection of system boundaries.

2. Methods

2.1. Relationship between exergetic improvement potential and efficiency improvements

The exergetic improvement potential may relate to the likelihood of efficiency improvements being made [5][10]. At a system level this could occur through improvements in the individual processes, additional options to substitute processes with more efficient alternatives, and opportunities to improve integration: in using exergy that would otherwise be destroyed. However, in practice the activity of different sectors varies and there may be limited scope for substitution or limited motivation to achieve savings. It may even be that the energetic "improvement potential" (i.e. energy loss due to inefficiencies) is sometimes a better indicator of future improvement. E.g. if taking advantage of the exergetic potential would require a significant change in practice such as replacing boilers with heat pumps.

Energy inputs to sectors within the EU-15 nations between 1960 and 2009 were sourced from the IEA [11]. These were used alongside the data and methodology supplied by Serrenho et. al. [12] to calculate the exergy inputs and useful exergy application relating to each sector. Equivalent energy figures were calculated from these data and the factors supplied by Serrenho et. al. [12]. For each year, the relative improvement potential (energy or exergy lost relative to inputs [3]) was compared to the efficiency improvement over the following 15 years. The R^2 values for linear regressions between these values were then averaged over each decade and compared.

2.2. Significance of embodied exergy inputs

The direct exergy demands of a process can be reduced through energy efficiency. However, typically a process will require other inputs that embody the use of exergy upstream in their supply chain. In some cases, the exergy that can be saved by reducing these inputs may be significant, even though their direct exergy consumption is low and they would be discounted under conventional analysis. Embodied exergy analysis addresses this. However, when assessing the scope to reduce the use of exergy embodied in the inputs to that process, the exergetic improvement potential of that process is less relevant. This study compares the magnitude of the exergetic improvement potential of industrial sectors to the magnitude of the potential for exergy savings by reducing other inputs to them.

The World Input-Output Database (WIOD) [13] was used with the standard Leontief input-output method (see [13]) to calculate the indirect requirements associated with activity in 30 economic sectors in 40 nations. The energy use extension data supplied with WIOD was adapted with the energy-exergy factors [12] to create an exergy use extension table. The embodied primary exergy inputs were then calculated for each sector and then the direct exergy use of that sector subtracted in order to determine the exergy losses in the supply chain. This method relies on the fact that total exergy inputs to a system will equal the sum of exergy losses and output. Price aggregation issues inherent in input-output calculations mean that a small proportion of embodied exergy use will have been misassigned.

2.3. Sensitivity of the calculation of improvement potentials to the selection of system boundaries.

When applied to an energy transformation process, the exergy of the output can be readily defined. However, the output of many sectors cannot be fully described in terms of exergy and so the definition of the exergetic improvement potential becomes subject to the selection of "useful exergy" flows relating to each sector. Despite the promising approach of distinguishing "active" and "passive" systems [5], this remains somewhat subjective and there is significant variation in the detail of the boundaries and methods adopted [14]. The selection of representative exergy flows has an effect on the apparent efficiency of the system and on the ways in which it might be improved [15][16]. For example, analysis of a transport sector might consider the aggregate efficiency of engines or drivetrains, the exergy per vehicle-km or the exergy per tonne-km; each of these metrics will provide different results. One might even question the need for the transport: could goods be substituted or sourced more locally? This is not purely semantics; improving the way that the selected exergy flow is used to provide the desired outcome presents significant potential to save energy and risks being underrepresented if focus is given exclusively to the improvement potential in providing that particular exergy flow.

Ideally, to assess the sensitivity of results to the selection of representative exergy flows, the change in results that occurs when the actual “minimum exergy content” of the product or service is used as the sector’s representative flow would be calculated. For example, for bulk material production, the “minimum exergy content” would be closely related to the chemical exergy content of that material. However, this is problematic; for most sectors it is hard to determine a meaningful exergy representation (or “exergy content”) of the final product or service produced. Instead, in this study, the relationship between exergy efficiency (i.e. the “useful exergy” used per unit of exergy entering the sector) and exergy productivity (i.e. the value added per unit of exergy consumed) is examined. Consistency in the ratio between these metrics would imply that there is both (i) good correlation between value of products and their (possibly hypothetical) “exergy content” and that (ii) the exergy flows selected for the efficiency calculations are representative of that “exergy content”. This would mirror Warr et. al.’s findings regarding economic growth [17]. Conversely, wide disparity in these ratios would imply that there is significant variation in the activities delivering the desired outputs using that exergy flow (proxied by the creation of value) and that there is variation in the scope within those activities for other improvements.

Additionally, changes in efficiency were compared to changes in productivity (for each sector in each nation). This provides some indication of the extent to which improvements in exergy productivity have been due to either improvements within the scope considered (e.g. exergy efficiency increases due to engine refinements) or improvements outside the scope considered (e.g. better logistics planning decreasing the need for journeys).

Data on the volume of sectoral output, (measured as chain-linked 2005-euros of gross value added) was obtained from Eurostat [18]. The selected data cover 64 sectors across 14 EU nations over the period from 1995 to 2009. The data was then compared to the exergy use metrics calculated as per section 2.1. To achieve this, a concordance matrix was constructed to relate the sector definitions [18]. From this, the ratio of each annual efficiency improvement to exergy productivity improvement was determined and the weighted average calculated for each sector and nation over the period from 1996 to 2009, see Equation 1.

$$R_{i,j} = \sum_{t=1996}^{2009} \frac{E_{i,j,t} - E_{i,j,(t-1)}}{E_{i,j,(t-1)}} \cdot \frac{\left|\frac{P_{i,j,t} - P_{i,j,(t-1)}}{P_{(t-1)}}\right|}{\frac{P_{i,j,t} - P_{i,j,(t-1)}}{P_{(t-1)}}} \Bigg/ \sum_{y=1996}^{2009} \left|\frac{P_{i,j,t} - P_{i,j,(t-1)}}{P_{(t-1)}}\right| \qquad (1)$$

Where $R_{i,\,j}$ is the weighted average ratio for sector i in nation j, E_t is the exergy efficiency in year t, and P is the exergy productivity.

3. Results and discussion

3.1. Historic efficiency trends

Figure 1 compares the changes in the energy and exergy efficiency of sectors over 15-year periods, with the relative improvement potential (i.e. normalized by dividing by energy / exergy use) at the start of each period. In retrospect, it can be seen that each metric had some predictive element but that neither energy nor exergy performs consistently better.

For some sectors, a reasonable fit to the data can be achieved through linear regression while for others the fit is far weaker. For several sectors, the fit achieved when using exergy analysis is better than energy analysis for one period (or vice-versa) and then the situation is reversed for a later period. These occurrences may correspond to situations in which the technical options for efficiency improvements that are economically favorable relate to either energy or exergy based losses but are then exhausted for the other period (or other technical options become available). For example, if techno-economic constraints mean that the technology for a heating process remains combustion based, then the low exergy efficiency of these systems will be less relevant than their high energy efficiency (and limited opportunity for improvement without using an alternative technology such as heat pumps). Conversely, during periods in which more radical changes are feasible, it may be that the improvements relating to the substitution of technologies correlate more closely to the exergetic improvement potential. However, whatever the reason for the varied relationships between these metrics, it is clear that they are very specific to the conditions and technologies within each sector for each time period.

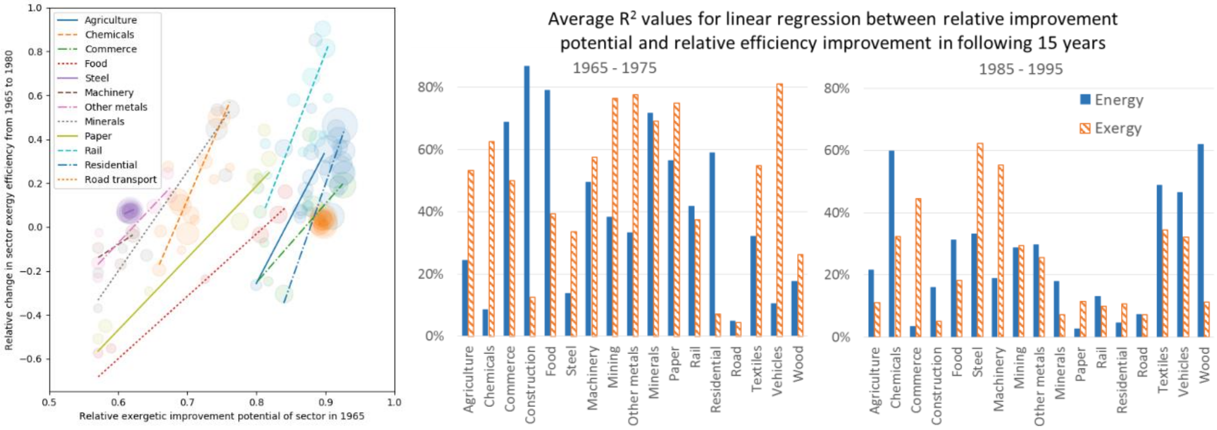

Fig. 1. Comparing historic efficiency improvement to initial improvement potential

3.2. *Significance of embodied exergy inputs*

Figure 2 shows the range of ratios of embodied to direct exergy use that relate to each sector (across 40 nations). While some of the extreme outliers are artefacts due to the input-output model used (see section 2.2), it is clear that there is typically a wide variation both in the ratio between different sectors and also for the “same” sector in different nations. Excepting the metals, non-metallic minerals, food and textiles sectors, direct exergy is a poor proxy for embodied exergy. The manufacturing types of sectors all exhibit much higher (typically 10-fold) embodied impacts than direct impacts. Many of the materials and services sectors are also responsible for high embodied impacts. For these sectors, the scope for saving energy or exergy by reducing other manufacturing inputs (e.g. through material efficiency, [19], [20]) is greater than the potential to reduce direct exergy use. The chemicals, metals, non-metallic minerals and transport sectors all have a lower embodied-direct exergy ratio. In most cases, the energy use of these sectors is dominated by a few energy intensive processes and the analysis of the sector as a whole may be similar to an analysis of these processes.

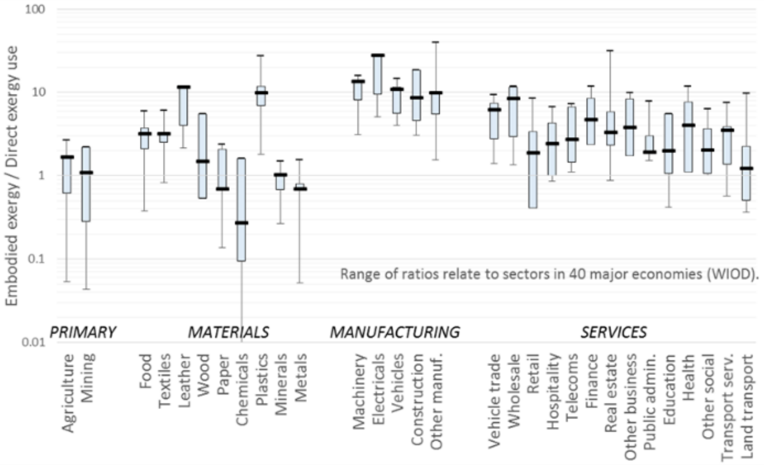

Fig. 2. Comparing significance of embodied and direct exergy use by sectors

3.3. Sensitivity to definition of energy service

Figure 3(a) illustrates the range of aggregate exergy efficiencies and exergy productivities that different sectors exhibit. The aggregate exergy efficiencies vary from around 12% to around 50% but the range of exergy productivities is far greater, with a hundred-fold difference between transport and commercial activities (N.B. logarithmic y-axis). The aggregate exergy efficiency of some sectors (metals, transport, agriculture) is quite consistent (varying by a few percentage points) while their exergy productivities are more varied (e.g. several with a factor of three difference). The chemicals and non-metallic minerals sectors demonstrate a stronger relationship between these metrics but still show far greater variation in productivity than efficiency (around a factor of two, compared to 10 to 12 percentage points variation, corresponding to around a third greater efficiency). The commercial sector has the strongest link between the metrics, with a limited (two-fold) range of productivities and relatively low exergy efficiency (15% to 25%) making the relative range in efficiency greater. The large variations in productivity lend credence to the idea that the “same” sectors in different nations are actually creating different products. To consider the relationship between exergy efficiency and productivity further, it is instructive to analyze changes in individual sectors over time.

Figure 3(b) shows the range of the average ratios of proportional change in efficiency to proportional change in productivity. This can be interpreted as the proportion of the change in productivity that can be explained by the change in efficiency. For example, if exergy efficiency were to increase from 10% to 20% (i.e. double) and exergy productivity also doubled, then the efficiency improvement could fully explain the increase in productivity: the same process would require only half of the energy input. However, for most sectors, the median case is that only a fraction (typically less than 50%) of the increase in productivity can be explained by the increase in efficiency. The rest is due to other factors such as an increase in the value or quantity of the goods or services that each unit of “useful exergy” is used to supply. The “quality factor” inherent in the exergetic improvement potential should not be assumed to mean that it can be used to quantify the maximum reduction in exergy that can be achieved while maintaining a given value of output.

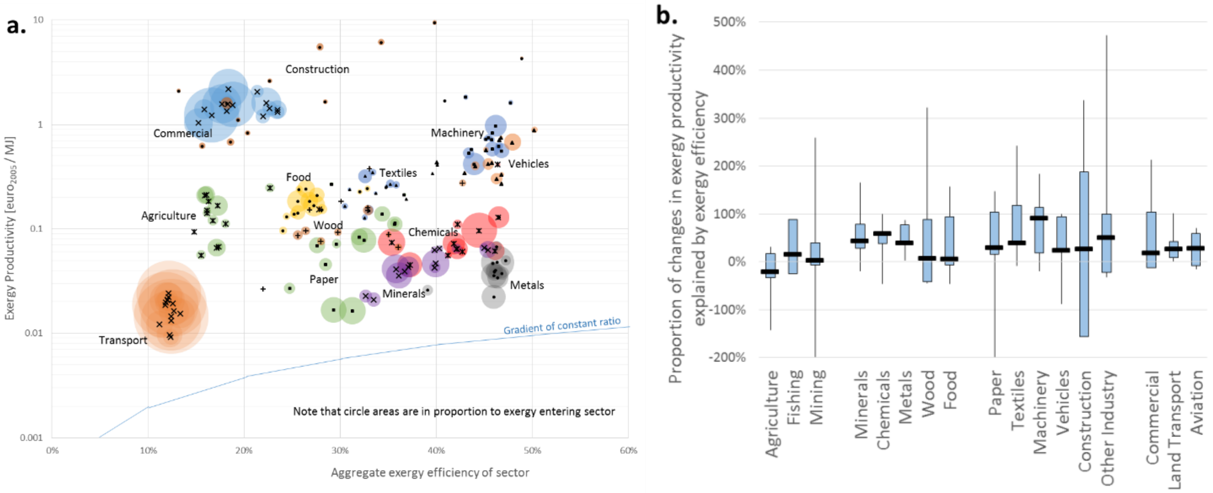

Fig. 3. (a) Comparing productivity with efficiency; (b) Changes in exergy productivity that relate to efficiency

4. Conclusions

Both exergetic and energetic metrics can help in estimating the likelihood of actual improvements in efficiency. The actual determinants of which metric (or both) are most helpful is highly sector specific and relates to the actual energy services consumed and the set of techno-economic considerations relating to them.

Sectors producing products that have a large exergetic content (e.g. chemicals, steel and of course fuels and electricity) are well suited to specific exergy analysis that can take account of the relatively low number of processes that are typically responsible for much of the exergy use. For many other sectors – especially those that manufacture goods and have extensive supply chains – the embodied energy and exergy use is very significant and it is important that over-emphasis on an exergetic improvement potential based on direct energy uses does not obscure the recognition of these savings.

Exergy analysis is a good tool to investigate the scope for change in a specified energetic system (and potentially apply that change to a larger system). For example, the total effect of reducing the exergetic losses in all turbines by a certain factor. However, while some indication of the potential for additional productivity improvements outside of its typical scope can be made, by their nature it cannot assess these fully. In practice, the challenge is likely to be not overestimating the scope of improvements that the quality factor of exergy enables it to consider.

Care is needed to ensure that the underlying reasons and implications of either energy or exergy analysis are communicated clearly and that they do not simply represent artefacts of the system under consideration. Exergy should not be elevated to a pivotal position in decision making. Rather, the use of energy and exergy analysis together, with an understanding of their respective merits is the recommended approach.

Acknowledgements

This work was supported by the RCUK Energy Programme's funding for the Centre for Industrial Energy, Materials and Products, grant reference EP/N022645/1. All data created during this research are openly available from the University of Bath data archive at https://doi.org/10.15125/BATH-00378. Author's names appear alphabetically.

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