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Energy efficiency in the Mexican iron and steel industry from an international perspective

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ABSTRACT

Mexico is an important iron and steel manufacturer; it is the 13th largest steel producer in the world. The Mexican iron and steel industry is first in energy consumption for industrial energy use, representing 14.3% of the total industrial final energy consumption and a similar share of related carbon dioxide emissions. The aim and novelty of this paper is to estimate both the energy intensity and CO_2 intensity of the Mexican iron and steel industry in 2010 based on defined system boundaries and an international comparison methodology and to compare the energy intensity of Mexican with those the US and China based on a literature review. The boundaries consider energy consumption for all coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing, such as galvanizing or coating. They also include energy use for net imported pig iron, direct-reduced iron, pellets, lime, oxygen, ingots, blooms, billets, and slabs. Under these boundary conditions, the Mexican iron and steel industry was shown to be more energy efficient and less carbon intense than those the U.S. and China. The reasons for this efficiency are mainly the large shares of the electric arc furnace route (69.4%) and continuous casting (100%) in production and the large share of natural gas in the fuel mix. This paper highlights the importance of the definition of boundaries and clear methodologies to analyse the iron and steel energy efficiency.

1. Introduction

The iron and steel industry is the main industrial source of CO_2 emissions due to the large volume of steel produced, the high-energy use intensity, and the significant use of carbon-based fuels. The principal steel producers in the world are China, Japan, the US, India, and Russia (Fischedick et al., 2014). Mexico is an important iron and steel manufacturer and is the 13th largest steel producer in the world. In 2014, Mexico produced 19 million metric tonnes (Mt) of crude steel, accounting for 1.16% of the world's crude steel production.

Because of the importance of energy use in this material industry, an important research area is the comparison of the energy intensity of different countries to identify promising areas to improve the efficiency and mitigate GHG emissions (IEA, 2007). In general, the comparison of energy consumption requires reliable indicators based on good data consistency, feasibility and verifiability (IEA, 2008) but also the definition of boundaries, production processes and technologies, feed stocks and products that are to be taken into account in the international energy consumption comparisons.

The system boundary defines the study area from raw materials to products. The system boundary is commonly used in life cycle assessment to define the major activities in the course of the product life span from its manufacture and use to its final disposal (US EPA, 2006). In contrast, in energy intensity studies, the boundary definition considers the activities from raw materials to products, as well as the imports and exports of raw materials that are included in the summation of energy consumption to produce steel products.

The production processes and technologies used to produce iron and steel can be divided into three major production routes (worldsteel, 2015). The most conventional route for making steel consists of sintering or pelletization plants, coke ovens, blast furnaces, and basic oxygen furnaces. It can be described by CO + PI-BF-BOF (Coking coal + Pig iron − Blast Furnace − Basic Oxygen Furnace); the other routes are melting direct reduced iron (DRI)

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and/or scrap steel in an electric arc furnace (DRI-EAF and SC-EAF).

For the products, there is a wide range of steel goods. In general, molten steel from furnaces passes through continuous casters and is formed into slabs, blooms and billets and then transformed into a wide range of finished steel products through hot and cold rolling processes (Cowling and Rezig, 2000). Secondary industries transform steel products into final products (machinery, automobiles, construction materials, appliances, etc.).

The objective of this paper is to estimate the specific energy consumption and carbon intensity of the Mexican iron and steel industry for the base year 2010 using a clear system boundary definition and methodology elaborated by Hasanbeigi et al. (2014a) and to compare the energy and CO_2 indicators with those of the iron and steel industries of the US and China. The paper does not analysed trends in energy intensity but develops a full methodology based on clear boundary definitions of both energy and CO_2 intensities of iron and steel industry that allows better international comparisons. There is a range of studies on international comparisons of energy efficiency in the iron and steel industry. In the following section, a review of this academic literature is presented.

1.1. Literature review of the energy intensity indicators for international comparisons in the iron and steel industry

In the late 1990s and early 2000s, the discussion was centered on the difference in economic and physical indicators. Worrell et al. (1997) developed one of the first comprehensive studies on international comparisons of physical and economic indicators of energy intensity in the iron and steel industry. In this study, they concluded that the use of physical energy intensity indicators improves the comparability between countries and provides detailed explanations for the observed changes in energy intensity. Farla and Blok (2001) discussed the accuracy of the physical energy intensity indicators and energy consumption data used and warned that energy analysts need to be careful when using energy data for international comparisons because of doubts regarding the quality and equivalency of definitions. Price et al. (2002) found inconsistencies in the reported statistical data of energy use values for steel production in China that are comparable to statistics used internationally. Kim and Worrell (2002) presented an in-depth decomposition analysis of trends in CO_2 emissions in the iron and steel industry using physical indicators for Brazil, China, India, Mexico, South Korea, and the United States.

Later, the discussion centered on the mitigation of CO_2 emissions and international scenarios. For example, Ahmad and Wyckoff (2003) developed one of the first studies on carbon dioxide emissions embodied in the international trade of steel among other goods. Hidalgo et al. (2005), on the other hand, presented an iron and steel world simulation model to analyse the evolution of the industry from 1997 to 2030, focusing on steel production, demand, trade, energy consumption, CO_2 emissions, technology dynamics, and retrofitting options. Hu et al. (2006) also developed world scenarios for iron and steel CO_2 emissions based on different technological processes. Wei et al. (2007) differentiated between technical changes (production frontier shifting effect) and technical efficiency changes (catching up effect) over time for China's iron and steel industry. Worrell et al. (2007) studied the best practices in calculating the energy intensity values for several industries, including iron and steel. However, most of these studies did not defined the boundary of the system, considering the different parts of the iron and steel production, as well as the material imports and exports.

Tanaka (2008) investigated, in a case study on Japan's iron and steel industry, the critical role of proper boundary definitions for a meaningful assessment of energy efficiency in industry. Depending on the boundaries set for the analysis, the energy consumption per ton of crude steel varies approximately 24%.

Regarding international comparisons, Guo and Fu (2010) studied changes in the energy intensity of China's iron and steel industry from an international perspective, but did not discuss boundary and methodological issues. Silitonen et al. (2010) analysed the specific energy consumption of a certain mill, using different system boundaries, such as the process level. The study showed that defined system boundaries help to clarify the role of on-site energy conversion and make a difference between the final energy consumption and primary energy consumption of an industrial plant with its own energy production. Oda et al. (2012) developed a study on international comparisons of energy efficiency in the power, steel, and cement industries. The evaluations were conducted using common system boundaries, allocation, calculation methods and sectors, such as with BF–BOF steel and Scrap-EAF steel. The results reveal that the characteristics vary by sub-sector and that available data were not yet sufficient for a straightforward evaluation of the steel and cement sectors.

Regarding the database for international comparisons, Morfeldt and Silveira (2014) considered the data availability and methodology used to study the specific energy consumption (SEC). They showed that the SEC, representing the iron and steel sector in the Odyssee energy efficiency index (ODEX)—the tool for policy evaluation recommended by the European Commission—is insufficient for capturing energy efficiency trends of European iron and steel production and proposed the use of the Malmquist productivity index (MPI) methodology.

In an analysis of the Swedish iron and steel industry, Morfeld and Silveira (2014) found that the energy efficiency indicators used for evaluating industrial activities at the national level are often based on statistics reported in international databases. In the case of the Swedish iron and steel sector, energy consumption statistics published by Odyssee, Eurostat, the IEA (International Energy Agency), and the United Nations differ, resulting in diverging energy efficiency indicators.

Concerning analysis of the Mexican iron and steel industry, Ozawa et al. (2002) analysed trends in energy use and carbon dioxide emissions by using decomposition analysis based on physical indicators to decompose the intra-sectorial structural changes and efficiency improvements. On the other hand, Sheinbaum et al. (2010) evaluated the primary energy intensity for the iron and steel industry in Mexico for 1990 and 2006 using decomposition analysis. According to the authors, the drop in energy intensity was mainly due to the increased use of the DRI-EAF and scrap-EAF process routes after 1999. Oda et al. (2012) estimated the specific primary energy consumption for the production of one ton of crude steel made under the scrap-EAF route in 2005. However none of these studies specified the system boundary.

To attend to this and other complications in comparing energy efficiency indicators from an international perspective, Hasanbeigi et al. (2014a) presented a boundary setup and a methodology to compare energy intensity in the U.S. and China. There is no such study for the Mexican steel industry to clearly define the boundary of the steel and calculate the energy intensity with respect to that boundary and compare it to the energy intensity of steel industry in other countries with similar boundary. Such meaningful comparison is important for both industry and policymakers to better understand the efficiency status of the industry and how it compares in the international context. Therefore, the approach developed by Hasanbeigi et al. (2014a) is used in this paper to estimate the specific energy consumption for the Mexican iron and steel industry in 2010 and to make a comparison with those of the U.S. and China.

Mexican iron and steel production varies according to Gross Domestic Product growth (especially when including exports and imports). As shown in Sheinbaum et al. (2010) and Sheinbaum-Pardo et al. (2012) iron and steel intensity might also change in years of economic crisis. For this reason it is important to select a year for the analysis where data is available for international comparisons but also a year with no economic stagnation. The end of year 2008 and 2009 were characterized with world financial crisis (Crotti, 2009). For this reason 2010 was selected for the analysis.

2. Energy use in the Mexican iron and steel industry: a general view

Steel production in Mexico grew by 3.3% per year from 1990 to 2010, with important reductions in 2001 and 2008 due to economic reasons (Fig. 1). In 2010, the Mexican iron and steel industry produced 16.87 millions of tonnes of steel, which accounted for 1.5% of the national GDP and 8.4% of the manufacturing GDP (INEGI, 2012). The EAF is the largest manufacturing route in Mexico, accounting for 69.4% of the total crude steel production in 2010, while the remaining 30.6% was made in BOFs (INEGI, 2012). In the same year, the Mexican iron and steel industry was first in energy consumption within industrial energy use in the country with 197.25 PJ, representing 14.3% of the total industrial final energy consumption (SENER, 2014). Natural gas is the main final energy source used, followed by coal coke and electricity (Fig. 2).

Most of the steel in Mexico is produced in medium to large-scale facilities. There are four major steel companies in Mexico, which produced 79.5% of the total crude steel manufactured in the country in 2010 (USGS, 2011). These companies also possess 57% of the installed capacity, with plants ranging from 1 to 5.3 Mt/year of capacity (USGS, 2011).

3. Methodology and data

Methodology is presented in the following subsections that are necessary for the calculation of energy and CO_2 intensities: study boundaries, methodology for the estimation of energy intensity and data. In the methodology for the estimation of energy intensity a breakdown of the different variables is also subdivided in estimation of final and primary energy for the Mexican iron and steel industry, methodology for the discount of energy use for ferroalloys, estimation of imported materials/products, SEC, and estimation of energy consumption for finishing/rolling.

As explained in Section 1.2 the boundary was selected similar to those evaluated for US and China in Hasanbeigi et al. (2014a) to allow international comparisons. The advantage in the methodology is that clearly defines the energy system that is analysed, avoiding both, double counting energy consumption and certain inputs such as ferroalloys that are out of the boundary system.

3.1. Study boundaries

Fig. 3 shows the boundaries that are taken into account for this study according to the process route. The boundaries consider energy consumption for all coke making, pelletizing, sintering, iron making, steel making, steel casting, hot rolling, cold rolling, and processing, such as galvanizing or coating. They also include energy use for net imported pig iron, DRI, pellets, lime, oxygen, and ingots, blooms, billets, and slabs.

On the other hand, this boundary definition does not consider energy consumption for both electricity self-generation and ferroalloy products. It also excludes the embodied energy of the scrap used in the iron and steel industry, as well as the energy demand for the mining and further processing of the steel by steel foundries.

3.2. Methodology for the estimation of the energy intensity

The energy intensity for the net production of crude steel is calculated using the following equation:

$$EI_{cs} = \left(\left(E_p - E_{fa}\right) + E_{pellets} + E_{pi} + E_{lime} + E_{ox} + E_{coke} - E_a\right) \Big/ (P_{cs} + NT_{cs}) \quad (1)$$

According to boundary setup, it accounts for the net consumption (produced + imported −exported).where

Ep: primary energy use
Efa: energy use for ferroalloy manufacturing
Epellets: energy use to produce iron pellets
Epi: energy use for pig iron manufacturing
Elime: energy use for lime manufacturing
Eox: energy use for oxygen manufacturing
Ecoke: energy use for coke manufacturing

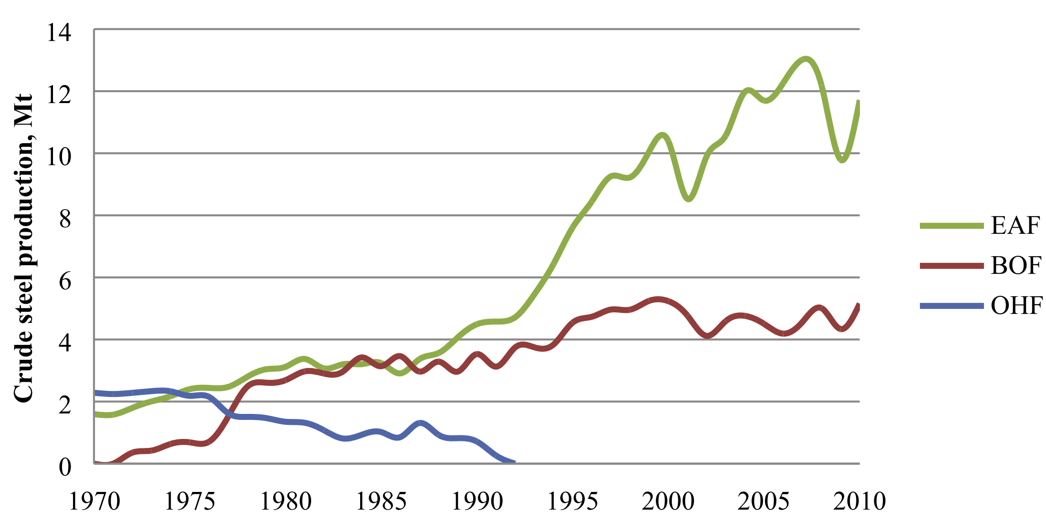

Fig. 1. Steel production by process in Mexico.
Source: INEGI (2012).

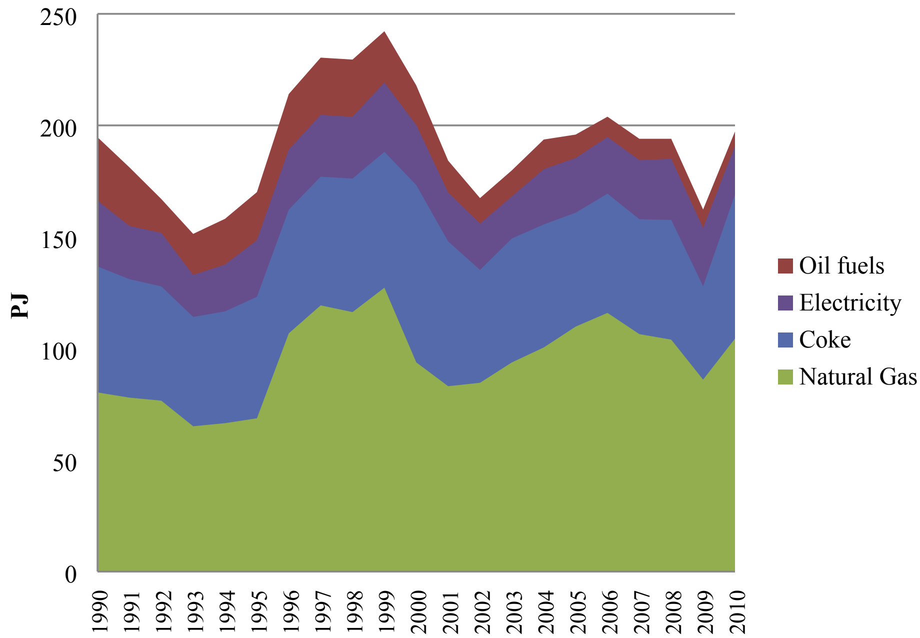

Fig. 2. Final energy use for iron and steel industry in Mexico.
Source: SENER (2012).

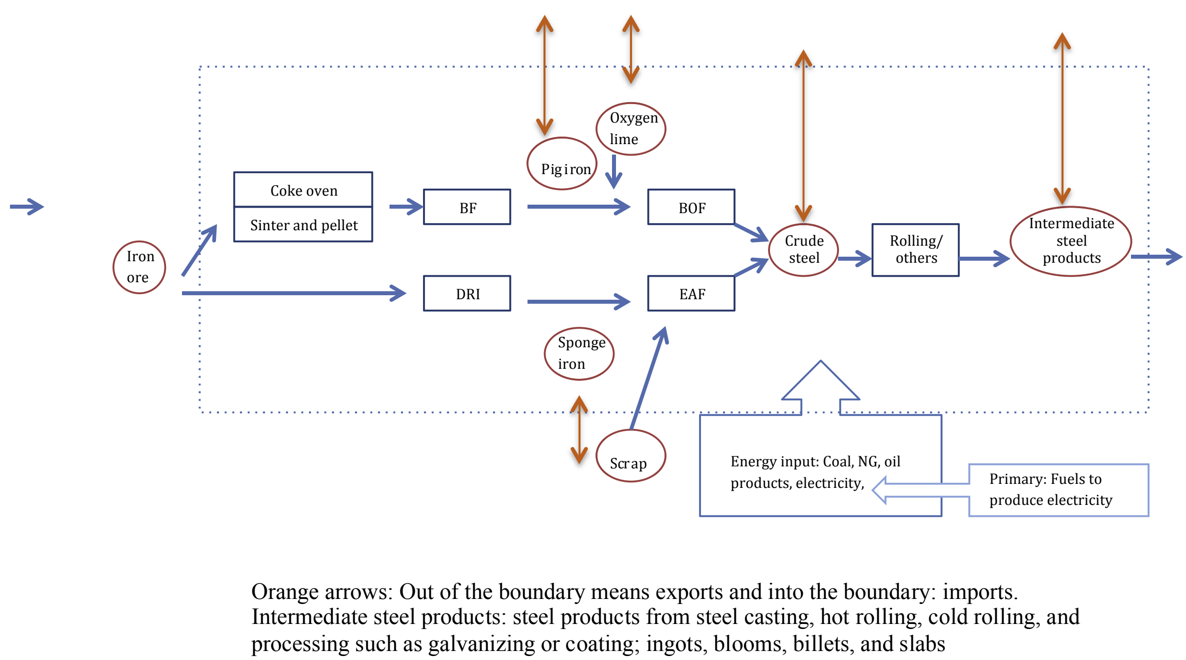

Fig. 3. Flowchart of Iron and Steel Sector Boundaries Used in this Study.
Source: INEGI (2012).

Ea: energy use for finishing/rolling of steel products
Pcs: crude steel production in Mexico in 2010
NTcs: net trade of crude steel

The energy intensity of the EAF process is calculated as

$$EI_{EAF} = \%scrap\ based*EI_{scrap} + \%DRI\ based*EI_{DRI} \quad (2)$$

where

EIEAF: final energy intensity of EAF process in Mexico in 2010
% scrap-based: 55%
% DRI-based: 45%
EIscrap: Energy intensity from scrap
EIDRI: Energy intensity from DRI

The energy intensity of the BF-BOF is estimated by the equation

$$EI_{BF/BOF} = \frac{EI_{CS} - \%EAF * EI_{EAF}}{\%BF/BOF} \quad (3)$$

where

EIBF/BOF: final energy intensity of the BF/BOF process for Mexico in 2010
EICS: final energy intensity of the overall iron and steel process
%EAF: share of the crude steel produced under the EAF process route in Mexico in 2010.
EIEAF: final energy intensity of the EAF process in Mexico.
%BF/BOF: share of the crude steel produced under the BF/BOF process route in Mexico in 2010.

3.2.1. Estimation of final and primary energy for the Mexican iron and steel industry

Final energy is presented separately as fuels (Ef) and electricity (Ee) based on the equation

$$E_f = E_{fuels} - E_{selff} \quad (4)$$

$$E_e = E_{elect} + E_{selff} \quad (5)$$

Where:

Efuels: Sum of fuels used in the iron and steel industry (including coke)
Eselff: Fuels used to produce self-generated electricity in the iron and steel industry
Eelect: Final electricity used in the iron and steel industry
Eselfe: Electricity produced by self-generation in the iron and steel industry
The primary energy is estimated based on the equation

$$E_p = E_{fuels} + \frac{E_{elect}}{\eta_{elect}} + \frac{E_{selfe}}{\eta_{selfe}} - E_{selff} \quad (6)$$

Where:

ηelect = Average national efficiency of electricity generation and transmission and distribution
ηselfe = Average efficiency of electricity self-generation

To convert the final electricity to primary energy, the average efficiency of the electricity generation and transmission and distribution (T&D) losses must be taken into account, as shown in Eq (7), and Table 1.

$$\eta = \frac{Final\ electricity\ use}{Primary\ energy\ consumed} = \frac{Net\ electricity\ generation*(1 - T\&D)}{Consumption\ of\ fossil\ fuels} \quad (7)$$

The fuel and electricity consumption for the Mexican iron and steel industry in 2010, as presented in the National Energy Balance (SENER, 2012), is shown in Table 1.

Iron and steel mills generate part of the electricity that they consume (Eq. (4) and Eq. (5)). In Mexico, the annual onsite generation of electricity within the iron and steel sector is approximately 1163 GWh according to the Energy Regulatory Commission (CRE, 2014). This amount of electricity is mostly generated from natural gas, and a small portion is from heavy fuel oil and diesel. The final energy use reported in Table 1 already includes the natural gas, oil and diesel used for onsite electricity generation, so it is necessary to take those amounts out of the final energy use. The amount of each fuel used to generate the onsite electricity is not reported by any institution in Mexico, but the installed capacity for each fuel is known; then, this installed capacity is multiplied by the typical energy efficiencies by technology, and the result is the amount of each fuel burned.

Table 1
Energy use and electricity conversion factors in the Mexican iron and steel industry (2010).

Final energy	PJ
Natural Gas	104.40
Coke[a]	62.82
Petroleum coke	1.76
Electricity	21.83
Heavy fuel oil	5.62
Diesel	0.81
LPG	0.01
Total	**197.25**
Electricity	
Consumption of fossil fuels, PJ	1699.6
Gross electricity generation, PJ	691.5
Self-generated electricity, PJ	46.5
Net electricity generation, PJ	645.0
Technical losses in T&D %	6.3%
Efficiency η, %	35.6%

[a] Reported as coke from coke factories + imported coke.
Source: (SENER, 2012, 2014).

To adjust the final energy use of the iron and steel industry, it is necessary to add the onsite electricity generation to the electricity use reported by SENER and to discount the fuels burned to produce it. Then, the adjusted final energy use is as reported in Table 2.

3.2.2. Methodology for the discount of energy use for ferroalloys

In addition, it is important to mention that in Mexico, SENER reports the final energy consumption of the iron and steel industry as the energy used by the NAICS 3311 branch "Iron and Steel Mills and Ferroalloy Manufacturing", with no further disaggregation (SENER, 2012). Therefore, according to the boundary set up and Eq. (1), the energy used to produce the ferroalloys has to be deducted from the energy consumption reported by SENER (2012). Because there is no information or previous studies related to the energy use or intensity for ferroalloy manufacturing in Mexico, the values of the final energy intensities obtained from a study by Haque and Norgate (2013) are used, along with the production of ferroalloys.

3.2.3. Estimation of imported materials/products, Specific Energy Consumption (SEC)

When one enterprise or country does not have enough upstream production capacity, it needs to purchase upstream products, such as pig iron, coke, and DRI, from abroad. According to the boundary definition of this study, the energy consumption to produce these products is accounted for in the total energy consumption. On the other hand, when there is a surplus in the upstream production capacity and a portion of the products are sold, the energy consumption of these sold products is deducted from the total energy consumption. In Mexico, the iron and steel industry imports iron pellets and pig iron (Table 3) and exports crude steel (SE, 2012). In 2010, Mexico produced 16.9 Mt of crude steel, exported 1.4 Mt and imported 0.3 Mt of ingots, blooms, billets and slabs (Table 3). Then, the net trade of crude steel in Mexico in 2010 was −1.1 Mt, and the production of crude steel used to calculate the energy intensity was 15.8 Mt.

There is no official information on the amount of oxygen and lime produced and traded for by the Mexican iron and steel industry. For this reason, international considerations of the amount

Table 2
Final and primary energy use and self-electricity generation within the iron and steel industry in Mexico in 2010.

	Final Electricity use (PJ)	Final Electricity use (GWh)	Final Fuel consumption (PJ)	Final energy use (PJ)	Primary energy use (PJ)
Energy use	26.02	7227	165.57	191.58	238.73
	Electricity generation[a], GWh	Electricity generation, PJ	Conversion efficiency[b]	Type of fuel used	Amount of fuel used, PJ
Gas turbine	1040	3.74	43.70%	Natural Gas	8.56
Oil turbine	120	0.43	34.40%	Heavy fuel oil	1.26
Diesel turbine	3	0.01	37%	Diesel	0.03
Total	1163	4.18			9.85

[a] Onsite electricity generation within the iron and steel industry (CRE, 2014).
[b] Typical energy conversion efficiencies by technology (IEA, 2008).

Table 3
Production and trade data of the iron and steel industry in Mexico, 2010 (Mt).

Product	Production	Exports	Imports	Net imports	Used
Iron pellets	7.93	0	4.92	4.92	12.85
Pig iron	4.71	0	0.23	0.23	4.94
DRI	5.37	0	0	0	5.37
Crude steel[a]	16.87	1.41	0.32	−1.1	15.78
BOF	5.16	–	–	–	–
EAF	11.71	–	–	–	–
Steel products	14.58	4.35	16.80	12.45	–
Rolled	14.58	3.27	5.71	2.44	–
Others	0.001	1.08	11.09	10.01	–

[a] Crude steel imports/exports include ingots, blooms, slabs and billets. Source: (INEGI, 2012; SE, 2012.

of oxygen and lime used by the iron and steel process routes are made, as well as the energy-specific consumption to produce these goods (Table 4). The energy use to produce imported/exported materials and products is calculated using international SEC values (Table 5).

3.2.4. Estimation of energy consumption for finishing/rolling

The energy consumption related to the finishing/rolling of steel products is calculated by taking the amount of crude steel processed in Mexico in 2010 and multiplying it by the energy conversion factor for the process of the finishing/rolling of steel products as also shown in Table 5.

3.3. Data

The National Institute of Statistics and Geography (INEGI, 2012) and the World Steel Association (worldsteel, 2015) are the main sources of information regarding iron and steel product manufacturing and materials consumption, such as the amount of crude steel produced (total and by process route), the amount of iron produced in the iron and steel mills (BF and DRI), the foreign trade of the steel products manufactured and the materials used by the iron and steel industry. The Economics Ministry in Mexico (SE, 2012) also publishes an annual document titled the “Mexican Mining Statistical Yearbook”, which was used to obtain information regarding materials usage in iron and steel manufacturing. Energy consumption information is from energy balances (SENER, 2012) and from the Energy Regulatory Commission (CRE, 2014).

To estimate the energy intensity by process route the following is taken into account. In Mexico, the official energy data (SENER, 2012) are not disaggregated by process route. Facing this data availability problem and aiming to make the best possible estimation, the energy intensities of the different process routes are calculated based on other previous studies developed by Kirschen et al. (2011) for 16 international EAF plants working under average conditions, both DRI-based and scrap-based. The information of this study is then adjusted to the Mexican case using the boundary definition (Fig. 3).

Table 6 shows the information obtained from Kirschen et al. (2011). The EAF operation parameters of the first column (inputs in physical units) represent the average of 16 international

Table 5
SEC for imported/exported products in Mexico.

Product	Units	Final energy		Primary energy*	
			%Elect.		%Elect.
FeMn	GJ/t	20.6	12%	24.7	26%
SiMn	GJ/t	32.5	12%	39.4	28%
Coke	GJ/t	3.7	4%	4.0	11%
Pellets	GJ/t	2.1	0%	2.1	0%
Pig iron	GJ/t	19.8	3%	20.9	8%
DRI	GJ/t	13.4	3%	14.1	8%
Lime	GJ/t	4.1	6%	4.5	15%
Oxygen	MJ/m^3	2.5	100%	6.9	100%
Rolling	GJ/t	2.0	20%	2.7	40%
Crude steel**	GJ/t	10.84	8%	12.41	20%

Sources: Haque and Norgate (2013); Hasanbeigi et al. (2014a, 2014b).
*To convert final to primary energy, the 9.8MJ/kWh factor from world steel is used.
**Mexican crude steelSEC, explained later in the ‘Calculations – Net imported product energy use’ section of this report.

Table 4
Estimation of oxygen and lime used in the Mexican iron and steel industry.

Process	Usage ratio of products		Iron/Steel[d] production (Mt)	Total	
	Oxygen (Nm^3/t)	Lime (t/t)		Oxygen (millions of Nm^3)	Lime (thousands of t)
BF (pig iron)	37.56[a]	0.10[b]	4.71	176.78	470.65
BOF (crude steel)	56.19[c]	0.04[c]	5.16	289.63	206.20
EAF (crude steel)	11.50[a]	0.012[a]	11.71	134.68	140.58
Total				601.09	817.43

[a] IEA (2010).
[b] WSA (2011).
[c] Stubbles (2000).
[d] Pig iron (BF) and crude steel produced by route (BOF, EAF) in Mexico, WSA (2015) Nm^3: normal cubic meters @20 °C, 100 kPa; t: metric tons.

Table 6
EAF scrap-based and DRI-based material usage ratios.

	Inputs in physical units	
	Scrap-based	DRI-based
DRI, t/tcs	0	0.8
Lime, kg/tcs	34	60
Coal, kg/tcs	17	23
Oxygen, m3/tcs	32	28
Nat gas, m3/tcs	5	1.5
Electricity, kWh/tcs	391	570

Source: Kirsschen et al. (2011); tcs: metric tons of crude steel

industrial electric arc furnaces, including furnaces of the Mexican steel manufacturer Ternium-Hylsa. Because there are no previous studies on the BF/BOF process energy use for Mexico, the energy intensity of this process is calculated using the overall energy intensity and EAF intensity, as shown in Eq. (3).

4. Results and discussion

4.1. Results

Table 7 shows a summary of the results of every step of the calculation procedure, along with the total energy use and energy intensities calculated according to the boundary definition (Eq. (1)).

On the other hand, Table 8 presents estimated final energy intensities for the EAF route based on scrap and DRI. Based on the previous information, it can be assumed that the shares of scrap and DRI as feedstocks for the Mexican iron and steel EAF process are 55% scrap and 45% DRI. Based on these data, it is estimated that within the EAF process, 55% was scrap-based and 45% was produced under the DRI-based EAF route. The CO_2 intensity related to fuel use, including electricity production (CO_2 emissions by tonnes of crude steel), are estimated based on IPCC (2006) emission factors. The electricity grid CO_2 emission factor for Mexico in the year 2010 was 0.51 $kgCO_2/kWh$ (140.41 $kgCO_2/GJ$). The weighted average fuel emission factor (without electricity generation) is 76.50 $kgCO_2/GJ$.

EAF electricity intensity is larger than BF/BOF because this process is based manly in electricity, however CO_2 intensity of EAF process is four times smaller than BF/BOF CO_2 intensity. This is due to the large participation of fossil fuels in BF/BOF but also to the relatively small CO_2 emission factor of the Mexican electricity production system. The importance of the share of the EAF process in total iron and steel production brings down CO_2 intensity of the iron and steel industry.

Table 8
EAF scrap-based and DRI-based final energy intensities for the Mexican iron and steel industry.

	Final energy intensity GJ/t[a]	
	Scrap-based	DRI-based
DRI	0	10.72
Lime	0.14	0.25
Coal[b]	0.41	0.55
Oxygen	0.08	0.07
Nat gas[b]	0.18	0.05
Electricity	1.41	2.05
EI_f (GJ/t)	**2.22**	**13.69**

Note: Final energy intensity of scrap-based and DRI-based EAF manufacturing was estimated according to the boundary described in Fig. 3.
[a] Based on data from Kirschen et al. (2011). Table 10.
[b] Conversion factors: 24.05 MJ/kg for coal, 35.04 MJ/m^3 for natural gas at 20 °C and 100 kPa.

To estimate the BF-BOF energy intensity (Eq. (3)), we use the overall iron and steel energy intensity from Table 7 along with the previous results from Table 8 as well as the share of crude steel produced under the EAF process (69.44%; INEGI, 2012). The result of the BF/BOF final energy intensity process route for Mexico in 2010 was 25.18 GJ/t. Table 9 shows a summary of the results of the energy intensities by process route.

Table 10 presents total energy and CO_2 emissions of the Mexican Iron and Steel Industry in 2010 and Table 11 shows energy intensity comparison with the US, and China for the year 2010 (Hasanbeigi et al., 2014a, 2016).

As can be seen, China has the highest and Mexico has the lowest total steel industry energy intensity. The larger share of the EAF iron and steel process route in Mexico is an important reason for the lower energy intensity. The next section provides a discussion of this and some other reasons for the results observed in the energy and CO_2 intensity values for Mexico's steel industry.

4.2. Discussions

The purpose of the analysis presented in this paper is to apply a methodology for quantifying and comparing the energy intensity of steel production in Mexico, China and the U.S. with defined boundaries and conversion factors. This section provides a discussion of some possible reasons that the energy intensity values differ in the three countries. Two explanatory variables are discussed: the age of steel manufacturing facilities in each country and the share of EAF steel in total steel production.

Table 7
Energy use and energy intensities of the Mexican iron and steel industry.

+/−	Component	Final electricity PJ	Final electricity GWh	Final fuels PJ	Final energy PJ	Primary energy PJ
+	Direct final energy use	26.02	7227.11	165.57	191.58	238.73
−	Ferromanganese	0.70	194.45	0.97	1.67	2.94
−	Silicomanganese	1.94	537.88	2.44	4.37	7.88
+	Net imported oxygen	1.50	417.43	0.00	1.50	4.23
+	Net imported lime	0.20	56.30	3.15	3.35	3.72
+	Net imported pellets	0.00	0.00	10.33	10.33	10.33
+	Net imported pig iron	0.14	38.66	4.35	4.49	4.74
−	Net trade of crude steel	1.00	275.67	10.94	11.94	13.76
+	Net imported coke	0.38	106.36	8.38	8.76	9.46
=	Total energy use	24.61	6837.86	17.43	202.04	246.63
Energy Intensities		Final electricity EI (GJ/tcs)	Final Electricity EI (kWh/tcs)	Final fuels EI (GJ/tcs)	Final energy EI (GJ/tcs)	Primary energy EI (GJ/tcs)
		1.56	433.21	11.24	12.80	15.63

Table 9
Electricity, fuels and combined energy intensities by process in Mexico, 2010.

	Final electricity EI (GJ/tcs)	Final Electricity EI (kWh/tcs)	Final fuels EI (GJ/tcs)	Final energy[a] EI (GJ/tcs)	Primary energy EI (GJ/tcs)	CO_2 intensity CO_2I $kgCO_2/t$
Overall process	1.56	433.21	11.24	12.80	15.63	1090.91
EAF	1.93	536.60	5.43	7.36	10.86	537.83
BF/BOF	0.71	198.24	24.47	25.18	26.48	2247.58

[a] Conversion from final to primary energy, considering 35.6% electricity generation efficiency from Table 2. Total energy intensities from Table 7.

Table 10
CO_2 emissions of the Mexican Iron and Steel Industry in 2010.

Component	Electricity		Fuels		Total final energy	
	Use (GWh)	CO_2 emissions (Gg CO_2)	Use (TJ)	CO_2 emissions (Gg CO_2)	Use (TJ)	CO_2 emissions (Gg CO_2)
Reported energy consumption *(excluding the energy use for the production of intermediary products given below)*	7227	3645	165,566	12,666	191,584	16,311
Energy use for the production of net imported coke	106	54	8382	793	8765	847
Energy use for the production of net imported pellets	0	0	10,335	791	10,335	791
Energy use for the production of net imported pig iron	39	20	4347	333	4486	352
Energy use for the production of net imported lime	56	28	3149	282	3371	311
Energy use for the production of net imported oxygen	417	211	0	0	1503	211
Energy use for the production of net imported crude steel	−278	−140	−10,945	−837	−11,945	−978
Energy use for ferro-manganese manufacturing	−194	−98	−967	−74	−1667	−172
Energy use for silico-manganese manufacturing	−538	−272	−2436	−186	−4372	−458
Total energy consumption with embodied energy of net imported/exported products included	**6836**	**3447**	**177,431**	**13,766**	**202,039**	**17,214**

Table 11
Energy intensity of the iron and steel industry in China, US and Mexico in 2010.

	Electricity kWh/tcs	Fuel GJ/tcs	Final energy GJ/tcs	EAF ratio in 2010
U.S.	780	13.6	16.4	61.3%
China	439	17.9	19.4	9.8%
Mexico	431	11.1	12.7	69.4%

Source: Hasanbeigi et al., 2016.

4.2.1. Share of EAF in total steel production

Mexico has one of the highest EAF ratios of the world's steel industries; in 2010, the share of crude steel produced under the EAF process was 69%. Fig. 4 shows the historical EAF ratio for Mexico for the 2000–2010 period. As explained earlier in this paper, higher share of EAF steel production can help to reduce the overall energy intensity of the steel industry.

4.2.2. Age of steel manufacturing facilities

Fig. 1 shows the evolution of the crude steel production by process in Mexico from 1970 to 2010. There were two major increases in the BOF capacity: the first one was from 1976 to 1978, when the BOF capacity increased by more than three times, and the second started in 1991 due to the closure of the open heart furnace plants (OHF). The exact age of the specific BOF plants is not clear

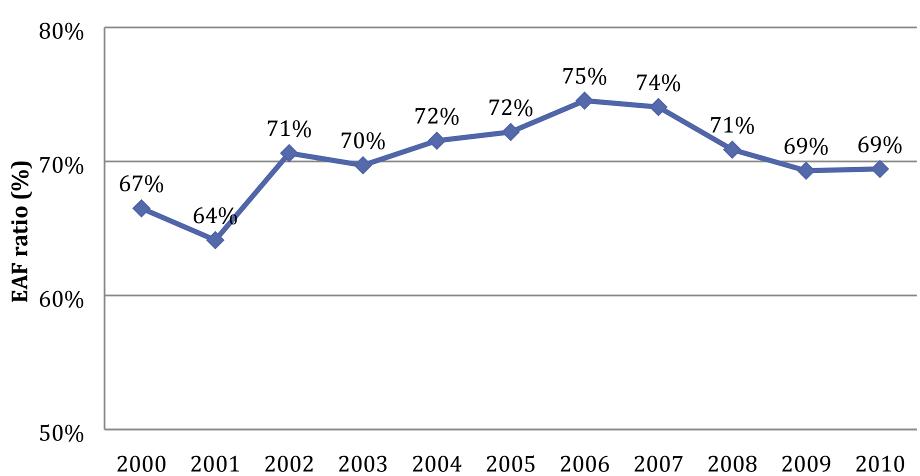

Fig. 4. EAF ratios for Mexico, 2000–2010.
Source: worldsteel (2013)

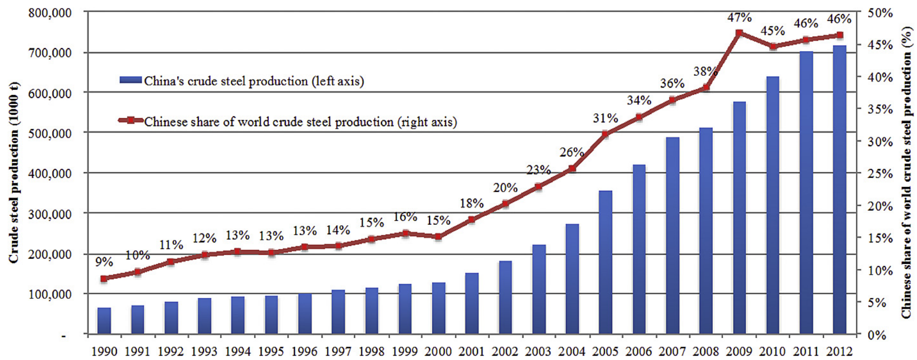

Fig. 5. China's crude steel production and share of global production (1990–2010).
Sources: Hasanbeigi et al. (2014a), CSM (2012–2013).

because the industry is in constant change and modifications and modernizations of the facilities are made continuously. However, based on the information from Fig. 1, we can assume that half of the installed BOF capacity in Mexico is approximately 30–37 years old and the newer half is approximately 14–22 years old. Most of the EAF plants were built from 1992 to 2000, and there was a second important increase from 2003 to 2007, so it can be said that the EAF plants in Mexico are approximately 7–20 years old.

As is evident in Fig. 5, most of China's steel production capacity has been constructed since 2000. Annual production jumped from 129 Mt in 2000 to 627 Mt in 2010. During that same period, production in the U.S. dropped from 102 Mt to 80 Mt.

Although no data are available on the exact age of each steel enterprise in China, we can infer from the production data that in 2011 about 500 Mt of production (or about 80%) was from plants that were 10 years old or younger. In contrast, the average age of BOF vessels in the U.S. is 31.5 years (AIST, 2010a), and the average age of EAFs in the U.S. is 30.9 years (AIST 2010b). Even though the U.S. vessels have been relined and other upgrades have been made, they are overall older than most of the steel production facilities in China and therefore could be less energy-efficient than the Chinese facilities At the same time, however, it should be noted that not all of the new Chinese plants have necessarily installed the most energy-efficient technologies.

4.2.3. Fuel shares

The share of different fuels used in the iron and steel industry in the 3 countries studied is an important variable that influences the industry energy intensity because some fuels burn more efficiently than others.

The types of fuel used in this industry differ among the 3 countries. For example, in 2010, in the U.S. natural gas accounted for 32.4% of steel-industry's final energy use, but in China natural gas represented less than 1%. The dominant fuel used in China is coal, which is more carbon intensive than natural gas. In Mexico in 2010, natural gas accounted for 53% of steel industry final energy consumption, followed by coke with a 32% share (SENER, 2014).

4.2.4. Steel products mix

Different steel products have different energy requirements in the rolling/casting/finishing processes. Therefore, the product mix is another key variable that should be considered when comparing energy intensities among countries. Table 12 shows the differences in the production of some of iron and steel industry products in China,, Mexico, and the U.S. in 2009.[1]

[1] 2009 was the latest year for which the product mix data was available for all 3 countries.

4.2.5. Penetration of energy-efficient/carbon dioxide emissions reduction technologies

Data on penetration of energy-efficient technologies and practices in China, Mexico, and the U.S. are not fully comparable. The types of information available in these countries differs, so direct comparison of the penetration of certain technologies is not possible. One direct comparison that is possible is the penetration of EAFs, which was presented above. The application of energy-efficient technologies depends on factors such as raw materials used, energy sources, energy and operation costs, product mix, and the regulatory regime in the country.

4.2.5.1. Penetration of energy-efficient technologies and practices in China's iron and steel industry. With the rapid development of China's iron and steel industry, energy-efficient technologies and processes have also greatly improved. Penetration of equipment and technologies for waste-heat and waste-energy recycling has increased. The main technologies utilized include: coke dry quenching (CDQ) for the coking process, top-pressure recovery turbines (TRTs) for BFs, pulverized coal injection, and continuous casting. CDQ is a heat-recovery technology that produces electricity. Other technologies, such as low-temperature waste-heat recovery, are also gradually being adopted. The application and popularization of these energy-saving technologies have helped improve energy efficiency in the iron and steel industry. Many Chinese steel companies benefited from the Kyoto Protocol's Clean Development Mechanism (CDM) for additional funding to support CDQ and TRT projects in their plants.

4.2.5.1.1. Coke dry quenching and top-pressure recovery technologies in China.. Fig. 6 shows the penetration levels of CDQ and TRTs in China's iron and steel industry since the 1990s, showing a rapid increase in adoption in recent years. Both CDQ and TRTs save significant energy. For example, CDQ can recycle more than 80% of the sensible heat from heated coke. For each ton of coke quenched, this technology can recycle 0.45–0.6 tonnes of steam (at 4.5 MPa) on average (Shangguan et al., 2009). The recycled steam can be fed directly into the streaming pipelines, or it can be used for power generation. In facilities using pure condensing steam turbines, on average 95–110 kWh of electricity can be generated from every ton of coke quenched.

TRTs can recycle large amounts of fuel to produce electricity without consuming any fuel. According to statistical reports, if operated under optimal conditions, TRTs can recycle 25–50 kWh per ton of hot metal, which can meet 30% of BF electricity demand. From 2000 to 2010, the number of BFs with TRTs in the Chinese steel plants increased from 33 to more than 400. By the end of 2007, all BFs with a capacity larger than 2000 m^3 were equipped with TRTs, and 95% of the BFs with a capacity larger than 1000 m^3 had TRTs. In addition, all of the TRTs on BFs smaller than 1000 m^3

Table 12
Product mix in iron and steel industry in China, Mexico, and the U.S. in 2009 (in thousand metric tonnes).

Steel Product	China	Mexico	U.S. [a]
Production of hot rolled long products[b] (excluding seamless tubes)	332,506	6468	16,081
Production of hot rolled flat products[c]	307,717	5938	37,863
Production of railway track material	5478	–	902
Production of heavy sections (≥80 mm)	9458	326	3763
Production of light sections[d] (<80 mm)	39,147	372	1087
Production of concrete reinforcing bars	121,509	3161	4615
Production of hot rolled bars[e] (other than concrete reinforcing bars)	55,393	425	3099
Production of wire rod	96,728	2184	1493
Production of electrical sheet and strip	4600	–	326
Production of tin-mill products	–	96	2016
Production of other metallic coated sheet and strip	20,693	1148	9677
Production of non-metallic coated sheet and strip	4588	–	–
Total production of tubes and tube fittings	–	1170	2129

[a] Deliveries.
[b] Total finished long products.
[c] Total flat products.
[d] Including light sections.
[e] Galvanized products only.
Source: worldsteel 2011.

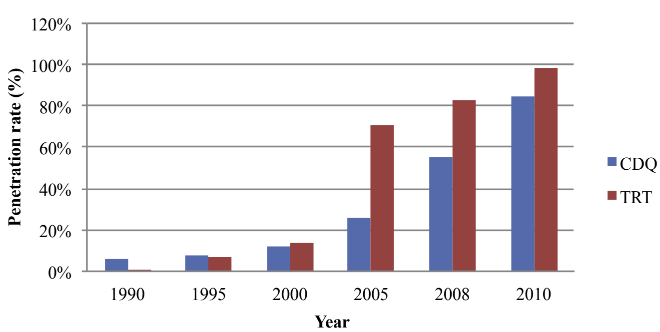

Fig. 6. Use of CDQ and TRTs in key medium and large steel enterprises in China. Note: Penetration ratio of CDQ is the ratio at internal coking factories of steel mills. Medium and large enterprises have more than 300 employees and more than 30 million RMB annual sales revenue.
Source: Yin (2009), CSM (2012–2013).

utilized dry-dust removal. Some facilities with BFs larger than 1,000m3 have also adopted this technology (e.g., the TRTs on two large BFs of 5500 m^3 in Tangshan Steel Mill in Cao Pei Dian, China utilize dry-dust removal). TRTs with dry-dust removal can be 30–40% more efficient than TRTs with wet-dust removal and can produce 54 kWh/t of hot metal (Shangguan et al., 2009; ECERTF, 2008), which can meet approximately 30% of electricity demand for blast blowing. Considering the scale of China's iron and steel industry, the energy savings from both CDQ and TRT are significant.

4.2.5.1.2. Pulverized coal injection in China. Pulverized coal injection can reduce BF coke consumption, thereby reducing Energy use. Recently, the level of pulverized coal injection in the Chinese iron and steel industry has increased to 149 kg/t hot metal in 2010, which is comparable to higher levels in other countries (the world average is 125 kg/t hot metal), as shown in Fig. 7.

4.2.5.1.3. Continuous casting in China. Continuous casting, in which molten steel is solidified into a semi-finished form such as a billet, bloom, or slab, saves energy compared to the use of stationary molds. Fig. 8 shows the ratio of continuous casting in China from 1990 to 2010. The continuous casting ratio in China before 1995 was less than 50% but increased rapidly with the development of China's iron and steel industry, to 87% in 2000 and 99.8% in 2010. The increase in continuous casting has reduced energy use in China's iron and steel industry.

4.2.5.2. Penetration of energy-efficient technologies and practices in the Mexican iron and steel industry

4.2.5.2.1. Continuous casting in Mexico. Since 2007, continuous casting has been used for 100% of steel production in Mexico. Fig. 8 shows the evolution of the utilization of continuous casting in Mexico from 1970 to 2010.

4.2.5.3. Penetration of energy-efficient technologies and practices in the U.S. iron and steel industry. We could not find information on the penetration of CDQ and TRT in the U.S. steel industry. However, information for other energy efficiency technologies and practices was available. For example, out of 348 establishments[2] in the U.S. iron and steel industry, only 16 used cogeneration technology in 2010[3] (U.S. DOE/EIA, 2013a). Also in 2010, 166 establishments reported using computer control for processes and major energy-using equipment, and 219 used adjustable-speed motors (U.S. DOE/EIA, 2013b). Table 13 shows energy management activities reported by U.S. iron and steel establishments in 2010.

4.2.5.3.1. Continuous casting. Fig. 8 shows the ratio of continuous casting in the U.S., which had already reached a high level in the early 1990s (about 76% in 1991), in contrast to the historical pattern in China.

Our analysis of the penetration and energy savings of energy-efficient technologies shows that each country exhibits its own characteristics in applying these technologies. In the U.S., there is more emphasis on energy management technologies whereas China has adopted more waste-heat/energy-recovery technologies.

4.2.6. Scale of Equipment

Overall, the Chinese iron and steel industry still has many small and inefficient enterprises and plants. There are many different types of steel enterprises in China, including large-scale integrated steel enterprises, independent rolling enterprises, and even independent iron-making enterprises. The total number of iron and steel enterprises in China is quite large, and it is almost impossible to obtain production and capacity information for every enterprise.

[2] "Establishments" includes units that reported using any of the five energy-saving technologies listed by the Manufacturing Energy Consumption Survey at any time in 2006, plus units where usage of those technologies was not ascertained (U.S. DOE/EIA, 2013c).
[3] This count includes only establishments that reported cogeneration technology in use at any time in 2006 (U.S. DOE/EIA, 2013c).

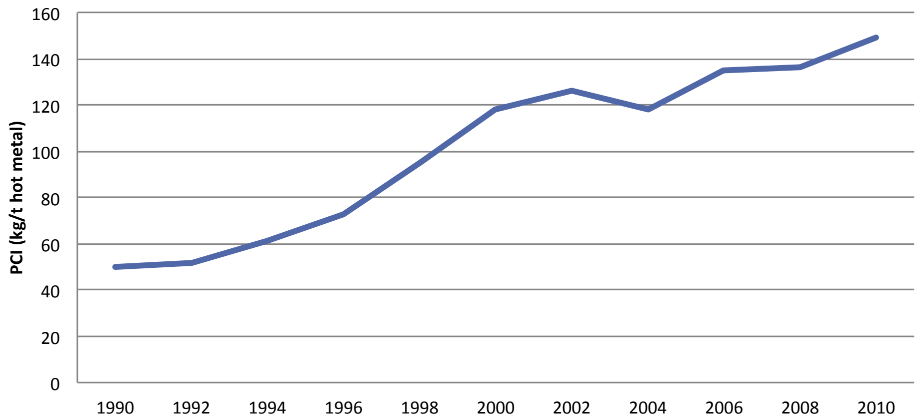

Fig. 7. Pulverized coal injection in the Chinese steel industry, 1990–2010.
Source: Yin (2009), China (MIPRI, 2012); USGS (2011); INEGI (2012).

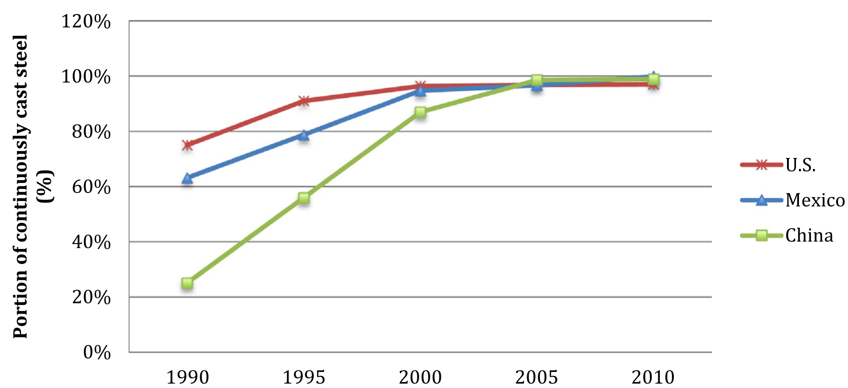

Fig. 8. Share of continuous casting in steel production for three countries (1990–2010).
Source: AIST 2008.

Table 13
Energy management in U.S. iron and steel industry in 2010.

Activity	# of plants[a]
Participation in one or more of the following types of activities	277
Energy audit or assessment	150
Electricity load control	125
Power factor correction or improvement	96
Equipment installation or retrofit for the primary purpose of using a different energy source	29
Standby generation program	42
Special rate schedule	128
Interval metering	88
Equipment installation or retrofit for the primary purpose of improving energy efficiency affecting:	
Steam production/system	36
Compressed air systems	102
Direct/Indirect process heating	59
Direct process cooling, refrigeration	27
Direct machine drive	107
Facility HVAC*	76
Facility lighting	135

*Heating, ventilation, and air conditioning.
[a] This count includes only establishments that reported this activity in 2010 survey.
Source: U.S. DOE/EIA, 2013c.

However, production from medium and large enterprises represents 87% of the national crude steel production (554 Mt in 2010) (EBCISIY, 2011), so these plants can represent the characteristics of major production equipment.

In 2006, China had 85 key medium and large enterprises with a total crude steel production of 349 Mt. The average annual production capacity of these enterprises was 4.1 Mt. China's average annual production capacity is greater than the U.S.'s. Since 2006, China has been implementing a policy focused on phasing out inefficient facilities in energy-intensive sectors. As a result, the overall efficiency of the Chinese iron and steel industry is increasing gradually. By the end of the 11th Five-Year Plan (2006–2010), China phased out 122 Mt of iron-making capacity and 70 Mt of steel-making capacity, surpassing the targets by 22% and 27%,

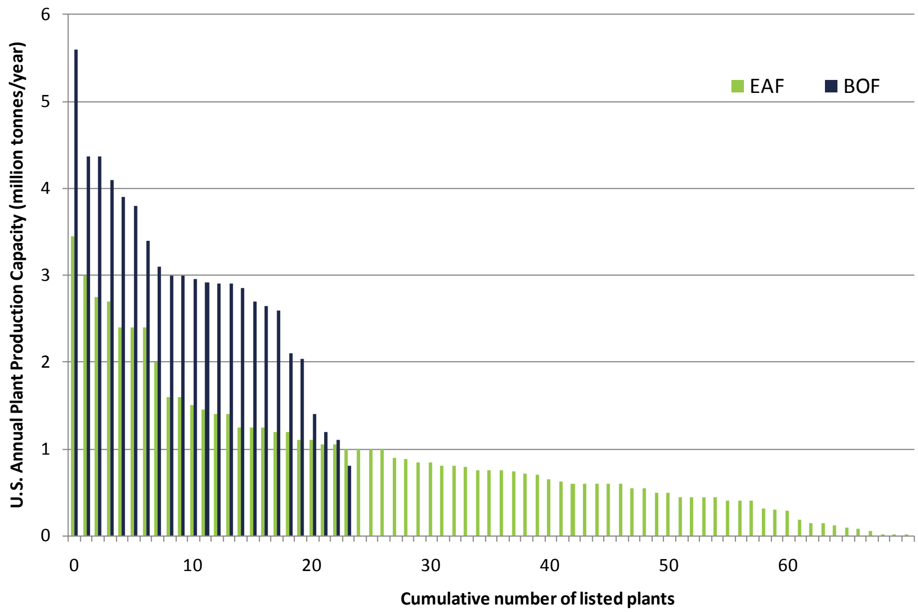

Fig. 9. Distribution of registered US steel plants by production capacity (2007).

respectively. In the current 12th Five-Year Plan, by the end of 2013, China phased out 17 Mt and 18 Mt of iron-making and steel-making capacity, respectively. The targets in the 12th Five-Year Plan are phasing out 48 Mt of iron-making and 48 Mt of steel-making capacity (MIIT, 2015; 2013). A key issue in China is the large share of small BFs.

The U.S. steel industry is characterized by consolidated, large-scale integrated steel producers and fragmented, mini-mill EAFs producers. Fig. 9 illustrates the distribution of self-registered U.S. steel production facilities by annual capacity. The average capacity of integrated BOF plants in the U.S registry was 2.9 Mt per year in 2007; EAF plant average capacity was 0.93 Mt (AIST, 2008).

4.2.7. Other factors

Other factors that can influence the energy intensity of steel production are:

- Capacity utilization of plants. Higher capacity utilization improves overall energy performance compared to lower capacity utilization if all other factors remain constant.
- Cost of energy and raw materials. Low-cost energy and raw materials are key components of managing costs in the steel industry. Changing energy and materials sources in order to optimize costs can affect the energy intensities of a plant.
- Differing environmental requirements from country to country. Environmental regulations affect industry energy intensity. Operation of pollution control equipment requires energy, which adds energy use.

4.3. Uncertainties

The actual energy consumed by ferroalloy manufacturing in Mexico would be different than that calculated in this study, as every industry works under different conditions. However, the possible error would not affect the results significantly, as ferroalloy manufacturing accounts for only approximately 3% of the final energy use.

On the other hand, as noted above, there has not been enough statistical information collected in Mexico to break down the energy consumption by the two different process routes: EAF and BF-BOF; therefore, the EAF energy and materials use data were taken from a previous study by Kirschen et al. (2011). Another source of uncertainty is the CO_2 intensity estimation because, as there is no information on the energy consumption by process route, it was assumed that EAF plants in Mexico work by mostly using natural gas as a fuel so that the fuel emission by process could be estimated. This assumption was made because there is no pig iron consumed in the EAFs in Mexico and because these furnaces were fed on a 45%DRI - 55%Scrap base in 2010. According to the IPCC (2006), the level of uncertainty associated with the stationary combustion data in the case of extrapolation is approximately 10%.

5. Conclusions

Energy consumption and energy intensity are often estimated based on different definitions of an industry's boundaries, making comparison at best difficult, at worse invalid (Tanaka, 2008). Therefore, boundary definitions are essential when measuring energy performance, and how these affect the appropriateness of country comparisons to guide policy decisions. This study presents energy and CO_2 intensities in the Mexican iron and steel industry based on a defined boundary system that allow to compare these indicators to those from other countries.

The results show that Mexico has lower energy intensity compared to US and China, mainly due to the large share of new EAF plants in Mexico (69.4% of total steel production in 2010), but also to the high penetration of continuous casting and other energy efficient technologies, and the use of steel scrap. In addition, the large share of natural gas in the fuel mix and the lower CO_2 emission factor of the electricity grid, contribute to the lower Mexican iron and steel CO_2 emission's intensity compared to China and the US.

Although important energy efficiency efforts from the Mexican iron and steel industry has been developed in the last decades, there are additional efforts to be made in order to reduce GHG emissions, not only related to technology modernization, but also to material re-use and efficiency, and reduction of emission intensity (especially related to reduction of fossil fuels in electricity generation).

A number of policy implications result from this study. First, it should be noted that even with the use of a common methodology, it is difficult to provide policy-makers with a single energy intensity value for steel production for each country to be used to compare energy intensity across countries. Policy-makers when making decisions related to energy, greenhouse gases, and competitiveness issues often seek such values. This analysis illustrates that such a single indicator does not provide enough information to fully explain country-specific conditions. In the case of Mexico, the key explanatory variable is the share of EAF steel. When comparing other countries, there may be other explanatory variables that are important. Thus, when providing policy-makers with a single indicator value for international comparisons, it is essential that explanatory variables also be evaluated and key results conveyed to policy-makers to accompany the single energy-intensity value.

This analysis also found that Mexico could strengthen data collection for the iron and steel industry in order to both better understand trends in the industry and to more easily allow for the use of the methodology outlined in this paper. Mexico could strengthen energy data collection and data management and consider adopting a system more similar to the system in the U.S. in which a detailed census of manufacturing industries is conducted every four years. Also, it could strengthen data collection and reporting related to facility and technology-level adoption of energy-efficient technologies and measures, such as coke dry quenching (CDQ).

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