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Bottom-up and Top-down Model Integration for Carbon Dioxide Emissions Calculation

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Abstract: Top-down and bottom-up model integration turns useful in order to inform the decision making process and management strategies with respect to greenhouse gases (GHG) mitigation projects; in particular, carbon dioxide emissions (CO_2). A bottom-up model specification comprises peculiarities of a manufacturing process, type of technology, productive efficiencies of different energy inputs and production volume, production capacity and age (i.e. technological obsolescence) of an industrial plant. However, because access to such detailed information faces large barriers, bottom-up and top-down model integration turns to be necessary. A top-down approach relies on general propositions and assumptions on the conditions of aggregate industry operations. Methodological assumptions in top-down settings are framed considering primary and integrated iron and steel making. This study specifies a bottom-up energy intensity function for a representative mini-mill using electric arc furnace (EAF) technology for a given year t. On the other hand, a sector aggregate energy intensity index (AEII) is calculated for the whole iron and steel industry in period t-n. The integration of both approaches allows tracing back the energy profile of a representative mini-mill. Afterwards, an average amount of CO_2 emissions is estimated on a cumulative basis from specific energy consumption in a mini-mill for a specified period. Opportunities to reduce CO_2 emissions are suggested since the productive efficiency of existing EAF in a representative facility is still far beyond that of latest-best-practice technologies.

Industry Overview

Iron and steel manufacturing is structurally linked to economic development in many industrial sectors as customers of steel products. Steel of many types represents a basic commodity in the manufacturing of high value added products and services such as cars and transportation, construction, and oil extraction industries. Increase in the demand of steel products can be understood as the result of economic growth in many industrial activities either in the domestic or foreign markets. On the other hand, higher value added iron and steel products contribute to foster competitiveness in an integrated value chain. Figure 1 and Table 1 present a snapshot of contemporary economic performance of the iron and steel industry in Mexico.

Iron and steel manufacturers are structurally large users of energy inputs and, in particular, fossils fuels and electricity. This is due to the nature of the production process and technology attributes where the combustion of fossil fuels is a necessary condition in order to generate high temperatures and the desired chemical reactions in iron and steel making. Iron and steel is also part of the so-called heavy and chemical industries (HCI) where energy is a fundamental input

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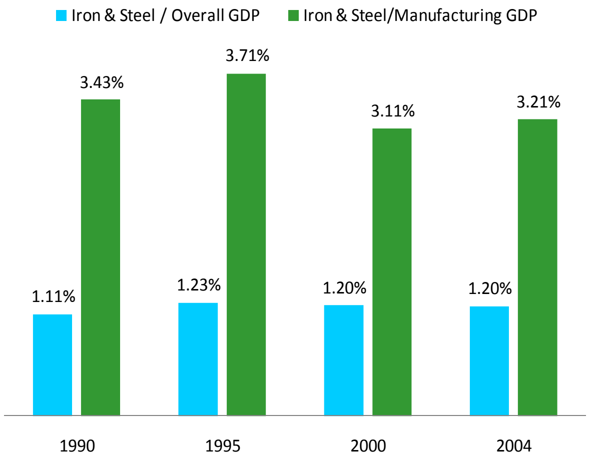
in the manufacturing of iron and steel products. The concept of energy holds at least four different scientific perspectives: energy as commodity, ecological resource, social necessity, and strategic material [1]. Energy like any other product can be bought or sold (i.e. the commodity view). In this approach, producers and consumers survey available energy alternatives; second, collect and analyze data significant to each alternative; third, perform a cost/benefit assessment for each potential strategy; fourth, make probability judgments on a risk/aversion setting; and fifth, optimize the outcome of their decision so they select the most/cost effective strategy [2]. Also, supply and demand representations are the most appropriate tools to analyze energy usages from a commodity perspective. On the other hand, the ecological resource view of energy is mostly concerned about the environmental impacts of resource depletion. This view relies on sustainability principles, parsimony in energy consumption, and the use of renewable as an alternative [3].



Source: INEGI, Estadisticas de Contabilidad Nacional, Mexico, 2008.

Figure 1: Iron & Steel Share in Overall Production and Manufacturing, Mexico, 1990-2004 (%)

Consumption of energy represents a significant proportion of the operating costs in production processes for iron and steel making. The view of energy as a commodity allows making a meaningful comparison between the costs due to energy expenditures, raw materials in steel making and labor costs. According to official national data, raw materials, fossil fuels, and electricity accounted for 74.7%, 3%, and 9.4% of costs for total inputs in iron and steel making in year 2005. From this perspective, it makes economic sense for a steel manufacturer to improve energy requirements in plant operations because this will turn into a source of competitive advantage due to lower energy costs per tonne of steel. Moreover, a facility in pursue of reducing energy costs will develop organizational and technical skills around energy management practices which will derive into a source of competitive advantage. Thus not only lower cost production structure due to lower energy bills but also knowledge accumulation and technological learning built over energy efficiency practices explain partly the competitive position of a facility.

Table 1: Iron & Steel Industry in Mexico, Indicators of a Decade

	2003	2005
Iron & Steel Employment Share in Total Mexican Manufacturing	0.91%	0.93%
Iron & Steel GDP/ Employment[3]	2,305.37	2,345.89[4]
Value Added Compound Annual Growth Rate (1994-2003)	15.56%	
Exports Compound Annual Growth Rate (1994-2007)	11.59%	

Source: INEGI, Encuesta Industrial Anual, Mexico, several years.

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[3] Thousands of constant pesos, based year: 1993.
[4] Value for 2004.

Optimization of Energy Requirements and the Industrial Ecology Approach

If the current analysis were only to be confined to the commodity view of energy, the main concern of study would not be so different to that one during the 70's and late 80's. In industrialized economies, most of the energy conservation literature represents a response to a growing concern on increasing prices of energy sources and in particular oil prompted since the Arab oil embargo in 1972. Increasing energy costs was a major driver for conservation activities and environmental considerations were taken into account to a much lesser extent.

However, there are three features of energy which the commodity view does not consider. First, consumption of fossil fuels (i.e. hydrocarbons) as energy source involves combustion processes with the disposal of atmospheric releases (i.e. nitrous oxides, nitrogen dioxide, carbon monoxide, carbon dioxide, sulfur dioxide; carbon tetrachloride from solvent uses; methane; hydro-fluorocarbons, and per-fluorocarbons for commercial applications). Second, some sorts of hydrocarbons (i.e. natural gas) of which requirements can enter a particular production process as a reducing agent (i.e. reductant) and not as a thermal energy source [4, 5]. Third, proved and unproved reserves of fossil fuels are said to be finite and therefore non renewable. Because the degree of environmental preservation depends on the speed of non renewable resource use and the amount of generated by-products, the ecological resource view of energy offers a more comprehensive explanation of sustainable uses of energy in industrial facilities.

In practice, managers and shop floor engineers in manufacturing establishments are mostly concerned on reducing energy costs. On the other hand, environmental regulation on air pollutants due to combustion processes has suffered a series of amendments towards higher complexity in recent years [6]. The environmental policy approach in Mexico is based on a voluntary scheme (i.e. Certificate of Clean Industry and Industrial Inspections administered by PROFEPA) and to some extent on pollution prevention rather than end-of-pipe pollution technologies. Pollution prevention is compatible with the principles suggested by supporters of an industrial ecology approach [7, 8, and 9]. According to this view, energy and raw materials optimization, *waste minimization*, *reused of by-products and recovery of exhausted gases* (i.e. thermal energy recovery and combined heat and power) have beneficial gains for environmental conservation. Industrial applications of by-products otherwise considered hazardous materials by law imply re-entering waste into other segments of the production process in a single facility or inter-industry linkages. In Mexico, the enacting of a project on *"Instrumentos Técnicos Normativos"* in year 2003 has prompted economic incentives and facilitated administrative procedures on recycling activities. *"Instrumentos Tecnicos Normativos"* is a legal mechanism allowing for a *win-win* solution [10] at the bottom-line of production. In some circumstances recycling (for example, steel scrap) may allow a facility lowering energy costs and thus increasing profit margins. This represents a private benefit. On the other hand, a social benefit occurs while reducing the effects of environmental impacts thus allowing for increases in social welfare due to higher quality standards of the natural environment. A concept which is relevant for optimization of energy requirements in a facility refers to productive efficiency. The units of output that can be manufactured given an amount of inputs are concerned with the term productive efficiency. The productivity of a business can provide a good indication of efficiency, which can be compared to different periods and business units [11].

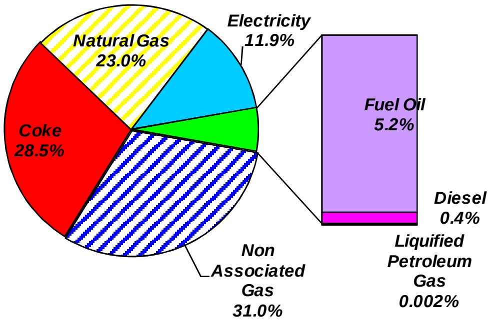
Bottom-up and Top-down Approaches in Identifying Opportunities for CO_2 Emission Reductions

Bottom-up and top-down are concepts which are supportive of specific methodologies for solving a particular problem of study. In a broadly manner, a bottom-up approach consists of looking at relevant peculiarities of a subject and integrating a set of features into a coherent and larger system. The bottom-up approach adopts specific definitions depending on the context of applicability. In public administration, the bottom-up approach is studied more systematically because governments benefit in instances where the general public has a stake and participate in the decision making process. The bottom-up concept falls into different interpretations and the use of this concept is largely determined by a set of specific relationships [12].

There are at least three different interpretations of the bottom-up approach in the definition of climate change mitigation commitments: 1) the regime development which can be multilateral or coalition based; 2) type of commitments delimited by a group of policies; and 3) for national targets distribution [13]. A bottom-up approach regarding the type of commitments consists of maximum allowable emissions of greenhouse gases (i.e. output commitments) and a pledge to behave according to policies and agreements on measures (i.e. input commitments) of which definition is based on technology and performance standards; research and development (R & D) incentives; sector Clean Development Mechanism (CDM); financial assessments; taxes, etc. On the other hand, an interpretation on national targets distribution consists of adding up national efforts to emissions control where differences in economic structure and potential for technological change in a country are taken into consideration [14]. Adding up national efforts and particularly emissions reduction from a group of industries (and firms) is also regarded as a programmatic climate change approach [15].

Because the purpose of this paper is to calculate sector CO_2 emissions in order to inform the decision making process, the definition of bottom-up and top-down aims at finding opportunities in industry for emissions reduction. CO_2 emissions and other generic greenhouse gases (GHG) are the outcome of combustion processes involving chemical reactions from industrial activity. In particular, energy uses involving fossil fuels generate air pollutants of which GHG is a particular type. This study identifies possible ways of reducing CO_2 emissions which are associated to the use of fossil fuels in iron and steel manufacturing. The approach followed in this study suggests that improved uses of energy sources have the potential to substantially reduce the amount of CO_2 emissions originated from industrial activity. However, fossil fuels which enter the production process in iron and steel manufacturing can also perform a function as reducing agents (i.e. *reductants*) and not energy sources [16, 17]. Figure 2 shows the distribution of major fossil fuels employed in iron and steel manufacturing. In particular, natural gas is employed as a heat source in conventional furnaces or reducing agent in the direct reduction reactor in order to produce sponge iron or direct reduced iron (DRI).

Previous CO_2 emissions calculations in iron and steel industry in Mexico have suggested an inter-related function between growth in physical production (i.e. tonnes of steel), process and product mix (i.e. technology and product structure), and energy efficiency performance in determining the overall amount of energy requirements [18]. This work relies on a bottom-up approach where the amount of CO_2 emissions is associated to specific energy consumption – SEC (i.e. primary energy requirements in iron and steel making) during the period 1970-1996. The authors found that *ceteris* *paribus* (including structure and energy efficiency), physical activity would have raised primary energy consumption by 211% in the period 1970-1996. Likewise, assuming physical activity and energy efficiency unchanged, technology and product structure would have the potential to reduce energy requirements in 12% less than the actual figure. Also, keeping physical activity and production structure constant, energy efficiency improvements would have the largest potential to push down energy consumption by 51% less than the observed figure in the same period.



Source: Ministry of Energy (Sener), Mexico, 2006.

Figure 2: Structure of Consumption of Fossil Fuels in Iron & Steel Manufacturing in Mexico, 2004 (%)

Energy and forestry mitigation scenarios for Mexico in the period 1994-2010 are also available from a bottom-up perspective [19]. The authors found that 729.6 Tg of CO_2 emissions are attributable to energy consumption by 2010. These results are obtained from integrating energy and non-energy sectors (i.e. forestry) into one single model which assesses mitigation potentials and costs of alternative choices in both sectors. One of the fundamental assumptions when modeling the Mexican energy sector is that CO_2 emissions are originated from energy consumption. The bottom-up specification consists of defining relationships between energy services, technologies, transformation, and energy supply. Likewise, in [18] the bottom-up model is built upon product specification using existing corresponding best practices; specification of feedstock (i.e. major raw materials) using in primary and secondary steel making; calculation of energy efficiency corresponding to a manufacturing process; and emission factors associated to specific fuels.

Although the previous analyses attempt to disaggregate factors accounting for energy consumption, they do not account for an in-depth specification of technology features, plant age, production line performance, capacity utilization, and so on. All these features can be regarded as specificities of an industry with respect to an energy consumption profile. In this paper, the bottom-up approach is interpreted in a more careful manner in the specification of critical factors explaining the amount of CO_2 emissions in sector specific energy consumption (SEC). The contribution of this study rests on opening up technology features of a representative steel making facility and delimiting the properties and functions of fossil fuels and materials when entering specific stages of the production process. In a situation of fully availability of information bottom-up models are aimed at specifying relevant features of technological choices which are relevant for energy requirements [20].

However, information is not always fully available and there is often no clear distinction between bottom-up and top-down models in the field of energy studies. More importantly, there is a source of discrepancy on the amount of GHG mitigation costs when applying one or another approach. GHG mitigations costs are generally said to be lower or negative in bottom-up models whereas higher in top-down settings [21]. There is also the assumption of technological innovation affecting productivity performance in a bottom-up representation. However, from an economic perspective productivity performance can be also affected by demand contraction and increasing uncertainties in spite of high technical efficiency of machinery [22].

On the other hand, top-down models show a high-level aggregation. One of the main criticisms of top-down models refers to the lack of thorough description of the underlying factors accounting for the dynamics of sector demand. General equilibrium models in the field of economics are usually regarded as top-down approaches. This type of framework is employed to specify vintage capital models where the research inquiry consists of testing the success of energy saving technologies in order to lessen the *trade-off* between economic growth and energy conservation [23]. Top-down models can also achieve more refined specifications without falling into the category of bottom-up approaches. For example, findings on the sources of CO_2 emissions growth are available in a top-down framework while decomposing their effects into an energy intensity factor, energy mix factor (i.e. fuel composition of an energy system), and a carbon content factor for the Canadian business sector during 1990-1996 [24]. Yet, a hybrid approach is possible using general equilibrium analysis in energy policy where energy sectors are specified in a bottom-up setting and other production sectors of an economy are defined in a top-down framework. In this latter case, constant-elasticity-of-substitution functions correspond to a top-down modeling [25].

With the purpose of integrating both approaches into CO_2 emissions calculations, an energy efficiency index is calculated using a top-down framework. Top-down settings allow for the construction of an autonomous energy efficiency index (AEEI) which provides an indication (i.e. rate of change) of overall energy efficiency due to dissemination of new technologies [26]. Energy intensity calculations are aimed at approximating features of efficiency in traditional thermodynamics which rely on the measurement of physical systems [27]. The formalization of this concept is as follows:

$$Efficiency(\eta) = \frac{useful\_energy\_output}{energy\_input}$$

The concept suggested above as a basis for energy intensity calculations relies on the specification of raw materials and fossil fuels as part of a particular segment process. Because energy holds an ecological resource view, an industrial ecology approach is found to be informative in the discussion of results on the amount of possible CO_2 emission reductions. Optimization can be viewed as a particular way of resource rationalization. The idea of rationalizing energy inputs originates from the recognition that the stock of fossil fuels and materials is finite [28]. Thus from an ecological economics perspective, a major strategy to achieve sustainability consists in applying efficiency of resource use [29].

The model proposed in this study is built upon the following key assumptions:

1) The amount of physical production is affecting the quantity of energy requirements.
2) The quality of steel products is affecting the volume of CO_2 emissions.
3) Differences in technological obsolescence affect performance of production processes.
4) Energy intensity reductions contribute to CO_2 emissions decreases associated to combustion processes.
5) Energy intensity reductions derive into energy efficiency improvements. However, energy efficiency gains may not necessarily lead to CO_2 emissions reduction in the long run.

Assumption 5 means that gains in energy efficiency per unit of steel may be counterbalanced by an increase in production in a defined period. Suppose

Q tonnes of steel are produced with an energy requirement $E-\delta$ (*peta-joules*) in period t. Energy savings per tonne of steel are represented by the value δ. Assume also that a reduction in production costs due to lower energy bills allows selling a tonne of finished steel at a price $P-\gamma$. The value γ is proportional to the energy bills reduction which is only possible due to gains in energy efficiency $[(E-\delta)/Q]^{-1}$ in t. A scenario where a cheaper price per ton of steel $P-\gamma$ generates an increase in market demand, production of finished steel may increase by an amount $\Delta Q = Q + q_2$ in period $t+1$. Indeed, ΔQ is carried out more energy efficiently in period $t+1$. However, the amount of CO_2 emissions in $t+1$ may be equal to that amount generated in t because q_2 tonnes of steel imply *additional energy requirements* at the efficiency level $[(E-\delta)/Q]^{-1}$ in $t+1$. A situation depicted in the previous example is known as the *"rebound effect"* in the field of energy economics [30]. In other words, it may be the case of a relative and not absolute saving in energy requirements *along time* when growth in market demand compensates energy savings achieved in previous periods. In this context, improvements in energy efficiency are conducive to relative reductions in CO_2 emissions in the long run. Thus energy efficiency is proposed as a strategy *to control* the amount of CO_2 emissions released into the atmosphere.

Layout of Integrated Iron and Steel Works

In a general level of aggregation, the iron and steel industry consists of integrated primary and secondary steel making. Integrated primary steel making consists of the provision of basic raw materials upstream in the production chain of pig iron. It involves relevant steps of which raw materials (i.e. iron ore, coal, and coke) are obtained in the mining sector [31]. Iron ore agglomeration, coking operations and sinter strand are generally vertically integrated functions of a company. This means that the selection of iron ore, production of coke and sinter product is under a single company's control and not obtained in the market place.

Formal industrial organization models proof that vertically integrated prices of intermediate products (i.e. raw materials) which are administered by a downstream company allow for a higher profit margin [32]. If a steel manufacturer can also integrate the functions of providing basic raw materials in crude steel manufacturing, prices of finished steel products will be cheaper. However, the approach of this paper turns attention to another specific domain when analyzing a vertically integrated arrangement: the *outcome on energy requirements*. An absolute energy consumption profile upstream operations can be reduced under the control of a single company rather than buying these products from different suppliers. One of the reasons supporting this view responds to physical and technological constraints of existing productive operations. Sinter product, coke and limestone are basic raw materials in the production of crude steel. If a facility counts on coking operations and sinter strand at a shorter location to the blast furnace, energy transportation sources are smaller and time delivery is marginal. Also, a facility or group of plants can define a production programme in order to optimize the provision of sinter product, coke and limestone among other materials according to the demand generated by pig iron production in a blast furnace. However, a fundamental reason supporting the view of a lower energy requirement profile in vertically integrated facilities is provided by an industrial ecology approach. In particular, coking operations produce coke as an intermediate raw material which comes along the generation of three by-products: *coke oven gas (COG), tar and residual fuel oil*. Downstream the production line pig iron (also known as crude iron) is produced in a blast furnace which comes along with *blast furnace gas (BFG)* as a generated by-product. The industrial ecology approach is mostly concerned on *closing the loops* of generated by-products into a sort of service-life-cycle rather than product-life-cycle with positive environmental benefits [33]. In this context, closing the loops means finding profitable applications of by-products or generated waste into other stages of the production process rather than disposing them to the environment in the form of air, water or solid pollutants. A second possibility on closing the loops consists of establishing suitable institutional arrangements which facilitate inter-industry linkages in order to trade by-products among companies [34] much in the sense of "*Instrumentos Técnicos Normativos*" addressed in section 2.

In practice, integrated primary iron and steel making facilities use coke oven gas (COG) and blast furnace gas (BFG) to generate electricity on site [35]. These sub-products are exhausted gases from coking and blast furnace operations in integrated production of crude iron. This is a bottoming cycle cogeneration scheme where a heat recovery boiler sequesters wasted heat from a combustion process in manufacturing. Steam is produced from waste heat and used to drive turbines for electricity generation [36]. Electricity which is a primary energy source is highly employed in steel manufacturing with the use of electric arc furnaces (EAF) and to a lesser extent in the operations of basic oxygen furnaces (BOF). Another component of electricity entering the production process occurs at the stage of rolling mills for semi-finished products. The amount of on-site generated electricity (measured in GJ) can be compared to the amount of purchased electricity from power suppliers for an evaluation of environmental externalities due to cogeneration schemes. On-site electricity generation in primary integrated facilities means giving up a certain amount of CO_2 emissions as compared to that amount from purchased electricity which is generated from consumption of fossil fuels.

Two warning distinctions are fundamental at this stage of discussion. First, although not part of the boundaries of a company's core operations purchased electricity is sometimes considered in the definition of CO_2 emissions calculations [37]. Second, the amount of CO_2 emissions vary substantially according to a particular energy mix associated to an electricity generation system. The energy mix consists of the distribution and uses of energy sources for electricity generation at a particular point in time [38]. Energy sources can be non-renewable (comprising fossil fuels and nuclear) and renewable. In the case of Mexico, ¾ (74.7%) of electricity generation are produced from fossil fuels whereas ¼ (25.3%) is obtained from renewable. Vapor based thermo-electricity accounted for 36.7% of gross electricity generation from fossil fuels whereas hydro-electricity represented 13.8% from renewable in 2007 [39]. Increasing the amount of on-site electricity generation due to re-use of by products and the amount of renewable share in electricity generation can control the amount of CO_2 emissions from industrial activity [40].

Secondary steel making consists of the use of steel scrap and/or a combination of steel scrap and sponge iron (also known as direct reduction iron – DRI) in order to produce crude steel. Because there are no blast furnace operations, secondary steel making is said to be less energy intensive. The concept of mini-mills is sometimes employed to describe a facility producing crude steel with the operation of EAF or BOF technology [41]. Secondary steel making can be viewed as a downstream stage of an integrated iron and steel facility where energy requirements are less intensive as compared to integrated iron and steel making [42]. It can also be regarded as undertaking the manufacturing of steel while skipping early stages in iron making. Secondary steel making using EAF technology is often associated to small plant capacity (also known as mini steel mills). A mini-mill consists of a small plant for making steel where the production process starts with the use of steel scrap as a basic input for steel making. The EAF technology in secondary steel making consists of a batch process with intervals of time of about two to three hours. A mini-mill represents a type of technological innovation allowing for increased productivity and higher flexibility according to continuous changes in market demand [43].

From a very generic classification, there are three sorts of iron and steel plants: 1) integrated primary steel mills; direct reduction-electric melting steel mills; and 3) scrap based mini mills [44]. DRI is a fundamental material in a range of high quality steel products oriented to specific markets including the automotive sector. On the contrary, low quality steels are associated to high contents of steel scrap which are oriented, for example, to the building sector. Mini-mills are placed in this second category of which products are relatively simple [45].

Feasible technological routes

Figure 3 represents a layout of plant operations in integrated primary and secondary steel making. The figure aids to clarify the previous discussion but also four technological core routes are identified while looking at this layout:

1) Blast Furnace Operations (BF) – Production of crude steel via Basic Oxygen Furnace (BOF).
2) Direct Reduction Reactor (DRI) – Production of crude steel via Electric Arc Furnace (EAF).
3) Recycling of steel scrap (RSC) – Production of crude steel via Electric Arc Furnace (EAF).
4) Blast Furnace Operations (BF) – Production of crude steel via Open Hearth Furnace (OHF).

Steel production in Mexico is not currently carried out using BF-OHF technological choice. According to official statistics, open hearth furnaces (OHF) were closed down in 1992 as part of a process of privatization and modernization in iron and steel manufacturing in Mexico. Therefore, those facilities which count on a blast furnace may employ BOF or EAF in the production of crude steel. As mentioned above, on-site electricity generation can be employed in EAF and rolling mills. Technological routes 1 and 4 are highly energy intensive in terms of total energy incorporated per ton of finished steel products. Although technological routes 2 and 3 are relatively less energy intensive, electricity consumption in EAF per ton of crude steel is highly significant [46].

Model Specification and Results based on a Mexican Plant

Aggregated energy intensity index on a top-down setting

The following exercise holds a top-down and a bottom-up component. An aggregated energy intensity index Ei_t for the period 1994-2006 is calculated on a top-down approach. This index is composed of end use energy consumption E_t (in peta joules) and physical output Q_t (i.e. steel in tones) for the whole iron and steel industry in year t:

$$Ei_t = \frac{E_t}{Q_t} \qquad \dots (1)$$

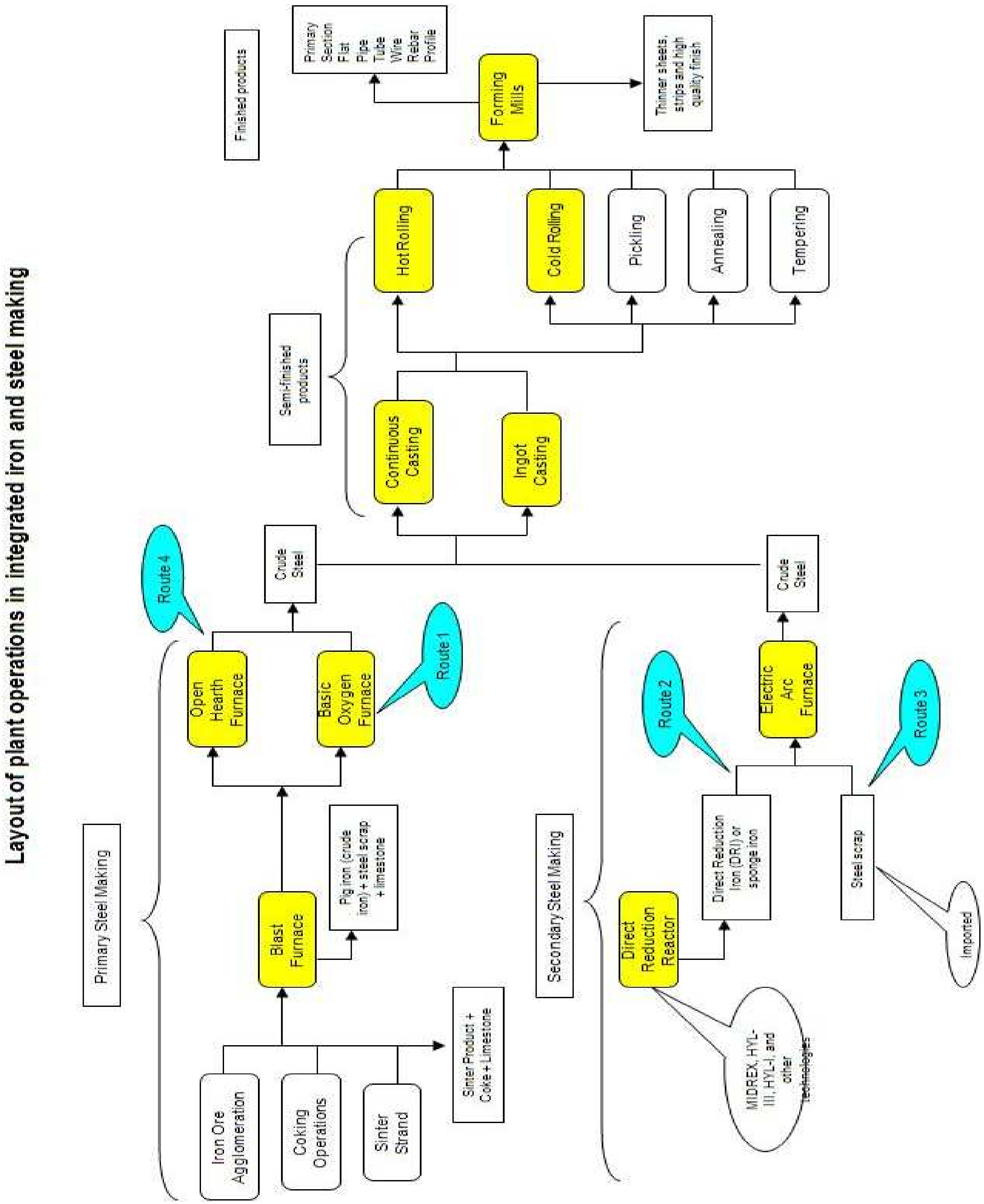


Figure 3: Feasible Technological Routes in Integrated Iron and Steel Making

An annual growth index is calculated for physical output taking 1993 as a base year. Similarly, an annual growth index is calculated for end used energy consumption using the same base year. Ei_t is computed as the ratio of end use energy consumption and physical output growth indexes. Figure 4 shows results obtained for aggregated energy intensity index calculations in iron and steel manufacturing. Energy intensity in this industry shows a 30% decrease in a 15 year period. The downward slope line can be broken down into three segments which suggest three stages of evolution in the performance of iron and steel with respect to energy consumption:

1) A sustained and gradual decrease of energy requirements per tonne of finished steel in the period 1993-2000 with a pressure towards higher energy requirements in year 2000.
2) A sharp drop in energy intensity accounting for a 26.8 % decrease in the period 2001-2003.
3) A steady-state in the evolution of energy intensity with an average index of around 74% in the period 2004-2008.

These calculations do not include monetary values of production with the purpose to capture structural changes in industry. Other studies have calculated energy intensity for iron and steel as the amount of average consumption measured in peta-joules by wealth of unit of production [47]. The author in [47] also finds evidence of a significant decrease in energy intensity for the iron and steel industry. Adoption of the electric arc furnace (EAF) as a dominant production technique and direct reduction iron (DRI) as major raw material in steel making caused a more beneficial environmental outcome because they have a relatively lower environmental impact and are less energy intensive. On the other hand, a higher share of semi-finished products into final production pushed towards higher environmental degradation and energy requirements [48]. The study in [18] found and commented on a series of structural changes accounting for a decline in overall energy intensity in the iron and steel industry. These changes include the shutting down of open hearth furnaces in 1992; growth in the share of continuous casting (from 9.8% in 1970 to 85.0% in 1996); a major utilization of coke oven gas and blast furnace gas for on-site electricity generation in integrated plants; improvements in HYL-III technology; and invention of a pneumatic system in HYL technology carrying on hot DRI directly to the EAF using DRI reactor exhaust reducing gases; and suppressing cooling and reheating operations. These structural changes which also include a high component of technological change represent driving forces pushing down the downward slope curve of energy intensity (Fig. 4).

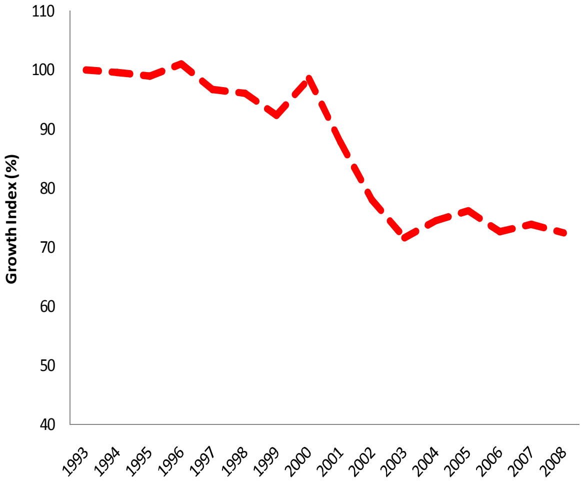


Figure 4: Aggregated Energy Intensity Index for Iron and Steel Manufacturing in Mexico, 1993-2008 (base year 1993: 1)

Energy requirements and CO2 emissions of a representative mini-mill on a bottom-up setting

A bottom-up approach is employed to estimate the amount of end use energy consumption in a representative mini-mill using EAF technology. Calculations are specific for technological route number 3. This plant employs 100% steel scrap in the melting of EAF process for billet production. A simplified plant layout which consists of two major departments is depicted in figure 5.

Department one consists of a melting process with the aid of EAF technology and continuous casting machine whereas department two consists of a rolling mill. $\alpha\%$ of total electricity requirements of the facility correspond to the melting shop whereas $\beta\%$ to rolling mill operations where $\alpha > \beta$. Natural gas is also a major fuel employed mostly in rolling mills $(\alpha\%)$ and to a lesser extent in the melting shop $(\beta\%)$.

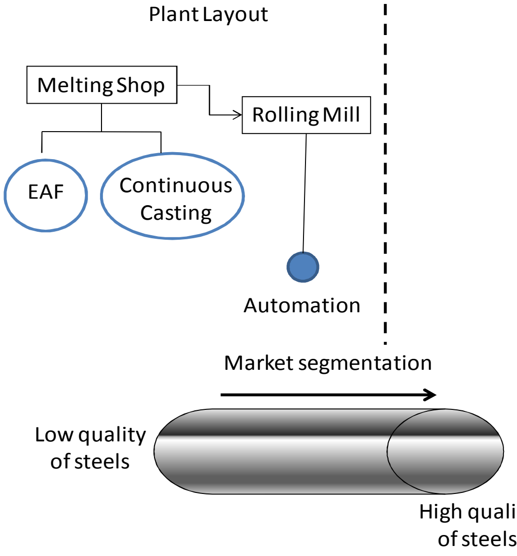


Figure 5: Plant Layout of Mini-mill A

In this model, the amount of electricity requirements (e) is a function of the amount of physical production of billets q_{At} in the melting shop, EAF productive efficiency η_t, and capacity utilization ω of a representative mini-mill A:

$$e = f(q_{At}, \eta_t, \omega) \qquad \ldots (2)$$

The functional form of (2) is as follows:

$$e = q_{At} * \eta_t * \omega \qquad \ldots (2.1)$$

Where $\omega = 1$.

Similarly, the amount of consumed natural gas (gs) is a function of the amount of physical production s_{At} in the rolling mill, a natural gas consumption efficiency parameter δ_t, and capacity utilization ω in mini-mill A:

$$gs = f(s_{At}, \delta_t, \omega) \qquad \ldots (3)$$

The functional form of (3) is as follows:

$$gs = s_{At} * \delta_t * \omega \qquad \ldots (3.1)$$

Where $\omega = 1$.

η_t and δ_t are specific parameters for period t. η_t is defined as the amount of kWh per tonne of crude steel (i.e. a ton of billet is the reference unit) whereas δ_t is defined as the amount of cubic meters $(cu.m)$ of natural gas per tonne of billet. These values are overall parameters for two reasons. First, η_t is reported from the melting shop but a fraction of electricity γ_e is also consumed in the rolling mill and by electric motors located in both departments. Likewise, δ_t is reported according to rolling mill operations but a fraction of natural gas γ_{gs} is also consumed in the melting shop. For example, a remaining γ_{gs} is employed in a combustion process in order to reach temperatures of approximately 1200 °C in n furnaces. Also, the speed of natural gas provision is determined by a supply pipe constraint in the plant distribution network.

Second, η_t is a constant for period t. However, period t may be discontinuous in $t = 1$. EAF productive efficiency is an index of performance which gives an indication of embodied technological change. In this exercise η_t corresponds to year 2007.

However, EAF is said to show higher values of η_t in the past. In this regard, a higher efficiency in productive operations may be the result of enhanced performance of machinery and equipment, and better energy consumption practices on the shop floor. Both factors can be understood as part of a process of technical change. Also η_t can vary by type of country according to the stage of technological development. In 1990, a typical value of η_t for Mexico corresponded to 938 kWh/tonne of crude steel with 51% EAF in total crude steel. Current average values for electricity consumption in EAF range from 500 to 600 kWh per tonne of crude steel [49]. The outcome on energy requirements in EAF operations are determined by a series of factors: furnace size and length of cycle; mix in charges; practices on charges; and casting temperature [50].

An indication of technological obsolescence is given by comparing different η_t values in Table 2. The 1990 value for Mexico is considered as a benchmark (BMK) against best-practices (i.e. the lowest existing value) can be compared with. The productive efficiency of the representative mini-mill A in this study is very close to the average value in Table 2.

Total electricity requirements in plant operations can be represented as:

$$\Sigma_t^{t-n} e_t = (q_{At} * \eta_t)(1 + 1/4) \quad \ldots (4)$$

With n representing a defined number of years.

Total natural gas consumption in plant operations can be represented as:

$$\Sigma_t^{t-n} gs_t = (s_{At} * \delta_t)(1 + 1/4) \quad \ldots (5)$$

Total energy requirements in facility A are as follows:

$$E_{At} = \Sigma_t^{t-n} \mid (e_t, gs_t) \quad \ldots (6)$$

Total physical output s_{At} in facility A is decomposed into:

$$s_{At} = q_{At} + q'_{At} + q''_{At} \quad \ldots (7)$$

q'_{At} represents an amount of billet which is not incorporated into final steel products due to a crude steel yield factor $\bar{y}_{At}$ which is assumed to be 1 in this exercise. Therefore $q'_{At} = 0$ at $\bar{y}_{At} = 1$.

q''_{At} accounts for a crude steel deficit in the plant due to incompatibility in the amount of production between the melting shop and the rolling mill. This incompatibility which creates a bottleneck can be solved while purchasing an amount of crude steel q''_{At} from an external supplier.

Thus overall energy intensity in facility A is the ratio between:

$$Ei_{At} = \frac{E_{At}}{(s_{At} - q''_{At})} \quad \ldots (8)$$

which can also be regarded as an engineering energy intensity function.

Table 2: EAF productive efficiency η_t

	Technological obsolescence	Label	kWh/ton	% EAF in crude steel
Mexico	1990	BMK	938.0	51
	Upper value[**]	UV	580.0	-
	Lower value[††]	LV	395.0	-
	Average value	AVG	487.5	-

Source: based on Meyers and Odón de Buen, 1993.

A hybrid model: incorporation of engineering energy intensity function into an aggregated energy intensity index for iron and steel manufacturing

Industry aggregate energy intensity can be understood as the outcome of a differentiated energy consumption behavior of its many industry facilities belonging to different companies. The exercise on energy requirements in this study corresponds to a mini-mill operating with EAF technology and a factor 1 for steel scrap charge. According to the classification proposed earlier this mini-mill corresponds to technological route number 3. The representative mini-mill A is assumed to mirror a similar pattern of aggregated energy intensity for overall iron and steel manufacturing. This assumption allows for matching a specific energy consumption value E_{At} of facility A to a corresponding overall energy intensity index for overall iron and steel industry Ei_t. The evolution of energy requirements in facility A can be traced backwards by setting a univocal correspondence: $E_{At} \rightarrow Ei_t$ if and only if $E_{At} = Ei_t$ in $t = 2007$. In other words, Ei_{At} is a calculated value using plant data for year 2007; afterwards, Ei_{At} is extrapolated to aggregate energy intensity index in iron and steel making which correspond to previous years.

Capacity utilization is assumed to be full $\omega = 1$. Thus the amount of finished steel production (in tones) $s_{At} = \omega_{At}$ except in year 2003 when $\omega_{A,2003} = 2/3$. This facility also experienced an increased in production capacity Δq_{At} in the melting shop at some point along 1990-2007. The previous assumption provides support of the following identity:

$$q_{At} + \Delta q_{At} + q''_{At} = s_{At} = \omega_{At} \quad \ldots (9)$$

Except in $t = 2003$

Changes in the amount of steel production in mini-mill A Δs_{At} with respect to overall EAF production in the aggregated steel industry $S_{EAF,t}$ are calculated with the following ratio:

$$\Delta Share.s_{At} = s_{At} / S_{EAF,t} \quad \ldots (10)$$

Ideally, the observed amount of finished steel products from facility A would be desirable when tracing backwards energy intensity of facility A. However, this information is only reported for year 2007. Equation (10) aids to solve partially this inconsistency. This equation is a proxy accounting for variations in s_{At}. It shows variations of s_{At} share with respect to total EAF steel production per year.

Figure 6 presents results on calculations following the hybrid model presented above. In this model, an engineering energy intensity function is developed with the aid of a bottom-up approach. An observed energy intensity value corresponding to year 2007 is obtained. This value is extrapolated to an aggregated energy intensity index for overall iron and steel making which is formulated on a top-down setting. It is worthy of noting that the bottom-up

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[**] 1970's EAF technology in North America.

[††] Latest-best-practice technology in North America.

component is integrated into the top-down setting and not the other way around. This exercise is also a type of simulation because energy intensity values are re-built for previous years. In general, the amount of energy requirements (MJ) per tonne of steel tends to increase due to growth in the share of finished steel from plant A in total industry EAF production. However, in the period 1993-2008, facility A has decreased its share in total industry EAF production in 5.13% while energy intensity has dropped by 1.99% on a compound annual growth rate. This means that figure 6 should properly be read from top-right to bottom-left hand side for an evolution comparison.

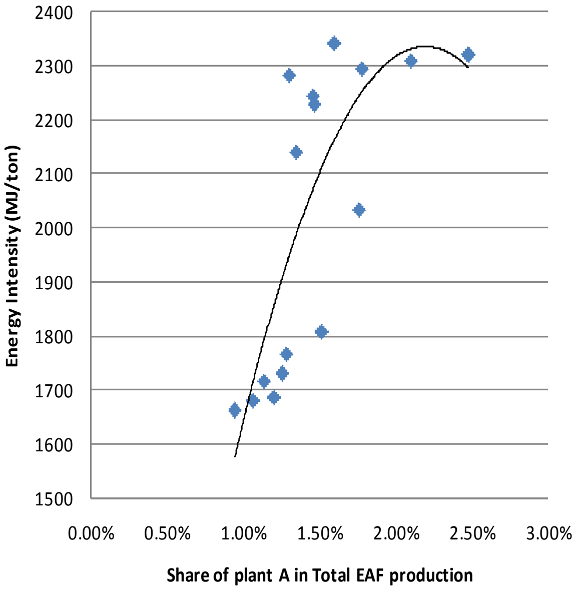

Figure 6: Production versus Energy Profile of a Representative Mini-mill using EAF technology, Mexico, 1993-2008

These results also suggest a discontinuity of the energy intensity function for a range of values where the function is evaluated. For a range of production share [0.01, 0.015], energy intensity varies approximately between 1,650 and 1,800 MJ/ton of steel. Surprisingly, a range of production share [0.013, 0.016] is associated approximately to energy intensity variations of magnitude 2,100 and 2,350 MJ/tonne of finished steel (i.e. evidence on discontinuity). For production shares higher than 0.016, energy intensity requirements appear to be stable of around 2,300 MJ/tonne of steel. The finding on discontinuity is difficult to interpret. EAF productive efficiency η_t is thought to improve gradually along time. Waste of materials due to failed optimization practices on energy requirements and material charge do not seem as a plausible explanation. However, a threshold effect on a high variability of energy requirements at plant level is located at a value of production share 0.013. A threshold effect suggests that energy requirements tend to increase more than proportionally the growth of production share for a range of production share [0.013, 0.016]. Results also suggest that the amount of energy requirements tend to be proportionally lower for higher values in production share. These results suggest the existence of scale economies in production of steel which in the context of energy intensity means that energy requirements per tonne of finished steel tend to be relatively low with higher production volumes [51]. Production scale economies tend to curve energy intensity because the amount of electricity incorporated in rolling mills, pumps for water circulation, pollution control and fans changes relatively shortly due to growth in steel production [52].

CO2 emissions calculation based on energy requirements of facility A

Equation (6) is used in the calculation of CO_2 emissions derived from energy requirements at plant level. CO_2 emission factors EF_x for purchased electricity from the Mexican electricity grid and natural gas enter the specification of the following equation:

$$CO_2(s_{At}) = \sum_t^{t-n}(EF_{pe})(e_{At}) + \sum_t^{t-n}(EF_{gs})(gs_{At}) + u \quad \ldots (11)$$

Where EF_{pe} is the corresponding CO_2 emission factor for purchased electricity from the Mexican electricity grid and EF_{gs} is the associated natural gas CO_2 emission factor. In this representative mini-mill which is composed of an EAF melting shop and rolling mill, natural gas consumption enters the production process as a fuel and not as a reducing agent (RA). This fact results from a simplistic deduction. However, in more complex plant layouts (for example, in integrated iron and steel making), a more careful specification on the uses of natural gas is needed.

In addition, u is a corrective value in CO_2 emissions calculation using a bottom-up approach. So far abstraction has been made on the use of electrodes in EAF for crude steel production. The U.S. Environmental Protection Agency suggests 0.0015 metric tonnes of released carbon from electrodes per metric ton of EAF steel production [53]. Thus u takes the following functional form:

$$u_{At} = f(CO_2) = 0.0015(s_{At}) \quad \ldots (12)$$

Substituting (12) in (11) gives the complete functional form for CO_2 emissions calculation at plant level:

$$CO_2(s_{At}) = \sum_t^{t-n}(EF_{pe})(e_{At}) + \sum_t^{t-n}(EF_{gs})(gs_{At}) + 0.0015(s_{At}) \quad \ldots (13)$$

Results on CO_2 emissions are presented using equation (13). CO_2 emission factors for the Mexican electricity grid correspond to four different years (see Table 3).

Table 3: CO_2 Emission Factors of Purchased Electricity

	Emission Factor	Units
2003	571.2	t CO_2/kWh
2004	549.6	t CO_2/kWh
2005	550.1	t CO_2/kWh
2006	528.3	t CO_2/kWh

Source: SEMARNAT, Mexico, 2007.

$EF_{pe,2003}$ is used for CO_2 emissions calculation for years before 2003 whereas $EF_{pe,2006}$ is used for years after 2006. CO_2 emission factor for natural gas consumption is 0.0581 ton CO_2/GJ. Figure 7 presents results on calculations of CO_2 emissions for plant A. It is worthy of noting that emissions are reported on a cumulative basis and represent a simulation exercise. Energy intensity of facility A is decreasing in t whereas cumulative CO_2 emissions are increasing. However, observed values of CO_2 emissions on a year basis decrease in the same proportion the energy intensity of facility A do. Cumulative emissions from plant A reach 1,092,664.8 tonnes of CO_2 whereas plant level energy intensity decreases from approximately 2,250 to 1,750 MJ/tonne in the period 1993-2008. The largest bulk of emissions are originated from electricity consumption in EAF. Emissions from natural gas requirements represent approximately $1/10$ the emissions from electricity consumption whereas emissions from electrode consumption in EAF represent of around 1.3%.

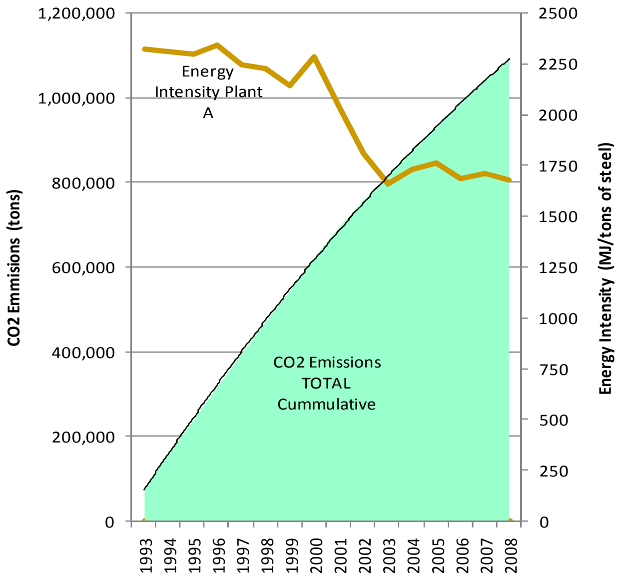

Figure 7: Carbon Dioxide Emissions and Energy Intensity of Mini-mill A, Mexico, 1993-2008

Conclusions

Because iron and steel making is a highly energy intensive industry, opportunities for CO_2 emissions reduction are still possible in production segments where: 1) energy efficiency gains are still far above the highest theoretical; 2) latest best-practice technologies are not fully deployed. The simulation model presented in this study suggests that it is still possible to curve further CO_2 emissions due to energy efficiency gains. The plant in this study and particularly EAF technology is around 30 years old. In some instances, Mexican manufacturing is featured by state-of-the-art steel making technology, for example, the HYTEMP system and HYL-ZR-process configuration in direct reduction reactors (DRI). However, there is still a number of mini-mills of which productive age is around facility A's stage.

The EAF productive (energy) efficiency η_t in facility A is far above that one for latest best-practice-technology (i.e. 395 kWh per tonne of crude steel). On the one hand, marginal and incremental gains in EAF efficiency are possible due to incorporating water cooling panels; increasing oxygen injection; and avoiding miscellaneous heat loss through radiation due to practices on charges and long operation cycles in EAF [54]. On the other hand, new capital investments are desirable in order to replace existing EAF as a means to further increase energy efficiency. In this regard, the avoided amount of CO_2 emissions due to further reductions in energy intensity and consequential environmental benefits need to be incorporated in total benefits of the cost/benefit ratio. So far project evaluations which incorporate environmental impacts on the side of the equation accounting for benefits are limited at the sub-sector or plant level. This constitutes a future research area which could inform the decision making process for climate change mitigation projects, and in particular, those projects under the Clean Development Mechanism (CDM) umbrella.

On the other hand, using steel scrap in EAF contributes to reduce the amount of waste disposal into the environment. However, one should be careful when thinking of recycling steel scrap as part of closing the loop in industrial metabolisms. Using steel scrap depends on the availability of this sub-product and regulatory mechanisms designed around steel scrap recycling. Steel and raw material prices are also determinant factors affecting the use of steel scrap. Likewise, the quality of steels for niche-markets determines the quantity and quality of steel scrap incorporated in a typical EAF charge. Therefore, variations in energy requirements in EAF operations do not depend solely on the use of steel scrap but on other economic and technical variables. In the formulation of feasible CO_2 emissions reduction strategies, these variables are to be incorporated in the calculation of cost/benefit ratios in environmental project evaluations.

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