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# How resource-efficient is the global steel industry?

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ABSTRACT

Resource efficiency is an instrumental mitigation option in the steel industry but, existing studies have failed to provide a global analysis of the sector's energy and material use. Despite the interactions between energy and materials in steelmaking, recent studies investigate each of these resources in isolation, providing only partial insight into resource efficiency. This study analyses the latest, most comprehensive resource data on the global steel industry and quantifies the savings associated with reducing this through energy- and material-saving measures. Three production routes are investigated for 2010, namely the blast furnace/basic oxygen furnace (ore-based); direct reduction/electric arc furnace; scrap-based electric arc furnace routes (secondary). The sector's resource efficiency – accounting for energy and materials – is expressed in exergy and measured at two levels, that of production routes and plants. The results show that the sector is 32.9% resource-efficient and that secondary steelmaking is twice as efficient (65.7%) as ore-based production (29.1%). Energy-saving options, such as the recovery of off-gases, can save about 4 EJ/year (exergy). Materialsaving options, such as yield improvements, can deliver just under 1 EJ/year extra. A global shift from average ore-based production to best available operation can save up to 6.4 EJ/year; a 26% reduction in global exergy input to steelmaking. Shifting to secondary steelmaking can save 8 EJ/year, limited only by the need to still produce half of steel from ore in 2050. Resource efficiency, measured in exergy, provides stakeholders with an instrument that treats energy and material efficiency measures on an equal footing.

## 1. Introduction: resource use in the steel sector

The production of steel, a key enabler of modern societal development, is responsible for over a quarter of industry's carbon dioxide ($CO_2$) emissions (IEA, 2016). The International Energy Agency's (IEA) 2 °C scenario for 2050 suggests that more than a third of the emissions reduction in industry (excluding power generation) will come from the steel sector, making steel the single largest contributor to industrial emissions reduction. Energy efficiency (EE) and material efficiency (ME) strategies, the combination of which is defined as *resource efficiency* (RE) in this article, are expected to deliver significant emissions reductions in the short term, especially while decarbonisation technologies such as smelt-reduction and carbon capture and storage are still under development. In fact, in their *Material Efficiency Scenario*, the (IEA, 2015a) shows "material efficiency could deliver larger energy savings in energy-intensive industries than energy efficiency", especially in the steel industry.

Customarily, to determine the improvement potential available from EE, the scale of the energy flows in a system is traced, and both a current and a target efficiency are defined. Yet performing a similar task for industry, where the main product outputs are materials, cannot be appropriately accomplished by solely evaluating the flows and efficiency of energy. In real industrial processes, including steelmaking, material and energy inputs interact and undergo chemical reactions to produce a range of energy and material products. Neglecting materials when analysing industrial RE only provides a myopic picture. To quantify the potential resource and emissions savings in the steel industry, a holistic understanding of both types of resources and appropriate metrics that capture their interactions is needed.

In this paper, a more complete *RE metric* is used, based on exergy, to measure the efficiency of energy and material use in the steel industry. By integrating energy and materials into a single measure, it is possible to consolidate a range of efficiency interventions: reducing energy/fuel inputs; reducing raw material inputs by improving material yield (Milford et al., 2011); recovering energy by-products (i.e. waste heat and waste gases); recovering by-product materials, i.e. slag and sludge (Canadian Steel Producers Association, 2007; ESTEP/EUROFER, 2014; European Commission, 2009) shifting production to scrap-based steelmaking (Cullen and Allwood, 2012; Pauliuk et al., 2013). This study sets out to answer three research questions:

- How resource efficient is the steel industry today?

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- What is the current heterogeneity of the RE between steel plants and production routes?
- What is required to raise today's average performance to best practice?

## 2. Previous work: energy and material efficiency studies

Most efficiency studies of the steel industry focus on either EE or ME. These studies are reviewed first, before introducing a third type of study that uses exergy to conduct an integrated analysis of energy and materials.

*Energy efficiency* studies are common in academia, industry and policymaking, and typically employ *energy intensity* metrics to identify potential energy savings. Worrell et al. (2008) published perhaps the most widely cited study of energy use in the steel industry. The analysis evaluates high performance reference plants, based on data from the International Iron and Steel Institute (IISI, 1998), with energy intensities (GJ/t of physical unit of output) reported at the level of fuels, steam and electricity inputs. A joint study by the European Steel Technology Platform (ESTEP) and European Steel Association (EUROFER) went further to breakdown fuel inputs by type, i.e. natural gas and oil (ESTEP/EUROFER, 2014). Similar energy-intensity studies have also been produced by national bodies, such as the Canadian Steel Producers Association (Canadian Steel Producers Association, 2007).

Phylipsen et al. (1997) proposed a modified energy-intensity metric called the Energy Efficiency Index (EEI), which enables the comparison of industrial EE between countries (Phylipsen et al., 1997). The EEI metric accounts for structural effects by measuring the ratio of average and best practice energy intensity for each country. This method has been applied: to benchmark industry sectors in the Netherlands (Phylipsen et al., 2002) in detailed EE studies of steelmaking processes (Arens and Worrell, 2014; Siitonen et al., 2010); and in global benchmarks (Saygin, 2012; UNIDO, 2010). In policy, the (European Commission, 2016) tracks EE improvements using the ODEX index, which transforms energy-intensity values into rates of energy savings in percentages. These studies all use energy intensity metrics to track and estimate energy-related savings.

Many studies predict the future emissions and energy use of the sector, such as (IEA, 2017a; Kuramochi, 2016; Morfeldt et al., 2015; OECD/IEA, 2007; Saygin, 2012; van Ruijven et al., 2016; Zhang et al., 2018). Within these, Saygin (2012) estimates that 6.1 ± 19% EJ/year can be technically avoided, whereas the IEA (2007) predicts between 2.9 and 5 EJ/year. These forecasts, however, disregard the entire gamut of ME strategies showed by (Allwood et al., 2010a) to be indispensable in achieving the agreed emissions reductions.

*Material efficiency* studies are less common as they require knowledge of larger sections of the supply chain. Cullen and Allwood (2012) outline six key ME strategies for energy-intensive materials such as steel: (1) using less by design; (2) reducing yield losses; (3) diverting manufacturing scrap; (4) re-using components; (5) designing longer life products; and (6) reducing final demand. Recent studies have attempted to assess the potential energy or emissions savings from these strategies. For example, Milford et al. (2011) calculated the savings available from yield improvements across various steel and aluminium supply chains. Whereas, Cooper et al. (2014) explored component-level strategies for extending the lifespans of steel products. Only two studies were found that include ME strategies as part of forecasting exercises: studies performed by (Milford et al., 2013) and (IEA, 2015a). Other studies have examined strategies for recycling and re-use, employing metrics such as recycling rates (%), recycled content (%), scrap diversion (%); re-use rates (%), material intensities (tonnes per area, volume or service) (Allwood, 2014; Allwood et al., 2010b; Cullen and Allwood, 2012; Densley Tingley et al., 2017; Graedel et al., 2011). *Embodied energy* (GJ/t) and *emissions* ($tCO_2/t$) also provide measures of cumulative savings, and are useful for making comparisons between ME options.

EE and ME measures are difficult to combine because they are measured in different units. To resolve this, academics in the later 1980s began using *exergy* (based on the work by Keenan (1932) and Rant (1956), among others) as a measure of both energy and materials in resource accounting studies. Szargut (1986) defined *chemical exergy* as the potential of a substance to do work due to its difference in chemical composition with respect to the environment. This development in the calculation of the chemical exergy of materials made it possible to apply exergy in industrial processes, for example: chemical reactors (Brodyansky et al., 1994; Sorin and Paris, 1998; Szargut et al., 1988a, 1988b) and manufacturing processes (Branham et al., 2008; Gutowski et al., 2009).

Today, exergy analyses have been applied to steel production: at the country level, for the US (Masini and Ayres, 1996), China (Wu et al., 2016), and the UK (Michaelis et al., 1998); for specific technologies (blast furnaces (Petela et al., 2002), electric furnaces or sintering processes (Bisio, 1993), smelting process (Akiyama and Yagi, 1988; Ostrovski and Zhang, 2005)); across individual or a combination of reference plants (Costa et al., 2001; Szargut et al., 1988a, 1988b) (de Beer et al., 1998). Some of these exergy analyses of steel production only give results as exergy intensities; those that provide efficiency metrics are summarised in Table 1.

In a few cases, estimates of the sector-wide potential savings were made based country-level statistics (Phylipsen et al., 1997; Saygin, 2012; van Ruijven et al., 2016) or specific technologies (Arens and Worrell, 2014; IEA, 2007; Milford et al., 2013). Yet no previous study captures the full picture of resource use and RE (in exergy) of the global steel industry. Additionally, ME options such as material by-product (i.e. slag) recovery were almost always ignored. Such an analysis helps reveal the global effort required to close the true RE gap between average and best practice steel production.

To answer the questions proposed in Section 1, the most representative and up-to-date data from worldsteel is analysed. An exergy approach is used to quantify the energy and material flows both for entire routes and individual plants, and a metric of RE is developed to compare between plants and routes. The analysis calculates the current global average RE for each route and the plants within these, and provides estimates of technical improvement potentials (IPs) available from implementing best practice technologies. Finally, the advantages of using an exergy-based RE metric are evaluated.

## 3. Method

Four steps are required to determine the RE of the global steel

**Table 1**

Exergy efficiency values found in the literature. (CO – coke oven; SI- sinter plant; PE – pellet plant; BF– blast furnace; BOS – basic oxygen steelmaking; EAF – electric arc furnace; DRI – direct iron reduction; HSM – hot strip mill; PP – power plant.

| Reference | Scope | CO | SI | PE | BF | BOS | EAF | DRI | HSM | PP | BF-BOS | DRI-EAF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Szargut et al.(1988a,b) | Case study | 78.5 | – | – | 28–59 | 85–92 | 52.2 | – | – | – | 29–30 | 34.0 |
| Masini and Ayres (1996) | USA | 83–90 | 4.3 | 15.7 | 44.8 | 67.6 | – | – | – | – | 36.1 | – |
| de Beer et al. (1998) | Reference plant | – | – | – | – | – | – | – | – | – | 29–48 | – |
| Costa et al. (2001) | Mix of plants | 68–85 | 12–24 | 26–29 | 52–80 | 75–85 | 67–69 | 65–68 | – | – | 30–56 | 28–49 |
| Wu et al. (2016) | Chinese network | 78 | 14.5 | 16.6 | 42.2 | 49.8 | – | – | 39.9 | 27 | – | – |