Journal of Cleaner Production xxx (2014) 1–11

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Substance flow analysis of steel and long term sustainability of iron ore resources in Australia, Brazil, China and India

Mohan Yellishetty*, Gavin M. Mudd

Department of Civil Engineering, Monash University, Gippsland Campus, Wellington Road, Clayton, VIC 3800, Australia

ARTICLE INFO

Article history:
Received 30 June 2013
Received in revised form
20 February 2014
Accepted 21 February 2014
Available online xxx

Keywords:
Substance flow analysis
Steel
Resource depletion
Sustainability and the GDP

ABSTRACT

Substance flow analysis (SFA) provides a helpful tool for the study of the industrial metabolism of a certain substance within a regional level. This paper presents SFA of steel in four countries, namely Australia, Brazil, China and India. These countries are traditionally economically mineral dependent and are major contributors in global iron ore production. For example, in 2010 together these countries produced 81% of world iron ore. Based on the analysis it was found that Australian and Brazilian iron ore stocks will deplete rapidly while China and India are accumulating. This paper then presents a discussion on sustainability issues related to substance flows of steel stocks. The study is aimed at providing better understanding of stocks and flows and to inform the policy making for achieving the industrial metabolism and consequently leading to better management of resources and recycling of steel in the countries under study.

1. Introduction

Substance flow analysis (SFA) is an analytical tool to systematically assess the flow and stock of a specific substance through a given system (e.g. productive, economic or social system), which should be clearly defined in space and time, and is concerned with identifying environmental problems associated with such flows. It includes element and chemical flow analysis (Bringezu et al., 1997). It can be used to estimate the losses and gains of a particular substance from a particular region(s) of study and the environmental impacts during various processes in its life cycle. The SFA makes use of the law of 'mass conservation' to track the fate of materials and to evaluate the environmental burdens thereof and thus it plays an important role in attaining industrial metabolism. By using SFA, we can analyse the amount and intensity of use of the substance, so as to offer a new method and perspectives setting for the environmental policy (Kapur and Graedel, 2004). The results of an SFA can therefore act as a good guiding tool for formulation of a better policy and practice in an industry, and can help to address the environmental concerns related to resource use. The results of SFA can be used to assess the sustainability of socio-economic development and environmental change, and therefore should be viewed as a tool for sustainability assessment.

The SFA has gained prominence, particularly in the last decade and a half, as an increasing number of researchers/organisations across the world have embarked on the task of developing country and/or regional specific studies with broad ranging applications in many fields. For example, studies on iron and steel (Michael, 1999; Michaelis and Jackson, 2000a, b), and copper (Xueyi and Yu, 2008; Kapur, 2003; Spatari, 2002). There are other studies focused on nonferrous metals, such as aluminum (Melo, 1999), zinc (Gordon, 2003; Spatari, 2003) and cadmium (Guinee, 1999).

The main objective of this paper is to present a substance flow analysis of iron and steel in Australia, Brazil, China and India (i.e. accumulation and de-accumulation analysis of steel stocks) and link these trends to the iron ore and/or steel industries' long-term sustainability issues. Although it is a well recognised fact that steel is a multi-substance material and can be used in a variety of different forms and products, for the purpose of this study we have expressed all of them in terms of their crude steel (CS) equivalents and thus the study is called a 'substance flow analysis' not a 'material flow analysis'. To facilitate the discussion, initially, an overview of iron and steel industry has been presented. This is followed by an analysis of results including linking them to iron ore resource sustainability.

* Corresponding author. Division of Mining & Resources Engineering, Civil Engineering, Monash University, Wellington Road, Clayton 3800, VIC, Australia. Tel.: +61 9902 7143.

E-mail address: mohan.yellishetty@gmail.com (M. Yellishetty).

http://dx.doi.org/10.1016/j.jclepro.2014.02.046

2. Methodology and data sources

Throughout the paper the tonnages of iron ore and steel refer to their CS equivalents and statistics are expressed in metric tonnes unless otherwise stated. Modelling of future production and consumption was done using regression analysis of the historical data assuming a 'business as usual' scenario. The gross domestic product (GDP) data are reported in nominal US dollars and were sourced from the United Nations database.

2.1. Data sources

All production and exports data cover 1980 to 2008, and data are primarily sourced from government, industry supported associations or research literature. In case of iron ore, both the United States Geological Survey (USGS) and British Geological Survey (BGS) reports were used, since they have reported annual data for total ore production and estimated iron content. Similarly, the USGS also reports data in respect of reserves and reserve base annually in its 'Mineral Commodities Section'.

The historic and future population data are available (for all years) from the United Nations (UN) census. The UN population projections of the world for the future are estimated using three different variants, i.e. high, medium, and low.

Specific sources include:

- Iron ore production and export statistical information: USGS, 2010, 2012; BGS, 2008.
- Iron ore mineral reserves and reserves base: USGS, 2010, 2012 and individual company reports.
- Steel consumption and exports statistical information: Worldsteel, 2012; Worldsteel, 2009; ISSB, 2008; and Worldsteel, 2007.
- Population and GDP statistical information: The World Bank, 2010; The United Nations, 2010; and UNSD, 2010.

2.2. System boundaries and scope of the study

The published amount of steel stock in each country under study is the value of the 'overall stocks', which include, the stocks in mineral reserves, stocks in industrial and governmental stockpiles, stocks in products in use, stocks in obsolete products undisposed, stocks in land-filled waste, and stocks in total. This amount is derived from the difference between annual material inputs and outputs. The material inputs consist of domestic steel consumption and indirect steel imports in year. The material outputs consist of the amount of recovered steel scrap (total of collected industrial scrap and obsolete scrap) and indirect steel exports of finished steel mill products (such as steel bars, sheets, and tubes) in a year. However, the steel exports embedded in final products (such as vehicles, machines, ships, etc.) are not included in the study, because getting good statistics on the tonnage of steel products exported (and imported) is very difficult. Therefore, the study doesn't capture the effect of steel being 'lost' from the country through being part of 'final products' exported.

While selecting the countries for this study, we have considered their strategic position and significance in the world's iron and steel trade and the size of their economy (e.g. production, consumption, population size, and the GDP growth). The countries in this study present diverse economic profiles and have been playing a major role in the world's iron and steel trade (i.e. production, consumption and exports). On the one hand, Australia is distinctive among industrialised countries for its degree of dependence on mineral sector and exports with very low population size and strong economy with high per capita GDP (besides Canada and Norway). On the other hand, China and India represent developing countries with very rapidly growing economies and massive population size, and finally Brazil represents a transition economy with moderate but growing economy and population size.

2.3. Steel de-accumulation modelling

The de-accumulation of steel stocks occurs as a result of exports of iron ore, semi-finished and finished steel products and the steel scrap from a country or region (all of which are expressed in their crude steel (CS) equivalents). The export tonnages are expressed in their CS equivalents [exports = exports of {iron ore + semi-finished and finished steel products + steel scrap}]. In calculating the exports in the future of iron ore/steel, exponential regression was used. This assumption was based on the fact that since 1950 steel consumption increased exponentially - exhibiting a high degree of correlation between the actual and predicted values. Although the analysis of residuals showed a fluctuating growth rate (between 1980 and 2008), for the purpose of future modelling we have assumed an average growth rate (derived from historical data) and the same was used to predict the future steel demand. This is a conservative assumption and therefore the predicted values are on their lower side. The other important reason for choosing an exponential regression was the population size of China and India, and their rapid economic progression in the past decade and a half. China and India together constitutes 40% of the world population, meaning that any modest increment in per capita consumption rate in these countries implies a massive tonnage on a national/global level.

2.4. Steel accumulation modelling

The steel consumption in this paper is defined as apparent per capita consumption in CS equivalents [Apparent consumption = Production + Imports − Exports ± Stock changes] and the accumulation of steel stocks is essentially due to consumption in the anthroposphere. For the purpose of accumulation modelling, a weighted arithmetic average value of 405 kg/capita/year of steel was assumed to be needed for a country to sustain higher growth rate and development (infrastructure, rails, industry, *etc.*). This per capita consumption value was calculated by performing a weighted average analysis of the historical data (1990–2008) of developed countries. Based on this value, the future predictions for individual countries were made using regression analysis and the analysis gave a reasonably good fit, with fairly good scatter of residuals.

3. Iron ore resources and their availability

Iron is an abundant element in the Earth's crust averaging from 2 to 3% in sedimentary rocks to 8.5% in basalt and gabbro, which ranks iron the fourth most abundant element in the earth's crust (US EPA, 1994). A mineral deposit is generally defined as an ore when it contains sufficient concentration of an element so as to facilitate its economic extraction of the required quality. These ores are extracted either through open-pit or underground mines and processed to concentrate or extract the element of interest.

Over 300 minerals contain iron but five are the primary sources of iron ore minerals: magnetite, hematite, goethite, siderite and pyrite. Amongst these, four minerals are of major importance because of their occurrence in large and economically minable quantities (US EPA, 1994). The most important use of iron ore (up to 98%) is as primary input in steel making with the remainder being used in applications, such as coal washeries and cement manufacturing (IBIS World Industry Report, 2009; Indian Bureau of