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ScienceDirect
Procedia CIRP 48 (2016) 122 – 127
www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

Unlocking plant-level resource efficiency options: a unified exergy measure

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Abstract

In this research we propose a physical measure of *resource efficiency*, based on *exergy*, which combines energy and material flows in a single dimensionless metric, bounded by 0 and 1. The inclusion of materials in the efficiency metric makes it possible to compare a wide range of industrial devices and processes, and even different sectors, using a consistent framework. Resource efficiencies for steel-making processes were computed as an example and were found to range from 10.0% in sinter plants to72.1% in coke ovens. A unified resource efficiency measure helps identify the drivers of resource consumption and reveal opportunities to reduce carbon emissions.

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
Keywords: Resource efficiency, embedded exergy, embodied exergy, resource efficiency metric, steel production

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1. Improving efficiency to reduce industrial resource use

The provision of goods and services involves the complex interaction of multiple resources – mainly energy, materials and water. Both the steel and chemical industries involve processes where the boundary between what is considered energy, and what is considered a material, is blurred. For material-transforming processes—e.g. a blast furnace or steam cracker—narrowing the scope of resource use analyses to include only energy consumption gives undue focus to the dissipation of high-value fuels into wasted heat. Alternatively, limiting the analysis to material use reveals only a small mass loss, with no indication of the amount of fossil fuels burned. The former approach fails to capture the key driver of the processes—an upgrade in material quality—while the latter fails to account for the environmental impact caused by the fossil fuels used in the transformation reactions. There is a clear need to understand multiple resources concurrently, as a single resource system, and yet today's resource efficiency narrative, at both the policy level and company level, is still dealing with resources separately.

Over the last five years, the concept of *resource efficiency* has grown in popularity, and has in part replaced energy efficiency in policy making. The policy recommendations from the European Commission [1], United Nations Environmental Programme (UNEP) [2] and the World Resources Forum (WRF) [3] show this transition away from just energy targets towards more holistic resource analysis. Many researchers and policymakers now realise the need to understand the wider interactions of energy, material and carbon emissions when designing resource policies, to prevent conflicting objectives and policy incoherence when pursuing climate change objectives [3].

However, the tools and methodologies for analysing multiple resources and environmental impacts are still at a conceptual stage of development. Historically, energy efficiency measures have been pursued by industry [4–6] with limited savings remaining [7–10]. Material efficiency measures, on the other hand, have only recently started to gain momentum [10–12]. However, to date, the strategies of energy efficiency and material efficiency have been pursued separately, leading to the creation of many different physical and economic metrics to measure environmental impacts and potentially conflicting mitigation strategies and targets.

The wide range of resource metrics used in recent policy documents [1,13] results from policymakers responding to different issues, ambitions and applications, i.e. economic, physical or environmental, and at different levels of economic activity [14]. Despite the clear need to assess impacts in a more integrated fashion, this has not to date translated into the development of quantitative, holistic resource metrics. Measures of resource use, at both the global and country level, still consider materials separately from energy, e.g. Gross Domestic Product per Domestic Material Consumption (GDP/DMC) [14]) compared with Energy Use per Activity [15]).

Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.111

At the policy level, this diverse range of resource efficiency indicators has two disadvantages: it increases data collection costs, and complicates environmental analyses. For example, Life-Cycle Analysis (LCA) uses a broad selection of environmental indicators to cover different environmental impacts [16], however at the expense of additional time and cost required to prepare the LCA. Finding the right balance between completeness and simplicity is challenging for firms, where the transactional costs of collating and processing data pose a significant cost burden [17]. Firms tend to prioritise simplicity over completeness, preferring simple energy efficiency and *energy intensity* metrics, i.e. joules per tonne of output [4,15].

However, the increased use of different *intensity* metrics to measure *resource efficiency* has led to a loss of consistency when defining efficiency. The efficiency measures being used no longer relate to the thermodynamic efficiency of physical processes but instead describe more abstract concepts such as the rate of resource consumption or environmental impact for a given level of economic activity (e.g. GJ/GDP or impact/GDP) [14]. A major disadvantage of this divergence in resource efficiency metrics is that they lack a common measurement unit, making comparison between different processes impossible.

This paper proposes to reinstate engineering rigour back into the measurement of *resource efficiency* by defining a unified metric for measuring the efficiency of energy and material use in industrial plants. Such a measure will identify options to improve resource use in industrial processes and reveal opportunities to reduce carbon emissions.

2. Quantifying resource use: an exergy approach

Over the last 25 years, researchers including Wall [18], Ayres et al. [19], de Beer et al. [20], Michaelis et al. [21] and Szargut [22] have been developing exergy as a method for quantifying both energy and material resources to reveal and prioritise industrial efficiency interventions. These studies exploit the fact that, as expressed by Valero et al. [23], any system with physical properties (e.g. temperature, pressure, composition or concentration) differing from those of the reference environment has exergy, i.e. the potential to do work [22]. Fuels have exergy even at atmospheric conditions because their *chemical potential* enables them to deliver work when combusted. Likewise, minerals or materials have exergy because they have ‘a specific composition and concentration different to that of the average dispersed crust’ [24].

Previous exergy analyses have quantified the flows of energy and materials across entire production plants and production lines revealing previously hidden efficiency gaps. de Beer et al. [20] mapped the exergy flows of raw materials and energy for an integrated steel plant and suggested savings could be made by reducing operational temperatures and optimising heat cycles. Wall [18] concluded that heating processes were the main factor contributing to inefficiency in production processes. Costa et al. [25] used an integrated exergy analysis to characterise exergy efficiency both at the process and plant level, although recommendations focused only on the effect of specific process variables on the consumption of electricity and oxygen.

Previous efficiency studies fall short of providing an integrated view of energy and material efficiency in three key areas. Firstly, the use energy or exergy intensity—a ratio of joules over tonnes of output—as the measure of efficiency does not allow for industrial processes to be compared because efficiency is measured in different units. Secondly, despite the integration of energy and materials in the development of exergy methods, studies still only focused on energy efficiency options rather than considering both energy and material efficiency options.Thirdly, most studies failed to recognise the links between industry resource use and the drivers behind resource use–the services provided to society—because the dominant focus on energy use means material services are ignored.

To overcome these issues, this study proposes a physical measure of *resource efficiency* that is based on *exergy* and: (1) combines energy and material flows into a single metric; (2) has the same unit on both the numerator and the denominator, i.e. is bounded by 0 and 1, making it possible to compare the efficiency of a wider range of processes; (3) captures the factors driving resource consumption, by linking the resource use to the material and energy services demanded by society.

3. Constructing a resource efficiency metric

Two concepts have been included in the development of the unified exergy metric: using exergy to measure energy and material in the same units; distinguishing between the exergy *embodied* during the process (i.e the resource inputs to each process) and the exergy *embedded* in the material (i.e. carried intrinsically in the material), as first proposed by Ashby [26]. Ayres et al. [19] noted that for chemical processes, only the chemical (B_{CH}) and physical (B_{PH}) components of exergy provide significant contributions to total exergy. While Szargut et al. [22] divides exergy losses usefully into external and internal, where external losses refer to the waste streams (e.g. flue gas, cooling water, heat loss) and internal losses result from irreversibilities (entropy-generating mechanisms) within each process [22]. The general expression for the total exergy of chemical processes (B_{TOT}) is:

$$B_{TOT} = B_{CH} + B_{PH} \tag{1}$$

Constructing a ratio of embedded to embodied exergy that combines energy and material flows involves three main steps, as outlined in the following sections. For simplicity, the examples presented in this paper only consider the energy and materials that directly enter or leave each processes.

3.1. First step: chemical exergy of fuels and raw materials

The chemical exergy of all energy and material flows entering or leaving each process must first be calculated. For energy streams, Nakicenovic et al. [27] presents conversion factors (f) and a method for converting fuel energy contents into exergy values. Typical fuel conversion factors relevant to iron- and steel-making are shown in Table 1 and exergies can be calculated using the following equation, where HHV and LHV stand for Higher and Lower Heating Values respectively:

$$B_{CH(fuels)} = f_1 \times HHV = f_2 \times LHV \tag{2}$$

Standard tables of specific chemical exergies for elements and compounds are used to calculate the chemical exergy of

Table 1. Exergy conversion factors for fuels [27]

Energy source	f_1	f_2
Coal (average)	1.02	1.06
Natural gas	0.93	1.03
Crude oil	0.99	1.04

materials (B_{CH}), for example Ayres & Ayres [28] and Szargut [29]. The definition of the chemical reference state specified by Szargut et al. (1988) [22] was adopted, which measures exergy in relation to one of three possible reference levels: to air (volatiles), to the ocean (soluble in water) or to the earth's crust (neither of the above). Once the chemical exergy of inputs and outputs has been computed, the next step is to compute their physical exergy.

3.2. Second step: physical exergy of fuels and raw materials

Physical exergy can be calculated using the direct method: using values of enthalpies (H) and entropies (S)

$$B_{PH} = (H - H_0) - T_0(S - S_0) \tag{3}$$

where H_0 and S_0 are those at ambient conditions. Commonly T_0= 25 $°C$ and P_0= 1 atm. For liquids, the phase state of water is considered the standard state. Physical exergy can also be calculated indirectly by using expressions that approximate the enthalpies and entropies of the substances, depending on the conditions. For example, assuming a constant specific heat (C_P), Querol et al. [30] use Equation 4.

$$B_{PH} = C_p(T - T_0) - T_0 C_p ln\frac{T}{T_0} + RT_0 ln\frac{P}{P_0} \tag{4}$$

where R stands for the gas constant. The physical exergy commonly results from heat generated in specific processes, which produces high-temperature waste gas streams and high-temperature material products. Generally, the effect of pressure is assumed to be negligible.

3.3. Third step: defining resource efficiency

Resource efficiency is defined as the ratio of embedded to embodied exergy, where the 'embodied' term represents the total direct energy and materials input into a given process, and the 'embedded' term describes the energy remaining in the output materials after undergoing any chemical and physical changes during the process. The choice of what is 'useful' and what is 'waste' for the metric numerator is often a subjective choice. Similarly, the boundary for the denominator can include all upstream energy use or just the direct process energy. To avoid counting errors, the system boundaries should be defined transparently, and an advantage of visualising processing using a Sankey diagrams is that the inputs and outputs to each process are clearly shown.

Figure 1 depicts the embodied and embedded components for a generic process in the form of a Sankey diagram. Taking the ratio of embedded to embodied exergy (EE ratio) provides a measure of the efficiency with which high-quality energy is degraded to transform raw materials into final products.

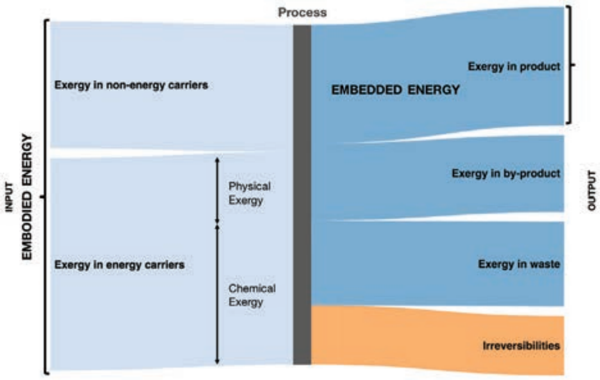

Fig. 1. Exergy components of input and output streams. The exergy of by-products and waste streams have both chemical and physical components.

4. Case study: an application to iron- and steel-making

This case study sets out to answer the following question:

Does a measure of efficiency that combines energy and materials in a single metric reveal previously hidden opportunities to reduce carbon emissions?

using iron- and steel-making as a case study and by comparing results obtained from traditional energy studies to those using the unified exergy efficiency metric. The energy and exergy balances for a reference Blast Furnace (BF) and Electric Arc Furnace (EAF) are depicted in Sankey diagram form in order to provide a clear understanding of the scale of resource flows through processes and comparison between processes. The World Steel Association (worldsteel) performed an energy analysis of the steel industry in 1998 [4] where various future technological efficiency improvement measures were proposed. This was updated in 2014 with an in-depth study and survey on the actual technology implemented and covered actual performance of energy intensity achieved by the industry [33]. Energy and material data for this study is based on a set of reference processes given in the 2014 report.

4.1. The Blast Furnace

The Blast Furnace (BF) transforms iron ore, in the form of pellets and sinter, into pig iron at about 1500°C and standard atmospheric pressure. Iron-making is CO_2 intensive because of the large quantities of coke (processed metallurgical coal) and other fuels (gas, off-gases) used in the blast furnace [4]. Coke is used as both source of heat for the process and as a reducing agent for the chemical reaction to make hot metal (the iron product). Both uses of coke release CO_2 emissions, however, whereas the combustion exergy used for heating is lost from the blast furnace, the chemical reaction exergy is embedded in the hot metal.

Fig 2 shows the energy balance (top) and exergy balance (bottom) for the BF. Traditional energy balances measure efficiency in the form of an *energy intensity*—the energy input in joules per product output in tonnes—combining energy and materials together in a hybrid ratio rather than a single dimensionless unit [4,15]. The energy intensity of the reference Blast

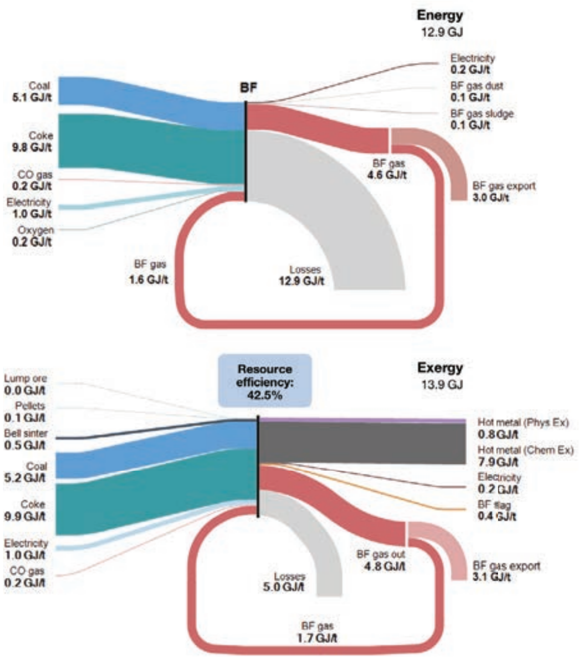

Fig. 2. Energy balance (top) and exergy balance (bottom) for the Blast Furnace (BF) process, based on reference data from World Steel Association [33].

Furnace process (Fig 2, top) is 17.9 GJ/t of pig iron, or 12.9 GJ/t of pig iron if credit is given to this re-use of the furnace top-gases [33]. The Sankey diagram shows no useful output from the furnace (i.e. the hot metal product is not shown) which makes the calculation of a dimensionless *efficiency ratio* meaningless.

In contrast, an exergy efficiency can be calculated for the reference BF (Fig 2. bottom) as both the energy and material flows are measured. The resource efficiency is calculated as 42.5%, excluding the physical exergy (heat) of the hot metal as this is unlikely to be recovered. The exergy intensity of the BF is 13.9 GJ/t of pig iron, slightly higher than the 12.9 GJ/t energy intensity.

4.2. The Electric Arc Furnace

Fig 3 compares the energy and exergy balances for the Electric Arc Furnace (EAF). Once again, the energy balance shows no input of scrap steel to the EAF or useful output from process, making the calculation of a dimensionless efficiency impossible, whereas an resource efficiency of 50.4% can be calculated for the exergy balance. The energy intensity for the EAF is calculated as 6.8 GJ/t of steel compared to the much higher value of 13.3 GJ/t of steel for the exergy intensity, reflecting the additional exergy embedded in the recycled scrap steel input.

4.3. Comparing resource efficiencies

Table 2 shows the resource efficiency calculations for the BF and EAF processes, alongside the resource efficiencies of coke making and sintering, and typical exergy efficiencies for steam power plants and electric motors. The resource efficiency metric shows how close an individual process is operating to the ideal efficiency, however care should be taken when comparing between different processes. In the same way that it is nonsensical to compare an electric motor to a steam power plant (as they perform vastly different functions), it is also incorrect to compare the BF directly to the EAF plant (one makes hot metal, the other steel), or coke-making to a sintering plant. In addition, drawing a boundary around each process neglects the upstream and downstream processing of energy and materials, for example, the coke making process which feeds the BF, the basic oxygen converter downstream, and the generation of electricity for the EAF. To make further comparisons requires an integrated analysis of all the processes in specific steel-making route and careful consideration of the study boundary, including the embedded exergy in recycled scrap steel.

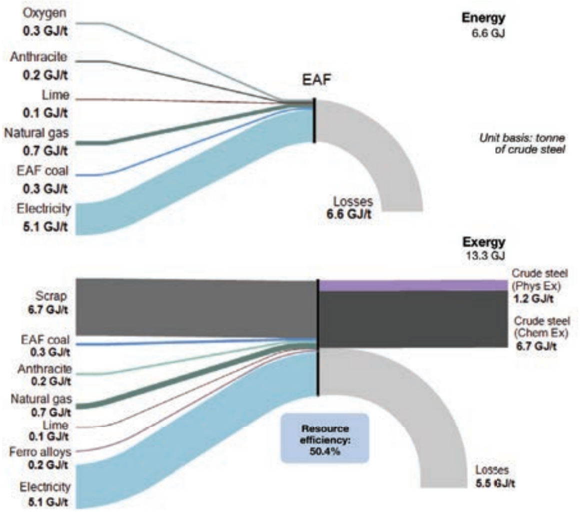

Fig. 3. Top: Energy balance of the electric furnace process; Bottom: exergy balance of the electric furnace process. Data sourced from worldsteel [33].

Table 2. Energy intensity, exergy intensity and resource efficiency

Process	Energy intensity (GJ/t)	Exergy intensity (GJ/t)	Resource efficiency (%)
Blast Furnace [33]	12.9	13.9	42.5
Electric Furnace [33]	6.6	13.3	50.4
Coke Oven [33]	5.7	5.2	72.1
Sinter Plant [33]	2.3	3.0	10.0
Steam power plant	-	-	30–50
Electric motor [36]	-	-	88–95

Nevertheless, current engineering understanding of the exergy efficiency for devices is well developed and knowledge of the types of exergy losses is commonly used for optimising device efficiencies. The extension of exergy analysis to processes, by measuring energy and materials on the same scale, opens up the opportunity to perform similar exergy loss analyses for industrial processes and to compare between similar

Table 3. Example of energy and resource efficiency improvement options for the blast furnace

Resource	Conventional energy analysis	Material efficiency analysis	Resource (exergy) efficiency analysis
Coal & coke	Through oil enrichment together with use of low volatile coal; natural gas or plastic waste injections [4]	-	*Equivalent to the energy analysis, but distinguishing between fuel quality*
Process off-gas	Recycling off-gas into BF process itself, or as heat source in other steel-making processes ; improved computer aided control [4]	Process yield improvements of by-products	Two options are revealed: recovering the chemical or the physical exergy in the off-gas.
Electricity input	Top gas recovery turbines enable electricity generation; improved blower efficiency; improved efficiency/control of motor driven systems [4]	-	*Equivalent to energy analysis*
BF slag	Heat recovery from the 1400°C slag [4]	Re-use or recycling of the slag into other processes , e.g. in cement industry.	*Equivalent to energy analysis, but with an additional indication of the stream temperature; hence the true available work output*
Iron ore in	-	Process yield improvements [34]	Process yield improvements [34];
Pig iron product	-	Yield improvements along the supply chain (e.g. casting or fabricating) [34]; re-using or recycling techniques.	Yield improvements along the supply chain (e.g. casting or fabricating) [34]; re-using or recycling techniques.
Losses	Radiation and convection loss reduction from improved furnace design; improved stove and blower energy efficiency [4]	Small material loss; no indication of energy losses	Main exergy losses: physical exergy in waste gases; losses from conversion of chemical energy to high-temperature gases; irreversibilities in heat transfer & undesired chemical reactions. Options: reduce temperatures/ heat cycles [20]
Combustion air	Preheat of combustion air through the use of process off-gas [4]	-	*Equivalent to energy analysis, but with an additional indication of the stream temperature; hence the true available work output*

types of devices and processes. For example, the BF is a large combustion device with a resource efficiency (42.5%) similar to that of typical steam power plants (30–50%). Comparing the exergy losses from each process whether low (e.g. sintering) or high (e.g. coke-making) may give insight into potential options for improvement, and characterising the process' resource efficiency is a prerequisite to do so. Information about the type of conversion mechanisms, and therefore of the specific types of losses involved, can also be valuable for identifying patterns for improvement across industrial devices. Furthermore, the use of a unified exergy efficiency metric will allow for cross-sector comparisons similar processes in industry.

5. Discussion and conclusions

Previous studies investigating the opportunities to improve energy efficiencies across the energy systems—such as Cullen & Allwood [38] and Hammond & Stapelton [39]—focused on identifying opportunities for improvement within energy conversion devices, whilst neglecting material-conversion processes. Energy or exergy efficiencies are commonly used to define potential energy savings in energy-converting devices. However, defining physical measures of energy efficiency for material-converting process is not meaningful as the process output is not energy but instead a material. The driving factors of consumption are better captured by incorporating materials in the efficiency metric, in this case the high-temperature steel product. Integrating energy and materials in a single metric enables options for reducing energy and material demand to be prioritised concurrently. The distinction made between *embedded* exergy and *embodied* exergy may also provide a consistent method for allocating energy use and emissions to future recycling, where process exergy is assigned to the first material use, while the remaining embedded exergy (less yield loss in use and recycling) is allocated to the next use.

The traditional use of *intensities* to describe process *efficiencies*—either in terms of energy or materials—provides an inferior metric that: no longer ranges between 0 and 1; neglects process losses by only considering energy inputs, and; is no longer equivalent across different processes, due to their disparate denominators. In contrast, a dimensionless metric is preferred as: it allows the comparison between the conversion efficiency of other devices to be made; and the identification of efficiency improvement potentials is no longer restricted to individual technologies, but can also be applied to the resource chains within which these technologies operate. Resource efficiencies for the BF and EAF have been calculated as 42.5% and 50.4% respectively, and can be compared (with care) to that of other combustion-based processes, such as steam power plants.

The joint analysis of both energy and material flows (using exergy) allows for the identification of more efficiency options and for these options to be assessed at the same time. Table 3, shows improvement opportunities identified for the BF using three approaches: traditional energy efficiency analysis; material efficiency analysis; and the resource (exergy) efficiency analysis. The table demonstrates that energy-only and material-only approaches both fail to reveal all the opportunities available to improve resource efficiency. Therefore using exergy to assess both energy efficiency and material efficiency options provides a more holistic approach and reveals more opportunities to reduce carbon emissions.

The ability to consistently measure and compare resource efficiencies, both vertically (from devices through to processes, plants, sectors and regions), and horizontally (between devices, processes and sectors), is potentially a game changer for the setting of policy to promote efficiency improvement potentials at the sector and regional scale. Equally, it is valuable for firms aiming to understand the practical efficiency limits of their process plants so as to develop future business strategies that align with environmental objectives.

This paper characterises the resource efficiency for iron- and steel-making processes, however, the methodology described can be used to compare across any energy or material transforming process, where resource efficiency is concerned. The next steps involve combining the resource flow analyses performed for individual iron- and steel-making processes into an integrated exergy map of the entire steel production value chain. In addition, performing the same analysis for other sectors may reveal cross-cutting opportunities for reducing resource use in industry. The resource efficiency approach described is transparent, showing the direct energy and material flows for each process, and how they interact with other processes. The allocation of resources across boundaries is clearly shown in Sankey diagram form, in contrast to many footprint based environmental impact methods. This enables a more holistic understanding of how resources are used to deliver final energy and product services, and shows where the greatest potential for resource efficiency improvements can be found.

Acknowledgements

This study was made possible with the support of worldsteel. This work was done as part of a project funded by Emerson Electric co.

References

[1] European Union: Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee on a Roadmap to a Resource Efficient Europe. 2011; 571 final.

[2] West J, Schandl H, Heyenga S. Resource Efficiency: Economics and Outlook for China. 2013.

[3] Schluep M, Quiros A, Strothmann P, Daz J, Versetti A, Leeuw B de, et al. Innovation, Competitiveness and Resource Efficiency. Peru; 2014.

[4] IISI. Energy Use in the Steel Industry. 1998; Brussels.

[5] IEA. Energy Management Programmes for Industry. 2012.

[6] IEA. Assessing measures of energy efficiency performance and their application in industry. 2008.

[7] Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy efficiency. Renew Sustain Energy Rev; 2013;19:290-308.

[8] Sorrell S, OMalley E, Schleich J, Scott S. The Economics of Energy Efficiency: Barriers to Cost-Effective Investment. Edward Elgar Publishing Limited; 2004.

[9] Rohdin P, Thollander P, Solding P. Barriers to and drivers for energy efficiency in the Swedish foundry industry. Energy Policy. 2007; 35(1):672-7.

[10] Allwood JM, Cullen JM, Milford RL. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ Sci Technol. 2010;44(6):1888-94.

[11] Fischedick M, Roy J, Abdel-Aziz A, Acquaye A, Allwood JM, Ceron J-P, et al. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the IPCC. 2014.

[12] Viere T, Ausberg L, Bruns M, Eschke J, Hedemann J, Lambrecht H, et al. Integrated Resource Efficiency Analysis for Reducing Climate Impacts in the Chemical Industry. J Bus Chem. 2014.

[13] European Environmental Agency. Resource efficiency in Europe. 2011.

[14] Huysman S, Sala S, Mancini L, Ardente F, Alvarenga R a. F, De Meester S, et al. Toward a systematized framework for resource efficiency indicators. Resour Conserv Recycl. 2015; 95:68-76.

[15] IEA. Energy Efficiency Indicators: Essentials for Policy Making. 2014; Paris.

[16] Neuhoff K, Cooper S, Laing T, Lester S, Rysanek A. Indicator Choices and Trade-offs: Facilitating the success of international climate policies and projects. Climate Strategies. 2009.

[17] Coase RH. The nature of the firm: origin. Journal of Law, Economics, and Organization. 1988; 4:3-17.

[18] Wall G. Exergy flows in industrial processes. Energy. 1988; 13(2):197208.

[19] Ayres RU, Ayres LW, and Masini A. An application of exergy accounting to five basic metal industries. Sustain. Met. Manag., 1996:141-194.

[20] de Beer J, Worrell E, and Blok K. Future technologies for energy-efficient iron and steel making. Annu. Rev. Energy Environ., 1998; 23: 123-205.

[21] Michaelis P, Jackson T, and Clift R. Exergy analysis of the life cycle of steel, 1998; 23(3).

[22] Szargut J, Morris D, and Steward F. Exergy analysis of thermal, chemical and metallurgical processes, 1988.

[23] Valero A, Valero A, Calvo G. Using thermodynamics to improve the resource efficiency indicator GDP/DMC. Resour Conserv Recycl.; 2015;94:110-7.

[24] Gutowski TG, Branham MS, Dahmus JB, Jones AJ, Thiriez A, Sekulic DP. Thermodynamic Analysis of Resources Used in Manufacturing Processes. Environ Sci Tech. 2009; 43(5):1584-90.

[25] Costa MM, Schaeffer R, Worrell E. Exergy accounting of energy and materials flows in steel production systems. Energy. 2001; 26(4):363-84.

[26] Ashby MF. Materials and the environment; 2013. 2nd ed. Butterworth-Heinemann.

[27] Nakicenovic N, Gilli PV, and Kurz R. Regional and global exergy and energy efficiencies. Energy, 1996; 21(3):223-237.

[28] Ayres RU and Ayres LW. Accounting for resources, 2: The life-cycle of materials. Edward Elgar Publishing Limited, 1999.

[29] Szargut J, Egzergia. Appendix 1. Standard chemical exergy. 2007.

[30] Querol E, Gonzalez-Regueral B, and Perez-Benedito JL. Practical approach to exergy and thermo-economic analysis of industrial processes. 2013; Springer.

[31] Cullen JM, Allwood JM, Borgstein EH. Reducing Energy Demand : What Are the Practical Limits? Environ Sci Technol. 2011;45:17118.

[32] Cullen JM and Allwood JM. Sustainable Materials: with both eyes open; 2012.

[33] World Steel Association. Energy use in the steel industry, 2014; Brussels.

[34] Milford RL, Allwood JM, and Cullen JM. Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors. Resour. Conserv. Recycl., 2011; 55(12):1185-1195.

[35] World Steel Association. Yield Improvement in the Steel Industry: working group report 2003-2006. 2009.

[36] Waide P and Brunner CU. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems, 2011.

[37] Kehlhofer R, Hannemann F, Rukes B, Stirnimann F. Combined-Cycle Gas & Steam Turbine Power Plants, 2009; PennWell.

[38] Cullen JM, Allwood JM. The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy. 2010 ;38(1):75-81.

[39] Hammond GP and Stapleton AJ. Exergy analysis of the United Kingdom energy system. Proceedings of the Institution of Mechanical Engineers-Part A: Journal of Power and Energy, 2001; 215(2):141-162.

[40] Cullen JM and Allwood JM. Theoretical efficiency limits for energy conversion devices. Energy, 2010; 35(5):2059-2069.