"Analysis of Steel Production in Vidarbha: Environmental impacts and solutions"

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ABSTRACT

Steels were the upstream of various products. The environmental performance of steel can affect those of the downstream products. In this work, environmental impacts of individual steels, i.e. slab, hot-rolled, cold-rolled, hot-dipped galvanized, and electro-galvanized steels, were studied, via life cycle assessment. The impact assessment methods of IPCC 2007 GWP 100a and Eco-indicator 99 (H) were used to cover the impact categories of Global warming potential, Fossil fuels, Ecotoxicity, Minerals, Carcinogens, and Respiratory inorganics. In all categories, the slab showed the lowest impacts and the hot-dipped galvanized steel showed the highest impacts. The main causes of the impacts were attributed to these inputs; steel, energy, and zinc. The emissions from steel production plants showed relatively low impacts. Small amount of zinc input can cause huge environmental impacts. The reduction of zinc consumption and the improvement of zinc production process, in terms of reduction of heavy metal emissions, could largely improve environmental performance of the galvanized steels.

1. Introduction

Steel has been one of the key materials for a "modern" society from the past to these days. It is basic materials for various indus-tries, including the manufacturing of car, furniture, building, and energy-used products. The demand for steel consumption does not show any declination although there are iron and steel recycling industries all over the world. World Steel Association reported that the total production of crude steel increased from 777 million metric ton in 1998 to 1351 million metric ton in 2007. In Vidarbha, it was reported that the steel consumption was raised from 12.7 million metric ton in 2004 to 13.5 million metric ton in 2008 . Iron was ranked as the highest produced metal. The increasing demand of iron could threaten environmental sustain-ability . A number of works have been carried out to solve this challenge. Many tools and indicators for assessing and bench-marking environmental impacts have been developed and applied to steel industry. In this work, life cycle assessment (LCA) method was used to find out how to improve environmental performance of steel industry in Vidarbha. This will subsequently be beneficial for all the work using steels as raw materials.

1.1. Steel industry

The steel industry can be categorized as three levels; crude steel, semi-finished steel, and finished steel. The semi-finished steels comprise slab, billet, bloom, beam, and blank, as shown in Fig. 1. The slab is used to produce flat products, such as hot-rolled steel, cold-rolled steel, and galvanized steel. The billet is used to produce long products, including bar and wire rod. The bloom, beam, and blank are used to produce heavy construction products. In Vidarbha, the flat products were consumed the most , and thus they were studied in this paper.

Nowadays the inputs for the steel production were mainly energy and iron or steel raw materials. The outputs were steel products, unwanted products, solid wastes, emissions to air and to water. The unwanted products such as scrap, slag, scale can be sold to cement or recycling industries. The emissions to air, e.g. CO_2, CO, SOx, NOx, dust, as well as emissions to water, e.g. oil, grease, chemicals, suspended solid, caused damages to ecosystem quality and to human health.

1.2. Life cycle assessment (LCA)

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, through production, use, end-of-life treatment, recycling, and final disposal . LCAconsiders all aspects of ecosystem, human health, and resources. This unique feature makes LCA useful for avoiding problem-shift-ing, for example, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another. Environmental impact assessment of any system needs a list of inputs and outputs of the system, called life cycle inventory (LCI). For example, LCI of a steel product at the production process consisted of (i) inputs, such as crude steel, chemicals, electricity, fuel, and water, and (ii) outputs, such as steel product, solid wastes, and emissions to air, to water, to soil. LCI is used to calculate impacts on the concerned environmental impact categories, such as global warming potential, eutrophication, acidification, ecotoxicity, resource depletion and damages to human health.

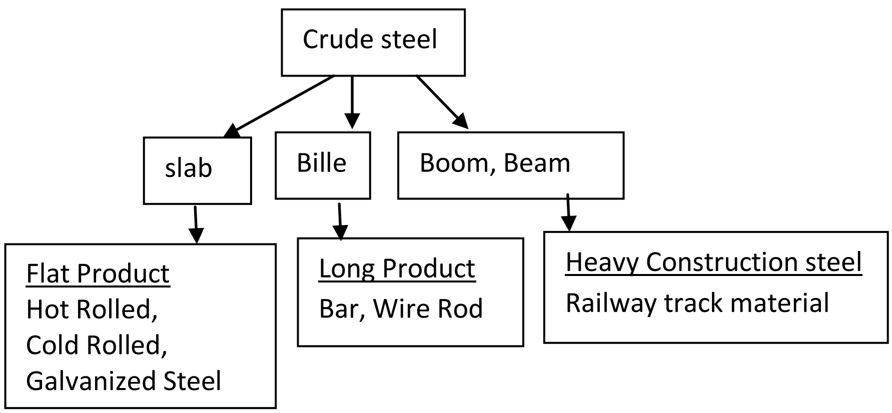

Fig. 1 Categorization of steel industry as crude steel, semi furnished steel, finished steel

Each input and output can contribute impacts to one or several impact categories. After being classified, each burden (i.e. input and output, excluding the products) is multiplied with its characterization factor (i.e. the environmental impact per unit of burden). The results of the multiplication are summed up, representing the impact of the system on the concerned category. Further assessment can be carried on, by applying weighting score to each impact category, depending on the aim of the study and availability of proper weighting methods. The process of classification, characterization, and weighting is called life cycle impact assessment (LCIA). There are several impact assessment methods in the form of software that can assist the classification, characterization, and weighting, such as Eco-indicator 99, CML, EDIP, TRACI, and IPCC 2007 GWP 100a.

Apart from the environmental impact assessment, LCA can be used for decision making on new product development. It can also be used for energy analysis, supplier management, critical resource planning, and product benefit claims. More information on LCA, LCI, and LCIA are described in ISO 14040 , ISO 14044 , and ISO 14047, respectively.

1.3. Environmental research on steel production

Steel was regarded as energy-intensive materials. The reduction of energy consumption and greenhouse gas emission has been seriously concerned in steel industry. The greenhouse gas emitted from the iron and steel industry, in Japan, was 15% of the total greenhouse gas emission of the country. The deficiency of energy and the impact of greenhouse gases, as well as the directives of greenhouse gas emission trading scheme supporting the Kyoto Protocol, have induced research and technology to overcome these challenges. Several measures for greenhouse gas emission reduction have been proposed, including the increase of scrap recycling, the use of carbon-free energy, the production of high performance steel to prolong the service life, the reuse and sequestration of CO_2 as dry ice, additives for beverage, and fire extinguishers. In Vidarbha, several steel companies have been making efforts to reduce greenhouse gas emission and improve their energy efficiencies.

Apart from the concern of greenhouse gas emission and energy consumption, the use of iron and metals, in steel production, is depleting mineral resources. Moreover, emissions (i.e. CO, NOx, SOx, oil, and heavy metals) from steel production can cause damages to ecosystem and to human health. Zinc was used in the production of galvanized steels. It was reported that zinc mining and refining were polluting industries, due to their toxic residue emissions. Lead (Pb) was a co-product and cadmium was a byproduct of the zinc production. Both lead and cadmium were found in the fume of zinc sinter plant These ecotoxic substances cause damages to living organisms. The dissolutions of nickel and zinc ions in water delayed the growth of an ampullariid snail embryo. The soil contamination of cadmium, copper and zinc decreased the germination rate of rice seeds and the growth of root cells.

LCA method as a tool to study environmental impacts from Finnish metal industry. In this study, the inventories of hot-rolled, cold-rolled, hot-dipped galvanized, and organic-coated steels were grouped as the inventory for "steel" product group. The assessments of environmental impacts from each life cycle stage of the product group, starting from mining to delivery of the product from the plant, were carried out. The impact categories of climate change, acidification, tropospheric ozone formation, and aquatic eutrophication were studied. The result showed that the production process contributed the highest environmental impact. The improvement of environmental performance was indicated in the form of partial eco-efficiency indicator (i.e. the environmental impact divided by the amount of liquid steel produced). From 1995 to 2005, these indicators for acidification, photo-oxidant formation, human toxicity, fresh-water aquatic Eco toxicity, eutrophication, and water use decreased by 45, 4, 52, 9, 11, and 33%, respectively, whereas the steel production increased by 17%.

The research mentioned above focused on steel industry as one product group (e.g. data of hot-rolled, cold-rolled, and hot-dipped galvanized steels were merged into the data of steel group). In this work, we focused on individual product of flat steels, i.e. slab, hot-rolled, cold-rolled, hot-dipped galvanized, and electro-galvanized steels. The environmental impacts on ecosystem, resources, and human health, due to steel production, were assessed using LCA method. The sources contributing to the environmental impacts were also investigated.

2. Methodology

2.1. Goal

As steel industry is trying to improve the environmental performance of their products, the environmental impact assessment of specific steel product would be beneficial, enabling them to know where and how the problems should be solved. Since the flat steels were consumed the most in Vidarbha, this work focused on environmental impacts of individual flat steel, i.e. of slab, hot-rolled, cold-rolled, hot-dipped galvanized, and electro-galvanized steels. The sources contributing to the environmental impacts were investigated and potential ways to cope with the challenges were discussed.

Relatively large amount of zinc was used for the production of the hot-dipped galvanized steel, while relatively large amount of energy was used for the production of the electro-galvanized steel. In this study, the difference of environmental impacts from these two types of steel was investigated.

The environmental impacts on ecosystem, resources, and human health were studied, via LCA approach. The impact assessment methods of "IPCC 2007 Global warming potential 100a" (IPCC 2007 GWP 100a) and Eco-indicator 99 (H) were used to cover the impact categories of Global Warming Potential, Ecotoxicity, Minerals, Fossil fuels, Carcinogens, and Respiratory inorganics. The classification and characterization were performed in the impact assessment. The weighting process was excluded from the study.

This work could be beneficial, not only to steel industry sector, but also to policy maker, researcher, and engineer, who could play important roles in improving the environment of the nation.

2.2. Scope

2.2.1. Description of the system and data under study

The system boundary of this study is shown in Fig. 2. The product systems comprised the acquisitions of raw materials (i.e. iron or steel input, chemicals, scrap, water) and energy (i.e. fuel, electricity), as well as, the production of the steel product. The collection, transportation, and processing of scrap were included in the system boundary. One ton of steel product at the factory gate was used as a functional unit of this study. The functional unit is the basis that enables alternative goods, or services, to be compared and analyzed . The inventory at the production stage was obtained from national steel LCI of Vidarbha, carried out in 2006, according to the ISO 14040, by National Metal and Materials Technology Center, together with Vidarbha Environment Institute, supported by Ministry of Industry. The acquisitions of rawmaterials, energy, and scrap were not comprised in the national LCI and thus these inventories were selected from the database, e.g. Ecoinvent, IDEMAT 2001, ETH-ESU 96, in SimaPro 7.1 software. For example, the electricity in Vidarbha was mainly generated by natural gas (>70%) and thus the database of electricity generated by natural gas in the software was chosen.

The national LCI is an average of the collected data from the steel production plants. The data coverage depends on their cooperation. The production processes and data coverage of the steel products under this study are described as follow.

Slab: The raw materials for slab production were 70% scrap and 30% imported pig iron. They were melted in an electrical arc furnace. After being refined, the melted iron was continuously cast to produce slab. The data coverage was 100% of all slab production capacity in Vidarbha.

Hot-rolled steel: It was produced from slab which passed through the process of re-heating, de-scaling by high pressure water, hot strip milling at 1100e1250 ⁻C, and finally coiling. The data coverage was 65.5% of all hot-rolled steel production capacity in Vidarbha.

Cold-rolled steel: After being passed through the process of pickling and cold rolling to reduce the thickness at room temperature, the hot-rolled steel was annealed and temper-rolled to obtain the cold-rolled steel. The data coverage was 81.6% of all cold-rolled steel production capacity in Vidarbha.

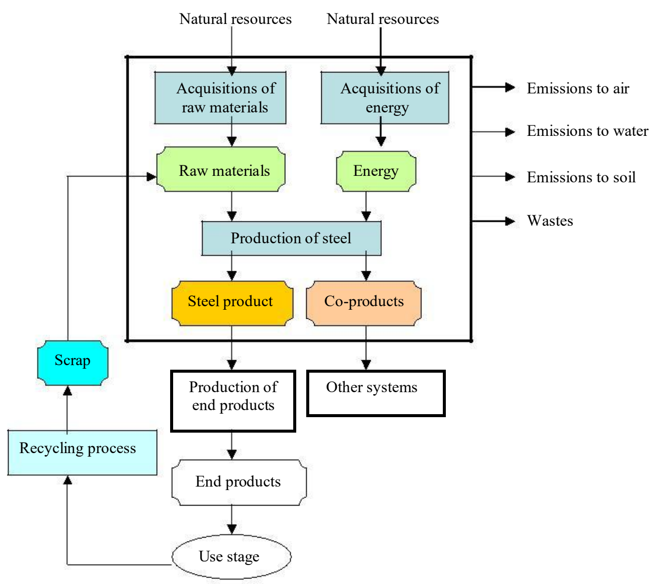

Fig. 2. Boundary of the product systems under LCA study.

Hot-dipped galvanized steel: The hot-dipped galvanized steel was produced from the cold-rolled steel. After being cleaned and annealed, the cold-rolled steel was dipped in melted zinc in a zinc bath having temperature of 465 ⁻C. Then, it was chemically treated to prevent corrosion and finally coiled. The hot-dipped galvanized steel is superior in corrosion protection. It is used for infrastructure work. The data coverage was 22.8% of all hot-dipped galvanized steel production capacity in Vidarbha.

Electro-galvanized steel: The electro-galvanized steel was also made from the cold-rolled steel. After being cleaned, the cold-rolled steel was electrically coated with zinc and then finally cleaned.The electro-galvanization was used for small pieces of steel that need very thin homogeneous zinc coating. The data coverage was 100% of all electro-galvanized steel production capacity in Vidarbha.

The inventory at the production stage covered these inputs; iron or steel, zinc, chemicals, fuel, electricity, water, as well as these outputs; steel product, co-products, wastes, emissions to air and to water, from both the main process and supporting systems. The supporting systems included the systems for water production, water cooling, waste treatment, fume and dust control. The water quality was measured after the treatment process. The emissions of CO, SOx, NOx and particulates were measured at the emission points of the production plants. The amount of CO_2 from fuel combustion was calculated using emission factors from the Final Report Life Cycle Assessment for Asian Countries E Phase III of JEMAI modified by average calorific values of fuels from Department of Alternative Energy Development and Efficiency, Vidarbha. Amounts of CO_2 from the reactions in an electrical arc furnace, i.e. combustion of coke, were calculated using emission factors from World Steel Association.

The raw materials less than 0.001% of the 1-ton steel product were excluded from the assessment. The buildings and machinery of the production plants were also excluded. This is because the building and machinery lasted several years, and thus their envi-ronmental impact contributions to the 1-ton steel product were very small. The transportations of raw materials from oversea and within Vidarbha were not included in this study, as this paper was aimed to improve environmental performance of the steel production at the production plant. The inclusion of all raw materials, building, machinery, and transportation, in the assessment, is costly and time-intensive.

There was small amount of co-products from the steel production, such as slag, scale and scrap. The environmental burdens were allocated to the main products and co-products by mass. Allocations by mass, energy, and economic value are the most commonly applied. Allocation by energy is normally used when the product is energy-related such as natural gas and refinery products. Tillman stated that when allocation cannot be avoided, the system's inputs and outputs should be partitioned among its different products or functions in a way that reflects the underlying physical relationships between them. If physical relationshipcannot be established or used as a basis for allocation, allocation should reflect other relationships between the products or functions of the system, such as economic value. Economic allocation is also applied when the products (and co-products) have economical values far different from one another. This has advantages on the promotion of utilization of low-value co-products. This allocation method might face uncertainty due to the variation of market price. Normally, mass allocation was not applied when the system produced small amount of high-value main products and large amount of low-value co-products. This is to avoid environ-mental load allocation to the co-products which are not the main purpose of the production. However, the choice of allocation is dependent on the definition of the goal and scope of the study. In this work, as the amounts of co-products were small, mass allocation was applied to avoid uncertainty, due to the market price variation.

2.2.2. Impact assessment and result interpretation

The impact assessment method of IPCC 2007 GWP 100a (version 1.01) was used to study the impact of Global Warming Potential. The unit of the Global Warming Potential is kg CO_2e (kg carbon dioxide equivalent), which represents global warming impact of greenhouse gas, expressed in terms of the amount of CO_2 that would have an equivalent impact. The impact assessment method of Eco-indicator 99 (H) (version 2.06) was used to study three main damage categories; (i) the damage to ecosystem quality caused by ecotoxic substances, (ii) the damage to resources caused by depletion of minerals and fossil fuels, and (iii) the damage to human health caused by carcinogenic substances and respiratory effects. The impact categories mentioned above are called Ecotox-icity (unit: $PAF^{*}m^{2}yr$), Minerals (unit: MJ surplus), Fossil fuels (unit: MJ surplus), Carcinogens (unit: DALY), and Respiratory inor-ganics (unit: DALY), respectively. The unit "$PAF^{*}m^{2}yr$" stands for Potentially Affected Fraction of species in relation to the concen-tration of toxic substances, multiplied by area (m^2) and year (yr). The PAF is used to express the effect on (mostly lower)organisms that live in soil and water. It is a measure of toxic stress, not a real damage, due to the exposure to a concentration equal to or higher than "No Observed Effect Concentration". The impact of 1 $PAF^{*}m^{2}yr$ means all species, in 1 m^2, are living under stress during one year, or 10% of all species, in 1 m^2, are living under stress, during 10 years. The unit "MJ surplus" represents the difference between the energy needed to extract a resource now and at some point in the future. An impact of 1 MJ surplus means that, due to a certain extraction, further extraction of this resource in the future will require additional energy of 1 MJ, as a result of the lower resource concentration, or other unfavorable characteristics of the remaining reserves. The point in the future was chosen as the time, at which 5 times of cumulative extraction of the resources before 1990, was extracted. The surplus energy is dependent on the choice of "N" times of cumulative extraction (of the resources before 1990), and thus the absolute value of surplus energy has no real meaning. The unit "DALY" stands for Disability Adjusted Life Years. The impact of1 DALY means, one life year of one individual is lost, or one person suffer four years from a disability with a weight of 0.25.

After the steel inventories were obtained, the classification and characterization method of IPCC 2007 GWP 100a and Eco-indicator 99 (H) were applied, via SimaPro 7.1 software. The sources contributing to the environmental impacts were classified as; (i) steel input (i.e. scrap and pig iron in the case of slab), (ii) water input, (iii) zinc input, (iv) energy input (i.e. fossil fuel and electricity), (v) chemicals input (any raw materials apart from (i) to (iv)), and (vi) emissions from steel production plants (i.e. solid wastes and emissions to air and to water,).

It should be noted that the inventory of any system depends on goal, scope, system boundary, methodology and exclusion criteria of the study. The inventory data is also time, geography and technology-related. The completeness of the inventory depends on technology availability as well as social and economic interests. The completeness and correctness of the inventoryaffect the impact assessment results. Thus all parameters mentioned above should be aware before making the result interpretation. The limitation of LCA and data quality requirement for LCI can be found in ISO 14044.
In this work, certain inventories from the database in SimaPro 7.1 software were applied. Therefore, the results of the impact assessments might not totally represent the status of steel industry in Vidarbha. Nevertheless, they can give an idea where and how the environmental performance can be improved, without spending much time and budget on the development of country-specific inventories.

3. Results and discussion

3.1. Characterization of environmental impacts

The environmental impacts of steels in the categories of Fossil fuels, Global warming potential, Ecotoxicity, Minerals, Carcino-gens, and Respiratory inorganics are shown in Fig. 3. In all cate-gories, the hot-dipped galvanized steel showed the highest impacts, while the slab showed the lowest impacts. This is because slab was the upstream of the studied steels and the hot-dipped galvanized steel was the downstream product. As a result of rela-tively large amount of zinc input, the hot-dipped galvanized steel showed higher impacts than the electro-galvanized steel. The main sources of the impacts were these inputs; steel, energy, and zinc. The impacts caused by chemicals, water, and emissions, were relatively low.

3.1.1. Steel input

In all types of steel products and in all impact categories, the steel input was one of the main impact contributors. As slab was the upstream of all studied steels, the reduction of the impacts caused by slab would subsequently affect the rest of the steels. The steel input of slab consisted of pig iron and scrap. Table 1 shows that the impacts caused by scrap were much lower than those of pig iron, although scrap content in the slab was relatively high.

When the inventories of scrap (from database of Ecoinvent, SimaPro 7.1 software) and pig iron (Ecoinvent, SimaPro 7.1 soft-ware) were assessed, using IPCC 2007 GWP 100a and Eco-indicator 99 (H) methods, it can be seen in Table 2 that, the impacts of 1-kg scrap were much lower than those of 1-kg pig iron. The impacts of pig iron in the categories of Fossil fuels, Global warming potential, Ecotoxicity, Minerals, Carcinogens, and Respiratory inorganics were 29.9, 30.7, 7.0, 7.9, 6.3, and 39.6 times of those of scrap, respectively. This is because scrap, unlike pig iron, does not go through the stages of mining, refining, melting, and thus resource consumption, as well as, emissions to air, to water, to soil, were relatively low.

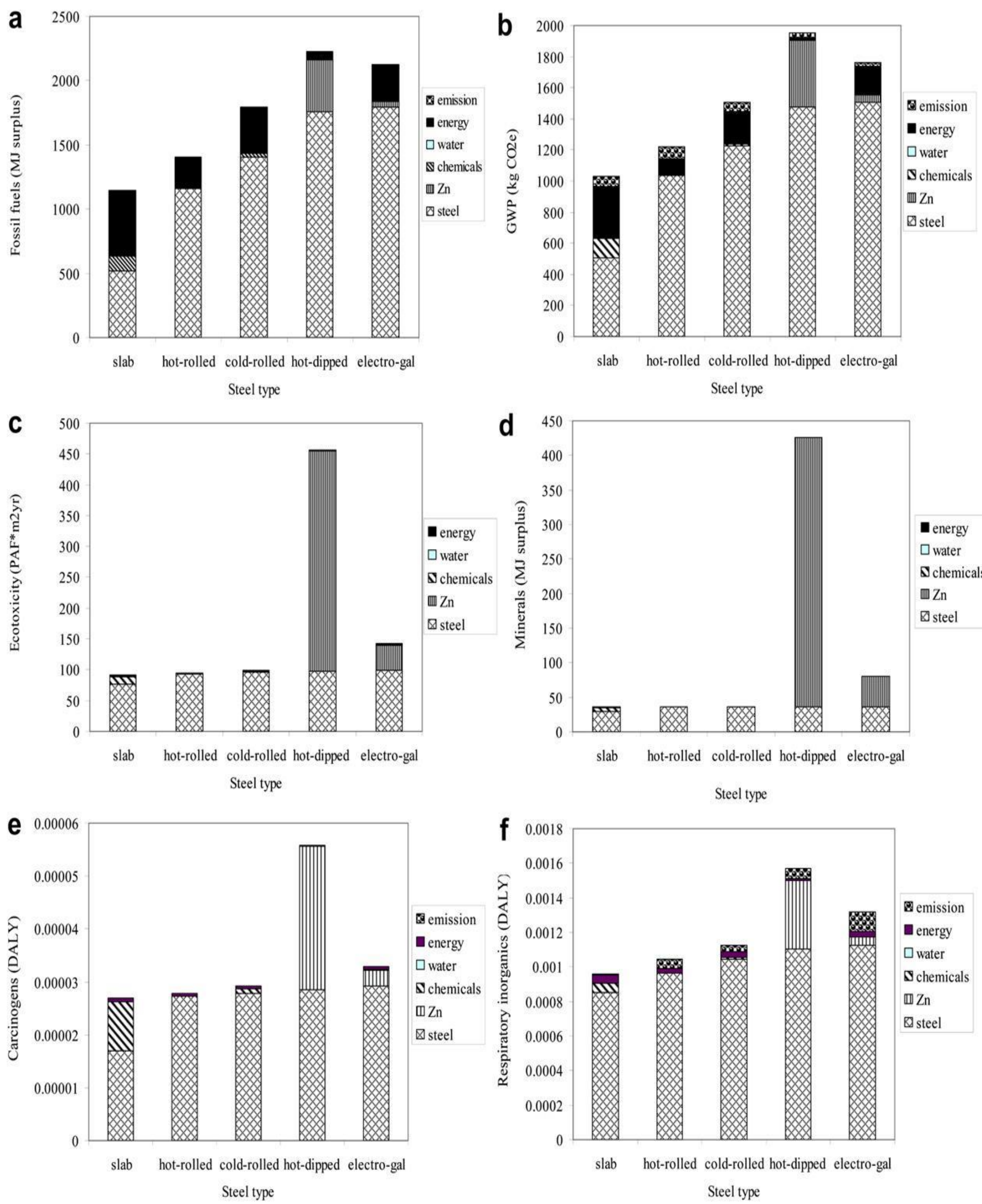

Fig. 3. The sources contributing to the impact categories of (a) Fossil fuels, (b) Global warming potential, (c) Ecotoxicity, (d) Minerals, (e) Carcinogens, and (f) Respiratory inorganics,for the 1-ton productions of slab, hot-

rolled, cold-rolled, hot-dipped galvanized, and electro-galvanized steels.

3.1.2. Energy input

Apart from the steel input, the energy input was also the main impact contributor, in the categories of Fossil fuels and Global warming potential (Fig. 3). The energy input included electricity and fossil fuels. In this study, the impact from electricity was relatively large (Table 1), due to the use of electrical arc furnace in the production process. The reductions of energy consumption and impacts from electricity generation are discussed in Section 3.2.

3.1.3. Zinc input

The zinc amount, used in the production of the hot-dipped galvanized steel, was only 8.5% by weight of total raw materials, but its impact was distinctly high (Fig. 3). In the categories of Ecotoxicity and Minerals, the impacts caused by zinc input were much higher than those of the steel input (i.e. cold-rolled steel). When the inventories of the cold-rolled steel and zinc (database of IDEMAT 2001, SimaPro 7. 1 software) were assessed using IPCC 2007 GWP 100a and Eco-indicator 99 (H) methods, it can be seen in Table 3 that, the impacts of 1-kg zinc were higher than those of 1-kgcold-rolled steel. In the category of Fossil fuels, 1-kg zinc caused an impact of 5.15 MJ surplus. This means that, the consumption of fossil fuel in zinc production reduced the fossil fuel concentration in natural resources, and thus additional energy of 5.15 MJ was needed to extract the same amount and the same type of fossil fuel in the future (see Section 2.2.2). Each type of fossil fuel has indi-vidual damage factor; coal ¼ 0.252 MJ surplus/kg, crude oil ¼ 5.9 MJ surplus/kg, natural gas ¼ 4.55 MJ surplus/kg . The cold-rolled steel of 1 kg caused an impact of 1.79 MJ surplus. This implied that the production of cold-rolled steel caused lower damage to fossil fuel resources than the production zinc. The damage caused by zinc was ¼ 5.15/1.79 ¼ 2.9 times of that caused by the cold-rolled steel.

Table 1Environmental impact contributions from steel and energy inputs for 1-ton slab production.

Impact category	Unit	Steel input		Energy input	
		Pig iron[a]	Scrap[a]	Electricity[a]	Fuel[b]
Fossil fuels	MJ surplus	478.4	38.7	443.9	64.3
GWP[c]	kg CO_2e	467.0	36.8	320.0	11.8
Ecotoxicity	PAF * m^2 yr	57.3	19.7	2.3	0.7
Minerals	MJ surplus	22.2	6.8	0.4	0.02
Carcinogens	DALY	1.2 _ 10^{-5}	4.7 _ 10^{-6}	5.6 _ 10^{-7}	6.3 _ 10^{-8}
Respiratory[d]	DALY	8.0 _ 10^{-4}	4.9 _ 10^{-5}	4.4 _ 10^{-5}	3.5 _ 10^{-6}

[a] Database of Ecoinvent.
[b] Database of ETH-ESU 96.
[c] Global warming potential.
[d] Respiratory inorganics.

The Ecotoxicity caused by 1-kg zinc was 39.6 times of that caused by 1-kg cold-rolled steel (Table 3). This can be explained as follow. The ecotoxic substances in Eco-indicator 99 (H) include (i) heavy metals, e.g. arsenic, cadmium, chromium, copper, lead, mercury, nickel, and their ions, as well as (ii) organic chemicals, e.g. dioxin, diquat, phenol compounds, benzene and its compounds. Several heavy metals were found in the inventories of zinc and crude iron (IDEMAT 2001, SimaPro 7.1 software). In order to obtain 1-ton zinc, 0.5 g of cadmium was emitted to air, and 1.5 g of nickel was emitted to water. These amounts were much higher than those presented in the inventory of 1-ton crude iron, where cadmium emission to air was 0.09 g and nickel emission to water was 0.03 g.

Table 3 shows that, in the category of Minerals, 1-kg zinc causedan impact of 4.30 MJ surplus. This means that, the consumption of minerals in zinc production reduced the mineral concentration in natural resources, and thus additional 4.30 MJ of energy is needed to extract the same amount and the same type of minerals in the future (see Section 2.2.2). Each type of minerals has individual damage factor; pure zinc ¼ 4.09 MJ surplus/kg, pure iron ¼ 0.051 MJ surplus/ kg, pure copper ¼ 36.7 MJ surplus/kg .The cold-rolled steel of 1 kg caused an impact of 0.04 MJ surplus. This implied that the production of cold-rolled steel caused lower damage to mineral resources than the production zinc. The damage caused by zinc was ¼ 4.30/0.04 ¼ 116.9 times of that caused cold-rolled steel. This corresponded to the comparison between "pure zinc" and "pure iron", as the impact of "pure zinc" was ¼ 4.09/0.051 ¼80 times of "pure iron". The impact of "pure zinc" was lower than that of the zincin IDEMAT 2001, as the latter needed fuel and electricity for transportation and production process. The impact of "pure iron" was higher than that of the cold-rolled steel. This is because the cold-rolled steel was originally made from slab, which was made from 70% scrap and 30% pig iron. The high content of scrap was a reason for relatively low impact of the cold-rolled steel (see Table 2).

Table 2 Comparison of environmental impacts of pig iron and iron scrap.

Impact category	Unit	Impact of 1 kg		Impact ratio of Pig iron:Iron scrap
		Pig iron[a]	Iron scrap[a]	
Fossil fuels	MJ surplus	1.54	0.05	29.9:1
GWP[b]	kg CO_2e	1.51	0.05	30.7:1
Ecotoxicity	PAF * m^2 yr	0.18	0.03	7.0:1
Minerals	MJ surplus	0.07	0.01	7.9:1
Carcinogens	DALY	3.96 _ 10^{-8}	6.28 _ 10^{-9}	6.3:1
Respiratory[c]	DALY	2.59 _ 10^{-6}	6.55 _ 10^{-8}	39.6:1

[a] Database of Ecoinvent.
[b] Global warming potential.
[c] Respiratory inorganics.

In the categories of Global warming potential, Carcinogens, and Respiratory inorganics, the impacts caused by zinc were 3.1, 10.2, and 3.9 times of those caused by the cold-rolled steel, respectively (Table 3). In order to reduce these impacts, IPCC 2007 GWP 100a and Eco-indicator 99 (H) methods were used to assess the zinc inventory (IDEMAT 2001, SimaPro 7.1 software), to indicate the sources of the impacts. The results show that the main contributors for Ecotoxicity and Respiratory inorganics were emissions from zinc production process (Table 4). The control of emissions and leakages of ecotoxic substances from zinc production process should be emphasized. The main contributor for Minerals was natural resource, i.e. zinc in ground, used as raw materials for zinc production. Research on reduction of zinc amount in the galvanized steel production process should be carried out. In the case of Fossil fuels, Global warming potential, and Carcinogens, energy consumption in the zinc production was the main impact contributor. The main energy type was electricity, which comprised the electricity generated by coal, gas, oil, nuclear and hydropower. After the impact assessment of 1-MJ electricity inventory (IDEMAT 2001, SimaPro 7.1 software), it is shown in Table 5 that, the coal-generated electricity was the main cause of Carcinogens, and the gas-generated electricity was the main cause of Fossil fuels and Global warming potential.

Table 3
Comparison of environmental impacts of zinc and cold-rolled steel.

Impact category	Unit	Impact of 1 kg		Impact ratio of Zinc:Cold-rolled steel
		Zinc[a]	Cold-rolled steel	
Fossil fuels	MJ surplus	5.15	1.79	2.9:1
GWP[b]	kg CO_2e	4.71	1.51	3.1:1
Ecotoxicity	PAF * m^2 yr	3.94	0.10	39.6:1
Minerals	MJ surplus	4.30	0.04	116.9:1
Carcinogens	DALY	2.97 _ 10^{-7}	2.92 _ 10^{-8}	10.2:1
Respiratory[c]	DALY	4.39 _ 10^{-6}	1.13 _ 10^{-6}	3.9:1

[a] Database of IDEMAT 2001.
[b] Global warming potential.
[c] Respiratory inorganics.

3.1.4. Emissions

The emissions from the steel production plants caused Global warming potential (Fig. 3b) and Respiratory inorganics (Fig. 3f). Their contributions to Global warming potential and Respiratory inorganics of the steel products were less than 7% and 9%, respectively. These were relatively low, compared to the impacts from the steel and zinc inputs. The Global warming potential was a result of greenhouse gas emissions. The research on greenhouse gas emission reduction for steel industry is mentioned in Section 1. The Respiratory inorganics was a result of the emissions of nitrogen oxides, sulfur oxides, and particulates, which arised from fossil fuel combustion. The reduction of fossil fuel consumption would subsequently reduce air emissions and finally Respiratory inorganics.

The amount of greenhouse gas emissions, from acquisition stage of raw materials to production stage, of the cold-rolled, hot-dipped galvanized, and electro-galvanized steels was close to those reported by International Iron and Steel Institute. This implies that the steel production process in Vidarbha was similar to inter-national production process, in terms of technology and resource consumption.

3.2. Reduction of environmental impacts

3.2.1. Reduction of the impacts from energy consumption

The impacts from energy consumption can be reduced via the reduction of energy consumption. Several approaches were proposed, for example, hot-rolling of warm slab, integration of steel production, improvement of furnace efficiency, energy recovery from slag and from furnace. Another approach was the use of low-impact energy. Environmental impacts of 1-MJ electricity generated by coal, gas, hydropower, and oil (database of IDEMAT 2001, SimaPro 7.1 software) are compared in Table 6. The coal-generated electricity showed high impacts in the categories of Global warming potential, Minerals, and Carcinogens. The oil-generated electricity showed high impacts in the categories of Fossil fuels, Ecotoxicity, and Respiratory inorganics. The electricity generated by gas and hydropower caused relatively low impacts.

Table 4 Environmental impacts from each component of 1-kg zinc (from the database of IDEMAT 2001, SimaPro 7.1 software).

Impact category	Unit	Total	Emissions/natural resources[a]	Energy	Transportation
Fossil fuels	MJ surplus	5.15	0	4.36	0.79
GWP[b]	kg CO_2e	4.71	0	4.32	0.38
Ecotoxicity	PAF m^2 yr	3.94	3.49	0.20	0.25
Minerals	MJ surplus	4.30	4.29	3.96×10^{-3}	3.18×10^{-5}
Carcinogens	DALY	2.97×10^{-7}	7.16×10^{-8}	2.25×10^{-7}	1.21×10^{-9}
Respiratory[c]	DALY	4.38×10^{-6}	2.09×10^{-6}	1.41×10^{-6}	8.83×10^{-7}

[a] In the case of minerals, it is natural resources.
[b] Global warming potential.
[c] Respiratory inorganics.

It should be noted that the results of the impact assessment are dependent on the completeness of the inventory and the concerned impact categories. For example, the electricity generated by hydropower might not create low environmental impact, consid-ering that the dam construction might interrupt the ecosystem. It might cause the change of river flow direction, the decrease of water level behind the dam, and thus the disappearance of certain species. This might deteriorate the lives of the people living behind the dam. The use of renewable energy might reduce one environ-mental impact and increase or create another environmental impact. Therefore, all possible environmental impacts should be considered before making the decision.

3.2.2. Steel recycling

It is shown in Table 2 that the Fossil fuels, Global warming potential, Ecotoxicity, Minerals, Carcinogens and Respiratory inor-ganics, of pig iron are 29.9, 30.7, 7.0, 7.9, 6.3, and 39.6 times of those of scrap, respectively. This means that the use of scrap, instead of virgin iron, could tremendously reduce environmental impacts.

It was reported that, in 2001, around 70% of steel scrap was recycled in UK and around 30% of scrap was lost or undocumented . In the Netherlands, 80% of scrap was recycled. In Vidarbha,among all the wastes, steel scrap was

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the most recycled. Although, there are several steel recycling companies in this country, the collection and management were not done efficiently. In 2004, 77.6% of the solid waste in Vidarbha was open dumps, and the rest was landfills. There was a possibility of toxic metal leaching from a controlled landfill. In 2000, the municipal solid waste in Vidarbha was 38,280 tons/day, including 1.15 ton of ferrous metal. It was reported that the recycling of steel saved energy of 5.34 MJ/kg. If all ferrous waste in Vidarbha was recycled, the energy saving would be ¼ 1.15 ton/day _ 1000 kg/ton _ 5.34 MJ/ kg ¼ 6141 MJ/day. Nystrom et al. reported that the recycling faced difficulty because people were lacked of technical under-standing, and were not receptive towards establishing the indus-trial recycling relationship. They suggested that this problem could be solved, using a middleman, or a broker, who played crucial roles in establishing the relationship. Although the use of scrap is beneficial to the environment, it should be aware that scrap can cause impurities in steel, leading to technical difficulty and performance reduction.

Table 5 Environmental impacts of 1-MJ electricity (IDEMAT 2001, SimaPro 7.1 software), that comprised the electricity generated by coal, gas, oil, nuclear and hydropower.

Impact category	Unit	Electricity sources				
		Coal	Gas	Hydro	Nuclear	Oil
Fossil fuels	MJ surplus	1.6 _ 10^{-2}	2.0 _ 10^{-1}	1.3 _ 10^{-6}	1.7 _ 10^{-4}	2.0 _ 10^{-2}
GWP[a]	kg CO_2e	1.1 _ 10^{-1}	1.2 _ 10^{-1}	2.4 _ 10^{-6}	1.2 _ 10^{-4}	1.1 _ 10^{-2}
Ecotoxicity	PAF ˆ m^2 yr	8.3 _ 10^{-3}	9.1 _ 10^{-4}	4.6 _ 10^{-7}	2.0 _ 10^{-5}	4.4 _ 10^{-3}
Minerals	MJ surplus	1.3 _ 10^{-4}	1.2 _ 10^{-4}	4.1 _ 10^{-8}	1.0 _ 10^{-5}	1.4 _ 10^{-5}
Carcinogens	DALY	1.3 _ 10^{-8}	2.0 _ 10^{-9}	1.5 _ 10^{-13}	1.2 _ 10^{-11}	1.7 _ 10^{-10}
Respiratory[b]	DALY	4.3 _ 10^{-8}	2.3 _ 10^{-8}	1.1 _ 10^{-12}	8.3 _ 10^{-11}	8.2 _ 10^{-9}

[a] Global warming potential.
[b] Respiratory inorganics.

3.2.3. Efficient use of steel

An electrical arc furnace was used in steel recycling process and it was reported to be the source of dioxin, depending on the scrap composition. The dust from the electrical arc furnace was composed of hazardous metals such as lead, cadmium, chromium, which should be properly treated. This raised a question if steel should be recycled or made for long-life use. The long-life steel, normally, is made from virgin iron, which causes higher environmental impacts than the scrap. However, due to its long life, the iron extraction rate (e.g. ton per year) is small. Further study should be done before making the conclusion and it is out of the scope of this work. Efficient use of steel is the best practice. It was reported that the steel wastes from the constructions were a result of poor structural design and poor material handling. Unnecessary scrap can be avoided by wise materials handling, reconditioning old machines and equipment, as well as promoting production yield, i.e. reduction of internal defects and surface flaws

3.2.4. Reduction of virgin zinc consumption

The environmental impacts of the galvanized steel were largely affected by the zinc input (see Fig. 3 and Table 3). The American Galvanizers Association reported that, for an average structuralEnvironmental impacts of 1-MJ electricity (IDEMAT 2001, SimaPro 7.1 software), that comprised the electricity generated by coal, gas, oil, nuclear and hydropower.Ssteel assembly, a hot-dipped galvanized steel contained 1.8%wt of zinc.

Table 6 Environmental impacts caused by the production of 1-MJ electricity, generated by coal, gas, hydropower, and oil (IDEMAT 2001, SimaPro 7.1 software).

Impact category	Unit	Sources of 1-MJ electricity			
		Coal	Gas	Hydro	Oil
Fossil fuels	MJ surplus	4.6 _ 10^{-2}	3.6 _ 10^{-1}	6.3 _ 10^{-4}	4.6 _ 10^{-1}
GWP[a]	kg CO_2e	3.0 _ 10^{-1}	2.2 _ 10^{-1}	1.2 _ 10^{-3}	2.5 _ 10^{-1}
Ecotoxicity	PAF ˆ m^2 yr	2.4 _ 10^{-2}	1.7 _ 10^{-3}	2.3 _ 10^{-4}	1.0 _ 10^{-1}
Minerals	MJ surplus	3.6 _ 10^{-4}	2.2 _ 10^{-4}	2.0 _ 10^{-5}	3.3 _ 10^{-4}
Carcinogens	DALY	3.7 _ 10^{-8}	3.6 _ 10^{-9}	7.2 _ 10^{-11}	3.9 _ 10^{-9}
Respiratory[b]	DALY	1.2 _ 10^{-7}	4.2 _ 10^{-8}	5.5 _ 10^{-10}	1.9 _ 10^{-7}

a

Global warming potential.
[b] Respiratory inorganics.

This amount was much lower than the zinc consumption in this study, which was 9%wt of the hot-dipped galvanized steel. The reduction of zinc amount in the galvanization process should be emphasized.

Another approach to reduce virgin zinc consumption was recycling of galvanized steels. A recovery of zinc from automobiles and personal computers was reported to be easy. When galvanized steel was heated in an electrical arc furnace, the zinc, which has higher vapor pressure than steel and low solubility in molten steel, ends up in the dust, where zinc can be recovered. The hydrometallurgical process, using acidic and basic solutions to treat low-zinc containing materials, was claimed to be more economical than the pyrometallurgical method which requires high energy, dust collecting, and non-corrosive construction materials. It was reported that the recycling of zinc increased air pollution as a result of transportation and heavy metals from dross. However, this was insignificant compared to the environmental problems caused by the consumption of large amount of energy for virgin zinc production.

3.2.5. Improvement of zinc production process

Table 4 shows that, in the zinc production process, the energyconsumption was the main contributors for Fossil fuels, Global warming potential and Carcinogens. The emissions were the main contributors for Ecotoxicity and Respiratory inorganics. The environmental performance of zinc production can be improved by the reduction of energy consumption, the use of low-impact energy, and prevention of heavy metal emissions to air, to water, and to soil.

4. Conclusions

Among the studied steels, slab showed the lowest impact and the hot-dipped galvanized steel showed the highest impact in all impact categories. As a result of relatively large amount of zinc input, the hot-dipped galvanized steel showed higher impacts than the electro-galvanized steel. The main impact contributors were these inputs; steel, energy, and zinc. The impacts caused by chemicals, water, and emissions, were relatively low. The steel input showed high impacts as virgin iron was used to produce slab, which was the upstream of the studied steels. The substitution of virgin iron with scrap could reduce the impacts of Fossil fuels, Global warming potential, Ecotoxicity, Minerals, Carcinogens, and Respiratory inorganics, by 29.9, 30.7, 7.0, 7.9, 6.3, and 39.6 times, respectively. Apart from the reduction of energy consumption, the impacts from energy input could be reduced by the use of low-impact energy, considering the effects of energy generation on resources, human health, as well as the ecosystem. LCA could assist the decision making.

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