Drivers and Barriers to Industrial Energy Efficiency and Climate Change Mitigation in Mexico – The Case of the Iron and Steel Industry

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I dedicate this thesis to my parents,

Elvira and Javier

For all their love and support

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Abstract

This research explores the drivers and barriers to *energy efficiency* in the Mexican iron & steel industry using a social science and energy modelling inter-disciplinary approach. The practices currently implemented in steel production facilities are explored in relation to *energy management* and *technological change* while technology-based attributes are explored in relation to impacts on energy consumption. From a conceptual stance, industrial energy efficiency is characterised by two alternative modes of governance: a) *market transformation* supporting energy efficiency and b) energy efficiency as implemented within a *firm.*

The holistic *energy modelling* approach draws on the quantification of energy/materials requirements in the iron and steel industry in order to calculate *carbon dioxide emissions* in that industry incorporating emissions originating throughout the integrated energy system. Included in are:

1) Fugitive emissions including venting and flaring practices in energy industries in relation to fossil fuels used in electricity generation
2) Emissions arising in electricity generation
3) Emissions attributed to fuels, materials, and electricity consumption in the iron and steel industry

The energy modelling approach explores alternative *energy policy scenarios* in relation to carbon dioxide emission abatement within electricity generation which, in turn, are incorporated into the estimates of emissions arising in the steel industry. Strategies to mitigate climate change are discussed in relation to what each organisation can do (i.e. the steel producers themselves as opposed to the electricity utilities and gas/oil suppliers) according to the attributes of the production process.

Two steel companies in Mexico are used as case studies in the identification of the relevant drivers and barriers to energy efficiency. Energy efficiency at the corporate level is explored in relation to strategic issues inclusive of capacity expansion, social corporate responsibility goals, and the market orientation of energy efficiency.

Reducing the cost structure in steel production is identified as a key market driver to energy efficiency and this is seen as part of the strategies to remain competitive in export markets. An inter-relation between the relative prices of raw materials, energy commodities, and the price of final steels affects energy related decisions. In some instances, the most economical choice may not necessarily increase energy efficiency since a choice for alternative raw materials may require additional *'steps'* in an integrated steel process with consequential energy requirements.

Among the technological drivers to energy efficiency, patenting the improvement of a technology represents a large incentive to raise energy efficiency with subsequent reductions of future investments in energy projects. But this feature is more the outcome of previous improvements as many stages of the integrated steel production are currently optimised. Integration of steel processes (sometimes regarded as *synergies*) in both companies with recovery and used of energy contained in previous stages is found as a significant technical driver to energy efficiency.

Production capacity projects are generally found to receive larger support in one of the companies as compared to energy efficiency projects. A priority strategy given to production capacity projects may, in some instances, work as a barrier to energy efficiency. Also, during the financial turndown in 2008, one of the companies placed a priority strategy on managing cash and adjusting the levels of operation and thus delaying the delivery of energy efficiency projects.

Incorporating energy issues in the policy guidelines of both companies work as a significant managerial driver to energy efficiency within organisations. Also, the more the bottom-line production personnel are involved and committed in energy management programmes, the stronger the development of firm-based capabilities supportive of *energy efficiency best-practice*. Energy efficiency is included in the eco-efficiency principles of the corporate policy in one of the companies whereas in the other company it is seen as part of the criteria of assessing corporate leadership. Also, the measuring and reporting of energy consumption appears as a very crucial organisational driver to manage energy efficiency.

Through the revision of energy efficiency at the company level, the following relevant drivers and barriers to energy efficiency are thus classified into four main classes: *i) economic – market driven; ii) technological; iii) priority strategies; and iv) managerial – organisational.*

The holistic approach introduced above allows quantifying and defining the relative importance of carbon emissions through different stages of an integrated energy system in Mexico. A baseline for fugitive carbon emissions of the fuels used in electricity generation amounted to 10,607.5 CO_2e whereas overall carbon emission in the steel industry amounted to 30,795,187 CO_2e in 2005. Thus the former accounted for nearly a third of the latter.

A carbon emission factor of the Mexican electricity grid amounted to 638.7 g CO_2e/kWh in 2005 with the use of a life cycle assessment (LCA) model. Electricity transmission loses are significant in Mexico (17% circa in 2005) and the carbon emissions grow proportionally to increases in transmission loses. Hence there appear two complementary climate change mitigation strategies: electric power producers can lower the amount of electricity loses while oil and gas suppliers can control the amount of fugitive emission during fuel production, processing, and delivery.

However, a large potential to reduce carbon emission in electricity generation correspond to diversification of the fuel mix towards a growing importance of non-fossil fuel technology in the future generation capacity. In this regard, the energy policy in Mexico has several alternatives on the path of the carbon emission factor. The worst case scenario correspond to a growing importance of coal-based technology in the future generation capacity whereas in the most ideal scenario renewable energy (such as solar and wind) gain a larger share in installed capacity. The most critical implication under a renewable scenario is a fall in the carbon emission factor by the year 2030 from the current 638.7 g CO2e/kWh to 297 and 320 g CO2e/kWh in low and high growth in electricity demand.

Carbon emissions from electricity consumption in the steel industry accounted for 15% of the overall emissions in 2005 where the remaining 85% correspond to uses of fossil fuels and materials. Clearly a significant area of opportunity demands strategies to reduce the carbon emission factor of the Mexican electricity grid.

In regards to a potential to reduce carbon emissions in the steel sector, the following strategies appear as relevant: a strategy of 2.1% annual growth in physical steel production would result into a decrease of the carbon intensity of the steel industry from 1.89 to 1.79 tonnes CO2e/tonnes of steel between 2005 and 2030.

A strategy of increasing electric arc furnace (EAF) steel production capacity while keeping the carbon emission factor for electricity and the energy intensity with no changes do not offer a potential to reduce carbon emissions. In fact, this strategy raises the amount of carbon emission by 2030. Hence a combination of strategies appears as more adequate in view of a potential for carbon emissions reduction from electricity consumption in the steel sector.

Implementing a strategy of a 2.1% growth in steel production as a baseline in combination with a reduction in the carbon emission factor under a renewable electricity future (i.e. a carbon emission factor lowers from 556.3 to 385.4 g CO_2e/kWh in the period 2009-2030), and reducing the energy intensity of steel production (due to grow in energy efficiency), allows reducing emissions from electricity consumption from 3,847.6 to 1,631.9 thousand tonnes of CO_2e between 2009 and 2030. It thus clearly that combining strategies on electricity generation and consumption offers a potential for carbon emissions reduction.

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Chapter 1

Introduction

1.1 Background of the Research

Energy efficiency in Mexico has been a concern of the government partly as a response to spurring economic development and as an environmental concern included in the National Strategy of Climate Action (CICC, 2006). The National Commission for the Efficient Use of Energy (CONUEE) is the first public agency responsible of promoting growth in energy savings, efficiency, and a higher share of renewable(s) in electricity generation. This Commission is a decentralised office of the Ministry of Energy and provides technical assistance to the agencies of the Federal Public Administration and the States of the Federation (Mata-Sandoval, 2008).

In addition, the Electricity Power Saving Fund Trust (FIDE) was created in early 1990s with the participation of different social actors. This organisation is oriented to encourage an efficient use of electricity by implementing programmes based on the inter-relationship between technological innovation and a market of energy efficiency technologies.

Recently, public policies to encourage higher energy efficiency and a sustainable approach to energy consumption have been facilitated by the revision of a constitutional framework. The coming into effect of a decree on the Sustainable Use of Energy which was issued as of 2008 provides the basis for the establishment of CONUEE (Senate of the Republic, 2008). Noteworthy in respect of environmental considerations is the fact that greenhouse gas emission issues appear to be incorporated for the very first time into an energy efficiency policy framework with the status of a public administrative decree.

On the other hand, strategies to reduce greenhouse gases are not only seen as part of a climate change mitigation agenda Mexico. In this regard, efforts and strategies to reduce greenhouse gases respond to the need of fostering a more competitive and proactive approach in the industrial sector in Mexico. This is the view held by the Ministry of Foreign Relations in Mexico. It requests from the private sector an increasing and more proactive participation in carbon markets and this is the case of heavy industries such as the energy sector (i.e. oil, gas, and electricity), cement, steels, chemicals, and the construction sector in order to curb CO_2 emissions to 2000 levels by 2050 (Bloomberg Newsroom, 2009; 2009b; 2009c; Point Carbon, 2009). It is important to note that at present time the way Mexico can procure with financial resources to reduce greenhouse gases is not clearly defined (The Economist, 2009).

Mexico as a non-Annex I country of the Kyoto Protocol has shown a sustained growth on the use of energy while following a path of economic development. This route of economic development has put a pressure on the CO_2 emitted from an increasing demand and use of energy. Overall, equivalent CO_2 emissions from energy generation and consumption have risen from 312.0 to 389.5 million tonnes between 1990 and 2002 which represent a 3.2% growth (Figure 1.1). Of the 389.5 million tonnes of CO_2 equivalent in 2002, 90% are emissions from overall fossil fuel consumption (350.4 million tonnes) whereas 10% correspond to overall fugitive emissions (39.1 million tonnes).

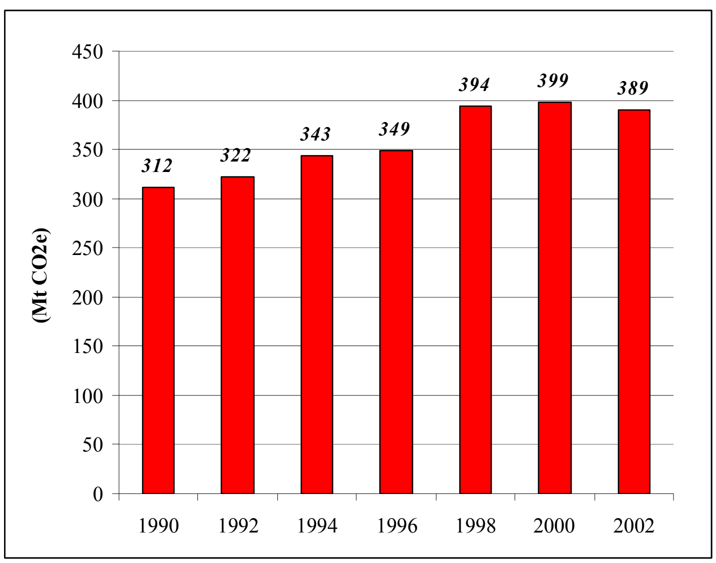

Figure 1.1 – CO_2e Emissions from Overall Energy Production and Consumption, 1990-2002 (Million tonnes of CO_2e)

Source: Comisión Inter-secretarial de Cambio Climático, México, 2007.

The way specific strategies to mitigate climate change need to be in place demands an identification of specific opportunities to reduce greenhouse gases. There are many attributes and stages of the energy sector in Mexico in which opportunities to reduce greenhouse gases are identified. According to the National Strategy of Climate Change in Mexico (2007), the largest potential to reduce emissions up to 2014 corresponds to overall industrial cogeneration (25 Mt of CO_2e), followed by growth in energy efficiency (24 Mt of CO_2e), and the reconversion of thermo-electricity plants in the Pacific from uses of oil to natural gas (CICC, 2007) – figure 2.1. The quantification of potential opportunities as presented in figure 2.1 was presented by the Inter-Ministerial Commission of Climate Change in Mexico.

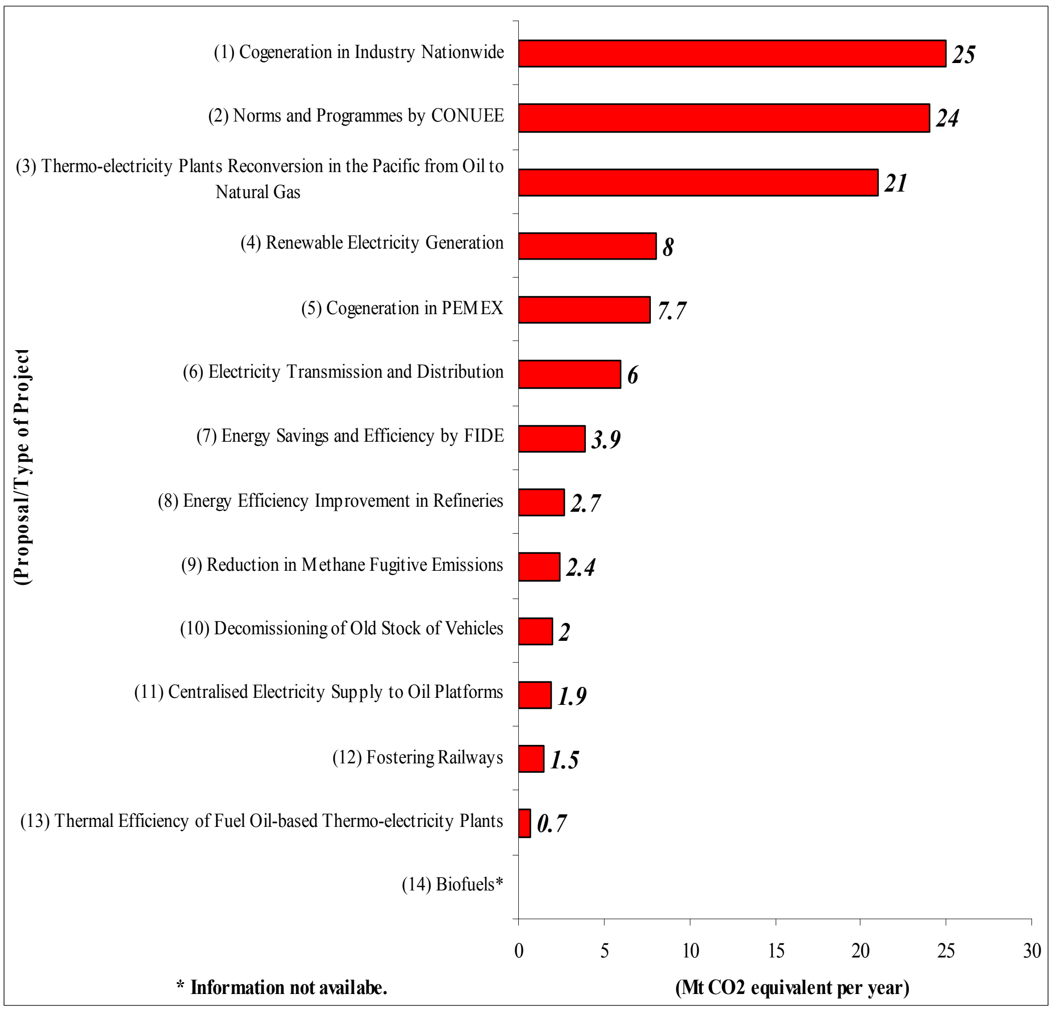

Figure 1.2 – Opportunities of Climate Change Mitigation based on the Estimated Potential of CO_2 Reductions up to 2014 (Mt CO_2e per year)

Source: Comisión Inter-secretarial de Cambio Climático, México, 2008.

In effect, this strategy is a response to the goals of a sustainable route of development defined in the National Development Plant (PND) for Mexico 2001-2006 and 2007-2012. This plan contains a definition of policy goals centred on the attendance of environmental sustainability while pursuing a route of economic development (Presidency of the Republic, 2007).

In addition, the Energy Sector Plan (PSE) is a specific governmental instrument which provides support to the policy goals included in the PND. The relevance of the PSE consists in defining public policy goals in relation to climate change mitigation measures taking place in energy production and energy related uses. The following five particular goals are re-taken from PSE and listed in table 1.1.

Goal I.2 – To encourage international efficiency standards, administrative transparency, and accountability in the operation of the hydrocarbon sector (i.e. energy industries) p.17
Goal II.2 – To level off (balance) the primary energy source portfolio, p. 28
Goal III.1 – To encourage energy efficiency and efficiency in energy generation p.33
Goal III.2 – To encourage the use of renewable energy and biofuels under a technical, economic, environmental, and social feasible conditions, p. 36
Goal IV.1 – To mitigate growth in greenhouse gas (GHG) emissions, p. 42
Source: SENER, 2008i, (these goals are translated from an official Spanish version of the Sector Energy Plan 2007-2012).

Table 1.1 – Climate Change Mitigation Goals in Energy Production and Uses in Mexico
Source: Energy Sector Plan 2006-2012, Mexico.

Evidence concerning both the areas of opportunity to reduce greenhouse gases (in figure 2.1) and policy goals of climate change mitigation (in table 1.1) indicate the need to understand specific features and stages of the operation of an energy system. The potential to reduce carbon emissions presented in figure 2.1 suggests a myriad of strategies the implementation of which differ in terms of technological attributes and particular stages of an energy system. In this regard, it is important to identify key stages of an integrated energy system in the overcoming of barriers to energy efficiency as compared to other strategies to mitigate climate change.

1.1.1 A Characterisation of the Energy System based on the Opportunities to Reduce Greenhouse Gases in Mexico

The mitigation measures presented in the National Strategy of Climate Change are organised within an energy system for Mexico (figure 1.3) the purpose of which is to show opportunities and technologies to reduce greenhouse gases.

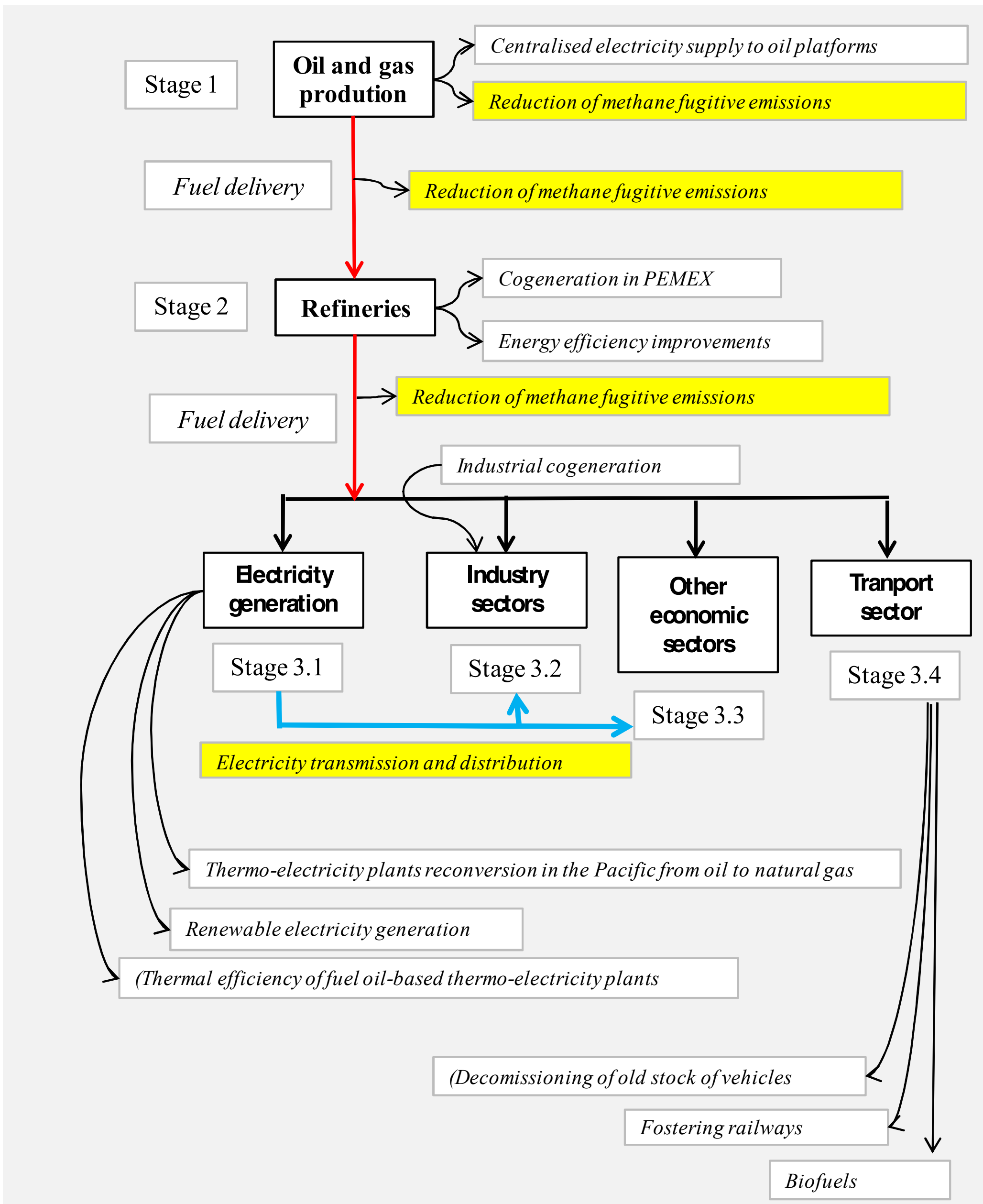

Figure 1.3 – Mitigation Strategies Presented in the National Strategy of Climate Change for Mexico

Upstream operations in an energy system such as coal, oil, and gas extraction correspond to energy production (stage 1 in figure 1.3). At this stage, potential reductions in greenhouse gases could be accomplished with more efficient electricity generation using ***natural gas combined cycle*** on oil and gas platforms.

A proportion of fuels such as oil and gas are sent to refineries for a subsequent transformation into oil related products such as diesel and fuel oil among other fuels (stage 2 in figure 1.3). At this stage, reductions of greenhouse gases can be achieved through the installation of ***cogeneration plants*** in the refineries of Petróleos Mexicanos – PEMEX – (an oil and gas producer). Also at this stage, the reduction of greenhouse gases is possible due to improvements of ***the thermal efficiency*** of the refineries.

Natural gas, oil and oil related products are either stored or delivered for different uses such as for electricity generation and industrial uses. In between oil and gas extraction and oil transformation in refineries some energy loses take place (from stage 1 to stage 2 in figure 1.3). Such energy loses also take place in the distribution of fuels between refineries and the point of energy use of the fuels for particular uses (from stage 2 to stage 3 in figure 1.3). Such types of energy loses are commonly regarded as ***fugitive emissions*** with a relevant importance in the share of greenhouse gases.

Opportunities to reduce fugitive emissions are also proposed with the improvement of the operation of the national oil and gas ducts of transmission and distribution. Opportunities to reduce fugitive emissions are also suggested at stage 1 with improvements in the ***efficiency of burners*** in oil and gas plants.

Further down in an energy system the reduction of greenhouse gases is possible through three combined strategies in electricity generation (stage 3.1 in figure 1.3):

- Firstly, improvement of the thermal efficiency of ***fuel oil fired power plants***.
- Secondly, reconversion of thermo-electricity plants located on the Pacific coast. This implies changes in the technology to ***switch from fuel oil to***

natural gas uses (i.e. natural gas combined cycle); and the installation of a natural gas liquid gasification terminal for gas imports.

- Thirdly, increases in the share of ***renewable energy*** for electricity generation are considered as a strategy.

Further down through the energy system, electricity is delivered to industry (stage 3.2 in figure 1.3) or to other economic activities (stage 3.3 in figure 1.3). Inefficiencies during the transmission and distribution of electricity in between stages 3.1 and 3.2 and 3.3 put a pressure on the carbon emissions due to electricity loses through the Mexican grid. Opportunities to reduce carbon emissions appear due to improvements in the ***efficiency of transmission and distribution lines*** of Comisión Federal de Electricidad – CFE (i.e. an electricity producer and supplier)

An important share of processed fuels (i.e. diesel, fuel oil, and natural gas) is used in specific industries in which exhausted gases are generated from combustion processes (stage 3.2 in figure 1.3). The potential to recover heat from waste gases and re-use this energy for electricity generation offers a potential to reduce carbon emissions in ***industrial cogeneration***. Notice the potential to generate electricity from both cogeneration in oil and gas refineries (stage 2 in figure 1.3) and the recovery of waste gases in the industrial sector (stage 3.2 in figure 1.3).

A key sector which puts a significant pressure on carbon emissions concerns transportation activities (stage 3.4 in figure 1.3). Opportunities to reduce greenhouse gases are indentified with the ***replacement of the old vehicle park***, ***promotion of railways***, and the use of ***bio-fuels***.

Finally, potential reductions of greenhouse gases are suggested with the implementation of targeted norms and ***programmes of energy efficiency*** the implementation of which is the competence of CONUEE and FIDE. The outreach of energy efficiency measures and programmes covers all the energy system inclusive of industrial activities.

The revision of the above strategies conveys a key message in the assessment of carbon emissions where carbon is embedded and localised at different stages of an integrated energy system and so are the mitigation measures. The corresponding mitigation strategies relate to the different emission sources, attributes of the technology, thermal efficiencies, a switch in the mix of fuels, energy recovery and so on, according to the stage of an energy system. This characterisation is kept in mind in the formulation of an analytical framework in the research presented in this thesis.

In the following section, recent advances in the literature on industrial carbon emissions in Mexico are discussed. In doing so, critical gaps in the existing knowledge are highlighted and afterwards a definition of the problem of study and research questions in this thesis is stated.

1.2 An Overview of the Current Knowledge of Carbon Industrial Emissions in Mexico

The National Strategy of Climate Change for Mexico (2007) presents a very complete list of opportunities for the reduction of greenhouse gases. This strategy is very comprehensive since it presents a break down of CO_2 emissions by main activity in the energy sector in the period 1990-2002. It also presents a scenario of energy consumption and related CO_2 emissions due to changes in the demand of fossil fuels up to 2014. In this scenario, overall energy and carbon dioxide intensities for Mexico are estimated of around 56,000 tonnes of CO_2 per PJ and 4.2 tonnes of CO_2 per Mexican inhabitant in 2013, respectively (CICC, 2006).

Nevertheless, the carbon emissions presented in the National Strategy of Climate Change are not organised into a life cycle framework which accounts for the carbon embedded at different states of energy production and its uses. Estimations of fugitive emissions are presented for the overall energy sector but little is known on an emission factor accounting for the share of fugitive emissions of the fuels used only in electricity generation. Overall emissions from electricity generation are also available in this strategy. However, a representative emission factor taking into account carbon emissions in power plants plus the emissions due to electricity loses through the grid is not available in this National Strategy.

Similarly, little has previously been investigated in relation to changes in the production capacity and thermal efficiencies of the different specific electricity generation technologies and how these affect the relative share of greenhouse gases.

The National Strategy of Climate Action does not present emission factors of the carbon embedded at different stages from the beginning of an energy system to a specific industrial end. This information is relevant in the comparison of opportunities to reduce carbon emissions at different stages of an energy system. With the use of a holistic approach it can be assessed how changes in the fuel mix for electricity generation may affect the carbon emissions of large electricity users such as iron and steel manufacturers. Thus there is the need of obtaining carbon emission factors for electricity requirements in industry with the use of a holistic approach.

On the other hand, the available energy literature on greenhouse gas emissions for Mexico focuses on specific aspects of the operation of an energy system in the estimation of greenhouse gases. For instance, the oil and gas industries in Mexico are analysed in terms of the fugitive emissions and leakages in transportation, storage, and refinery while carbon and methane emissions in overall energy uses (i.e. electricity generation plus industrial uses) are estimated following the methodological guidelines provided by IPCC (Cuatecontzi Santa-Cruz, 2005). However, these emissions correspond to total overall fuels irrespective of the fugitive emissions specifically associated to the fuels used in electricity generation.

Llamas et al., (2005) suggest also the need to diversify the fuel mix in electricity generation given the high prices of natural gas and a growing dependence on the use of gas in Mexico.

Early research on the electricity sector in Mexico also reports the emissions of three types of greenhouse gases (i.e. CO_2, SO_2, and NO_x) in each single generation power plant in 2002 (Miller et al., 2004). However, as in the case of Llamas et al., (2005), it is difficult to conclude the estimates on CO_2 take into account emissions from electricity loses.

Sector studies on carbon industrial emissions for Mexico present estimates on the amount of CO_2 associated to specific energy consumption (SEC) in sectors such as iron and steel (Ozawa et al., 2002), and cement manufacturing (Ozawa, 2007). Scenarios relating to the reduction of CO_2 are also available and these are important when comparing potential opportunities in the electricity and forestry sectors in Mexico (Sheimbaum and Masera, 2000).

The analytical value of the methodologies as reported above consists in defining specific parameters in relation to physical output (production), changes in technology, changes in the mix of fuels, and changes in specific energy efficiency parameters. However, it is difficult to conclude that the carbon estimations for electricity uses in industrial sector studies such as iron and steel (Ozawa et al., 2002) incorporate the amount of carbon content associated to fugitive emissions upstream operations or electricity loses through the grid.

In this regard, an analytical framework is needed in which the carbon embedded at different stages of energy generation and the efficiency of energy uses can be explicitly incorporated in a model. The value of the approach covered in this thesis lies in the assessment of the emissions from energy uses in industry while incorporating the carbon content of relevant stages of an energy system. This latter aspect on the role of energy requirements and energy efficiency in industry is central to the notion of an integrated energy system.

1.3 Definition of the Problem of Study and Research Questions

The present research reported in this thesis focuses on the drivers and barriers to industrial energy efficiency in Mexico and the assessment of carbon emissions from observed and future energy requirements. The research addresses the case of the integrated iron and steel industry using a holistic approach in energy analysis and the corresponding quantification of CO_2 emissions in industry.

This research is based on the definition of two research goals. Firstly, a general goal in this research consists in assessing the overall total impact of electricity and other fuel requirements in the Mexican iron and steel industry with regard to carbon emissions. Secondly, a particular goal consists of understanding the existing energy efficiency practices in iron and steel facilities using a social science base and its contribution to reductions in CO_2 emissions.

Given the attribute of a holistic approach looking at several aspects of an integrated energy system, the above objectives are pursued with the following five research questions:

1. What are the relevant drivers and barriers to energy efficiency accounting for a process of change in the Mexican iron and steel industry?
2. What is the significance of fugitive emissions in energy production and delivery as compared to the emissions in the iron and steel industry?
3. What is the significance of carbon emissions in electricity generation in terms of electricity requirements in the steel sector?
4. What is the overall contribution of carbon emissions in the Mexican iron and steel industry?
5. What are the potential opportunities to reduce carbon emissions in the steel sector from electricity uses and other energy requirements?

1.4 A Holistic Approach to Energy Efficiency and Carbon Industrial Emissions

The following diagram (figure 1.4) indicates how the research of this thesis will proceed in view of the variety of research questions defined above. The diagram also intends to show the attributes of a holistic approach looking at inter-related aspects in the study of industrial carbon emissions. This approach suggests what each organisation can do (i.e. oil and gas producers versus refineries and suppliers, power plants versus steel plants and so on) in the implementation of mitigation strategies. The thesis is organised around the three main following components:

1.4.1 Fugitive Emissions in Energy Industries

In the first component, the quantification of fugitive emissions in the extraction, production and loses in the delivery of fossil fuels is investigated (x_1, x_2, and x_3 in figure 1.4). This type of emissions is generally captured in a national inventory and is not taken into account in the emissions factors for electricity generation in the grid or at an industrial site. A key methodological contribution in this research consists in incorporating the fugitive emissions, emissions in electricity generation, and loses in the calculation of carbon emission factors for electricity uses with the use of life cycle analysis.

1.4.2 Emissions in Power Plants and Electricity Loses

The second component investigates the carbon emissions associated to the combustion of fuels in power plants in addition to the emissions originating from electricity loses through the Mexican grid. Because electricity uses are largely significant in steel facilities, it is important to obtain carbon emissions for electricity including both fugitive emissions ($\sum x$: $x_1 \ldots x_3$ in figure 1.4) and emissions from electricity generation and loses using a life cycle analysis (($\sum x$: x_4, x_5, in figure 1.4). This approach will lead to more accurate emission factors for electricity requirements in steel facilities.

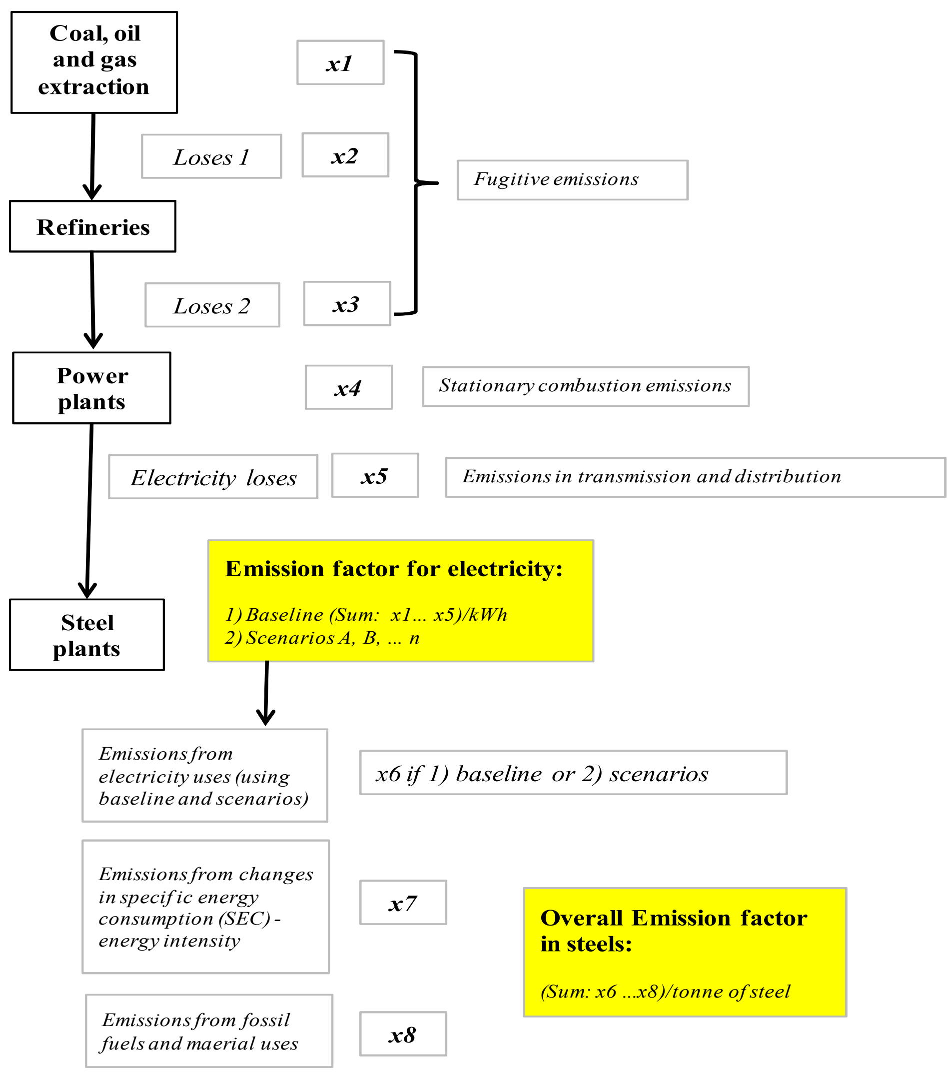

Figure 1.4 – A Life Cycle Assessment of Carbon Industrial Emissions in the Iron and Steel Manufacturing in Mexico

The thesis also incorporates alternative electricity scenarios and associated carbon emissions the purpose of which is to show how a change in the fuel mix for electricity generation affects an emission factor of electricity uses. Carbon emissions from electricity uses can be curbed by a growing share of renewables in the mix of fuels (i.e. *scenarios A, B ... n in figure 1.4*). Increasing energy efficiency of electricity uses in steel facilities will also contribute to reduce carbon emissions (i.e. *changes in SEC (x_7) in figure 1.4*). Thus it is important to analyse how both strategies on electricity scenarios and energy efficiency in the steel industry represent potential opportunities of mitigation.

1.4.3 Energy Efficiency and Emissions in the Steel Industry

Finally, the third component investigates changes in energy efficiency in integrated iron and steel facilities with the use of two methodological approaches.

1.4.3.1 Energy Uses and Efficiency by Steelmaking Technologies

The first approach is an extension of the holistic approach in the calculation of carbon emissions in the steel sector ($\sum x$: $x_6 ... x_8$ in figure 1.4). This latter incorporates changes in electricity futures in the calculation of carbon emissions from electricity requirements in steel facilities. It assesses how changes in electricity generation futures (for instance, a scenario of higher share of renewable among other scenarios) in combination with growth in energy efficiency in steel facilities affect the overall amount of carbon emissions in the steel industry. Regarding the uses of electricity, fossil fuels and materials in the steel industry, the model also incorporates changes in the share of major steel making technologies the impact of which is assessed in terms of total overall emissions.

1.4.3.2 A Social Analysis of Energy Efficiency in the Steel Industry

The second approach dwells on the identification of drivers and barriers to industrial energy efficiency from a social science base. The richness of inter-disciplinary studies as is the case of this thesis lies on the understanding of social processes putting a pressure on carbon emissions. Underneath the observed amount of energy uses and the corresponding carbon emissions there is a social process around the industrial organisation of energy activities.

Organisational aspects of energy efficiency looking thoroughly into the attributes of a firm such as the accumulation of firm based capabilities are practically inexistent in the case of Mexico. For instance, little has been said on how technical and organisational capabilities on the shop floor of steel plants affect the energy intensity of steel works. Specific examples indicating how firm-based capabilities are used to improve the efficiency of particular technologies such as electric arc furnace are also missing in the literature. The knowledge of how energy efficiency programmes work in specific steel plants or how the change of organisation affects the operational aspect of energy uses in a plant is also scarce. Much research work is needed in this direction and this is an aspect explored in this research.

1.5 Thesis Structure

The thesis consists of eleven chapters. Chapter 2 presents an overview of the main technological routes in the Mexican iron and steel industry, the purpose of which is to introduce the reader with steelmaking technologies, a layout of the integrated steel industry according to Mexican plants, and the main energy inputs and exhausted gases in each stage of the production process. The reading of this chapter is a prerequisite in the exploration of drivers and barriers to energy efficiency in the context of the steel industry (chapters 6 and 7) and the assessment of overall carbon emissions in chapter 10. A road map showing the connection between the chapters in this thesis is presented as figure 1.5.

Chapter 3 provides a conceptualisation of the concept of energy, energy efficiency, and its relative significance in relation to overall economic efficiency. This chapter is built upon a reflection of the existing literature on market transformation for energy efficiency technologies. With the revision of this literature, a relevant group of market and non-market barriers and drivers are used as a conceptual basis in this thesis.

In Chapter 4 a theoretical framework is developed for the analysis of drivers and barriers to industrial energy efficiency using an organisational perspective. The chapter is based on the revision of the Resource-based View of the firm within the field of Strategic Management. This chapter of the thesis represents a response to the need of expanding from a social science base the study of organisational and technical factors leading to energy efficiency growth. A new contribution in the chapter is to assess the relevance of knowledge on energy efficiency within firms using a VRIO framework as a theory test.[1] The chapter explores the circumstances under which a company may have a strong incentive to increase energy efficiency.

The ideas presented in chapters 2, 3, and 4 are part of the knowledge found in the existing literature which the latter part of Chapter 4 corresponds to my own contribution as discussed in this thesis. In the roadmap of the thesis structure chapters 2 to 4 are flagged in yellow to point out the material in these chapters as part of the previous literature. Chapters 5 to 11 represent my own contribution to the thesis since the content refers to the analysis of the data I gathered during fieldworks in Mexico in 2007 and 2008. These latter chapters are flagged in green.

Chapter 5 consists of a methodology for the study of drivers and barriers of energy efficiency using a qualititative data analysis from a social science base and with the use of case study research.

Chapters 6 and 7 present two case studies the purpose of which is the exploration of critical drivers and barriers to energy efficiency. Some insights sketched in chapter 4 are reflected in the presentation of each case study to assess the relevance given to energy efficiency in a company.

In chapter 8 the estimation of fugitive emissions as outlined in section 1.4.1 is introduced in the life cycle analysis of carbon emissions in the Mexican steel industry. Through this chapter as is the case in chapter 9 and 10, a quantitative methodology is developed.

In chapter 9 the estimation of carbon emissions from power generation and electricity loses is introduced in the life cycle analysis in relation to electricity uses in the steel industry.

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[1] VRIO stands for firm-base resources as being valuable (V), rare in itself (R), difficult to imitate (I), and resources which are unique to the organisation (O).

In chapter 10, a CO_2 emission factor obtained from a life cycle assessment is used in the estimation of emissions from electricity uses in steel facilities. Overall carbon emissions for the steel industry are calculated as discussed in section 1.4.3.1. The model in this chapter firstly develops an overall estimation of carbon emissions using a top-down approach and secondly, it estimates carbon emissions by main technological route using a bottom-up specification from observation of the configuration of technologies in Mexican steel plants.

Finally, conclusions are presented in chapter 11 in which the main findings around the research questions posed above are discussed.

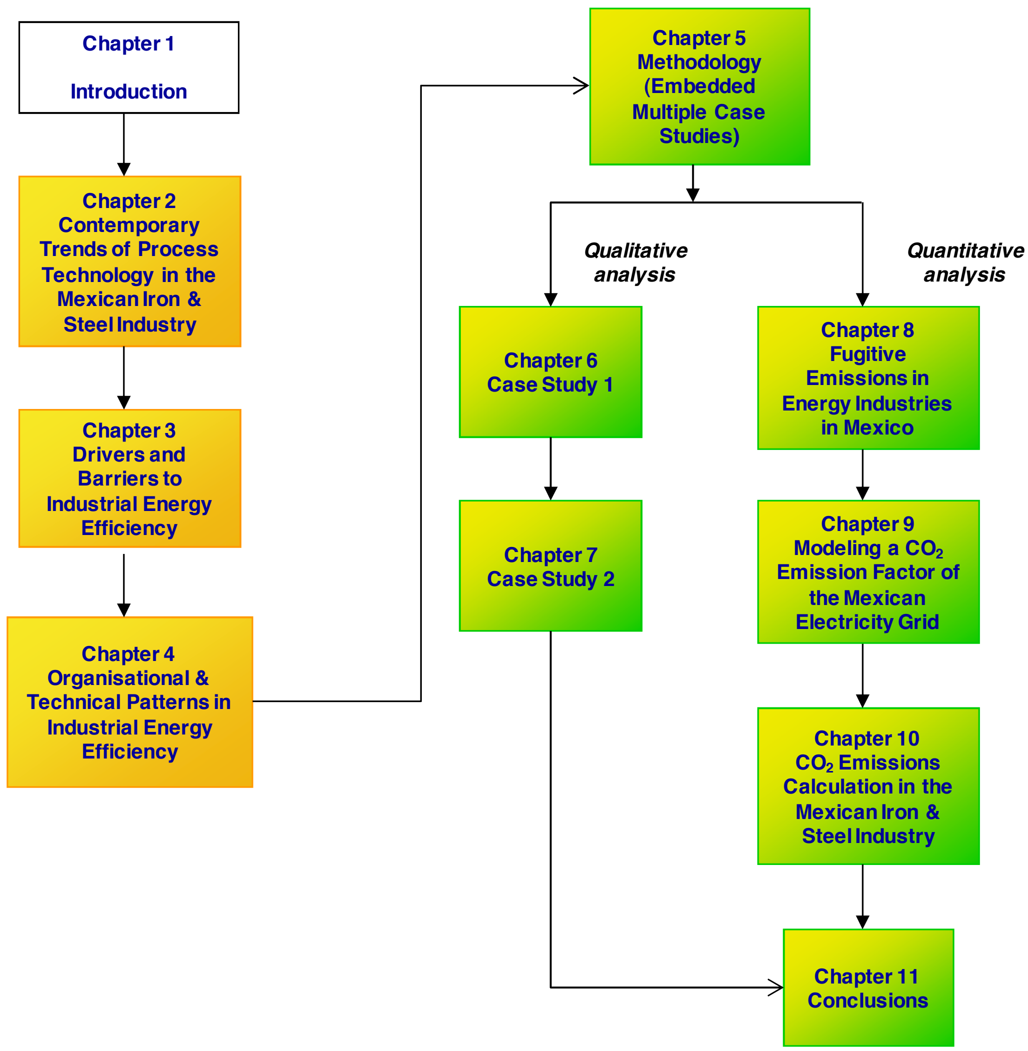

Figure 1.5 – Road Map of Thesis Structure in the Thesis

Chapter 2

Contemporary Trends of Process Technology in the Mexican Iron and Steel Industry

Introduction

The Mexican iron and steel industry consists of both integrated primary and secondary steel making. Integrated primary steel making consists of a process of iron ore reduction by the use of reducing agents (RA) such as coke, hydrogen (H_2) and carbon monoxide (CO). Pig iron which is also regarded as first-fusion iron is an intermediate product from primary steel making which is used in the production of liquid steel. Primary steelmaking is based on the works of blast furnaces in the production of pig iron. On the other hand, secondary steel production is based on the use of steel scrap as the main input in order to produce liquid steel (APERC, 2000). Secondary integrated steelmaking also relies on the works of direct reduction reactors in the production of sponge iron. In the Mexican steel industry, direct iron making (DRI) represents an alternative technology with respect to pig iron production. The use of DRI techniques in Mexican steel plants has significantly increased in recent years.

The purpose of this chapter consists of giving a characterisation of the manufacturing process in terms of the current steelmaking technologies in Mexican plants.

Specification of the main steelmaking technologies in Mexican steel plants is based on data obtained during fieldwork visits to steel plants in the period 2007-2008 and technical documentary revision. For a specification of the methodology used in the research of this thesis see Chapter 5. The iron and steel industry in Mexico is based on both integrated primary and secondary steel making. The distribution of steel plants is as follows:

1) Primary integrated plants with blast furnace (BF) and basic oxygen converter (BOF) steel production (2 plants)
2) Secondary steel making plants with steel scrap and electric arc furnace (EAF) steel production (12 plants)
3) Secondary steel making plants with direct reduction of iron (DRI) and electric arc furnace (EAF) steel production (4 plants)
4) Single rolling mills (RM), (6 plants)

In total, 24 plants were analysed thoroughly in order to build up a layout of integrated steel works according to the Mexican case. Plants included in points (1) to (3) above represent the complete integrated iron and steel industry. On the other hand, rolling mills listed in point 4 are non-integrated steel facilities. In this latter case, there are other non-integrated rolling mills in Mexico but which are not considered here due to unavailability of specific data. EAF and BOF facilities also have rolling mills at the bottom-end of a production line.

In addition, there is a category of plants regarded as single foundries which is not part of single plant data used in the research presented in this thesis. The production process of single foundries consists of casting of specialised metallic pieces used in the manufacture of axles, steel car components, valves, and connections to the mains. Strictly speaking, foundries are not strictly part of the steel industry because they not only incorporate crude iron but also aluminium ingots, copper, and alloys in the manufacturing process. The array of plants as listed in points 1 – 4 above allows the specification of layout of steel works according to the Mexican case. Afterwards, a characterisation of the technologies is based on revision of the technical literature on steel making and documentary data on some Mexican plants.

In the remaining of this chapter, the specification of steelmaking technologies in two major technological routes in Mexico is provided.

2.1 Specification of Steel Making Technologies

Integrated primary steel making consists of the following technologies (see figure 2.1 – layout of integrated primary steel making):

1) Sinter plant
2) Coking plant
3) Blast furnace (BF)
4) Cupola Furnace (CP)
5) Basic oxygen furnace (BOF)
6) Casting (i.e. continuous and ingot)
7) Hot rolling mill(s)
8) Cold rolling mill(s) and finishing

Secondary steel making consists of the following technologies (see figure 2.2 – layout of secondary steel making):

1) Pellet plant
2) Direct reduction reactor (DRI)
3) Purchased steel scrap
4) Electric Arc Furnace (EAF)
5) Continuous casting
6) Hot, cold rolling and finishing

Pellet plants are also present in primary integrated steelmaking. However, in most cases pellets represents the major raw material in the production of sponge iron in DRI reactors. Sponge iron is produced through the secondary steelmaking route. In this respect, only for illustrative purposes pellet plants are grouped as part of secondary integrated steelmaking.

Steel scrap is not a production technique but part of the charge of an EAF. According to the definition of secondary steel making (APREC, 2000), steel scrap represents a raw material which re-enters the production process in mini steel plants (i.e. mini-mills). There are three main sources by which steel scrap can be obtained:

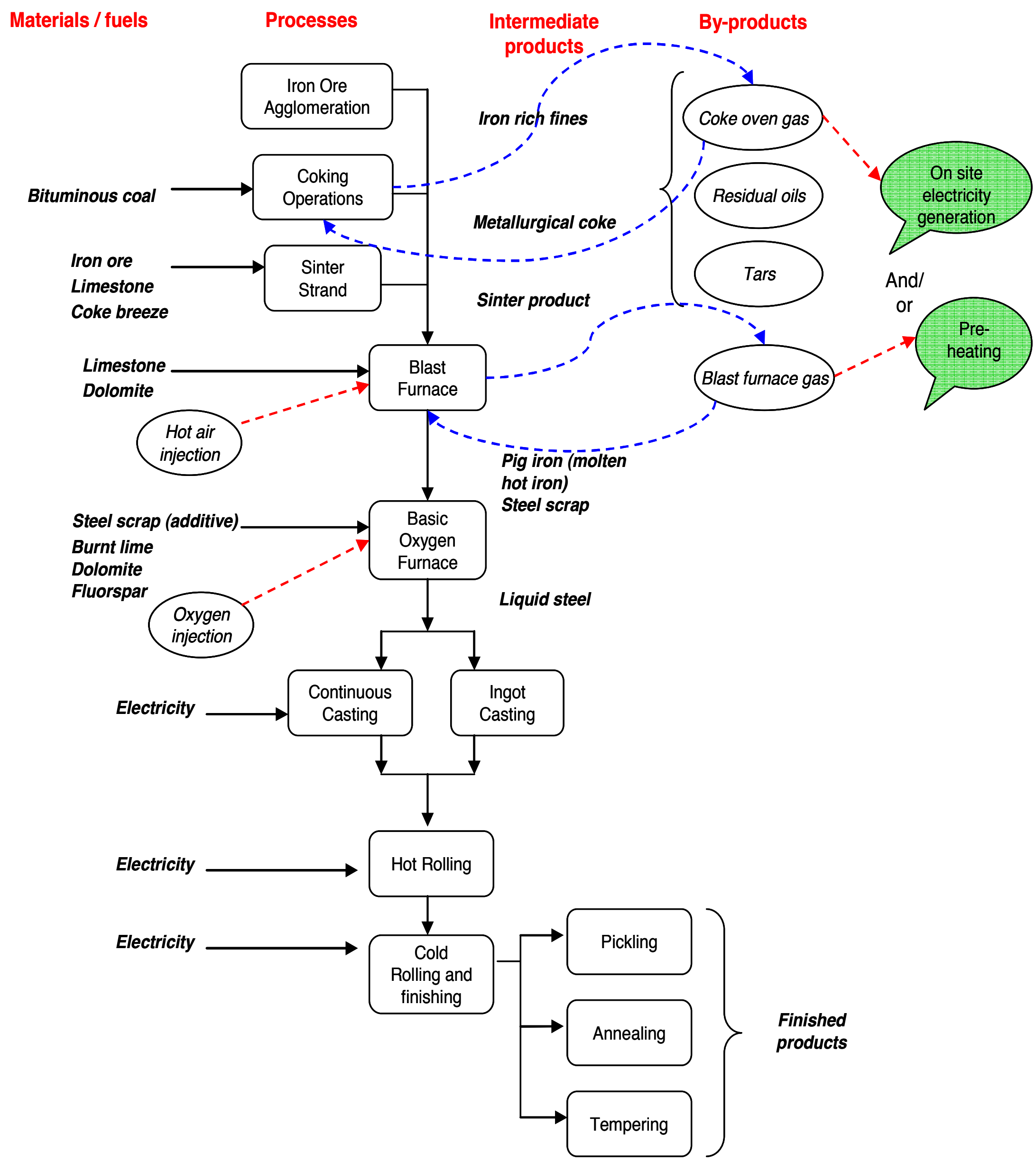

Figure 2.1 – Integrated Primary Steelmaking in Mexico, 2007-2008

1) Waste during the production process which is sent back to the melting processes. Availability of low waste steel scrap tends to decrease with improvements in the efficiency of electric arc furnaces and enhancement of the continuous casting technique (Metals Advisor, 2009).

2) Goods of which manufacturing consists of steel (for instance, cars) and which are disposed at the end of their life-cycle (i.e. a domestic market of steel scrap)

3) A foreign market of steel scrap (i.e. imports). In the Mexican case, there are some specific regulations on the use of local and imported steel scrap.

Steel scrap and sponge iron (or direct reduction iron) are complementary intermediate materials in the manufacturing of liquid steels. Steel manufacturers have flexibility in combining uses of steel scrap and sponge iron and this consists of the following three possibilities:

1) Some EAF facilities incorporate only steel scrap into the charge of a furnace for the manufacturing of steel, the proportion of which scrap is defined as "the factor of steel scrap (SP) charge", and in a case where only steel scrap is used, SP is unity. Steel scrap represents the majority of a charge in an EAF and the remaining consists of fluxes.

2) Some steel facilities combine steel scrap (up to 30%) and sponge iron into the charge of an EAF. The rest of a load consists of sponge iron (DRI).

3) A proportion of steel scrap is also part of a charge in BOF in some Mexican facilities. In this latter case, pig iron is the main content in a BOF charge and steel scrap is used as an additive input.

The observation in point (3) above indicates a certain flexibility of the concept of primary steel making. In practice, this observation points out routines in EAF and BOF plants which combine steel scrap into different proportions with molten iron (pig or sponge iron) according to specific needs.[2] These needs are dictated by market trends according to specific customer requirements (i.e. the quality of some steels is tailored-made in each specific industry). This is a crucial remark in terms of the overall impact on the emission of carbon dioxide which relates to the properties of raw materials.

[2] Different combinations of steel scrap with pig iron and sponge iron resembles a similar situation of the fuel mix for electricity generation (see chapters 9, 10, and 11). However, this specific example points out the mix of raw materials whereas in electricity generation the concept is indicative of the fuel mix (i.e. diesel, fuel oil, coal, and so on). Both concepts the fuel mix (i.e. in electricity generation) and the raw material mix (i.e. in steel making processes) have an effect on the amount of carbon dioxide emissions.

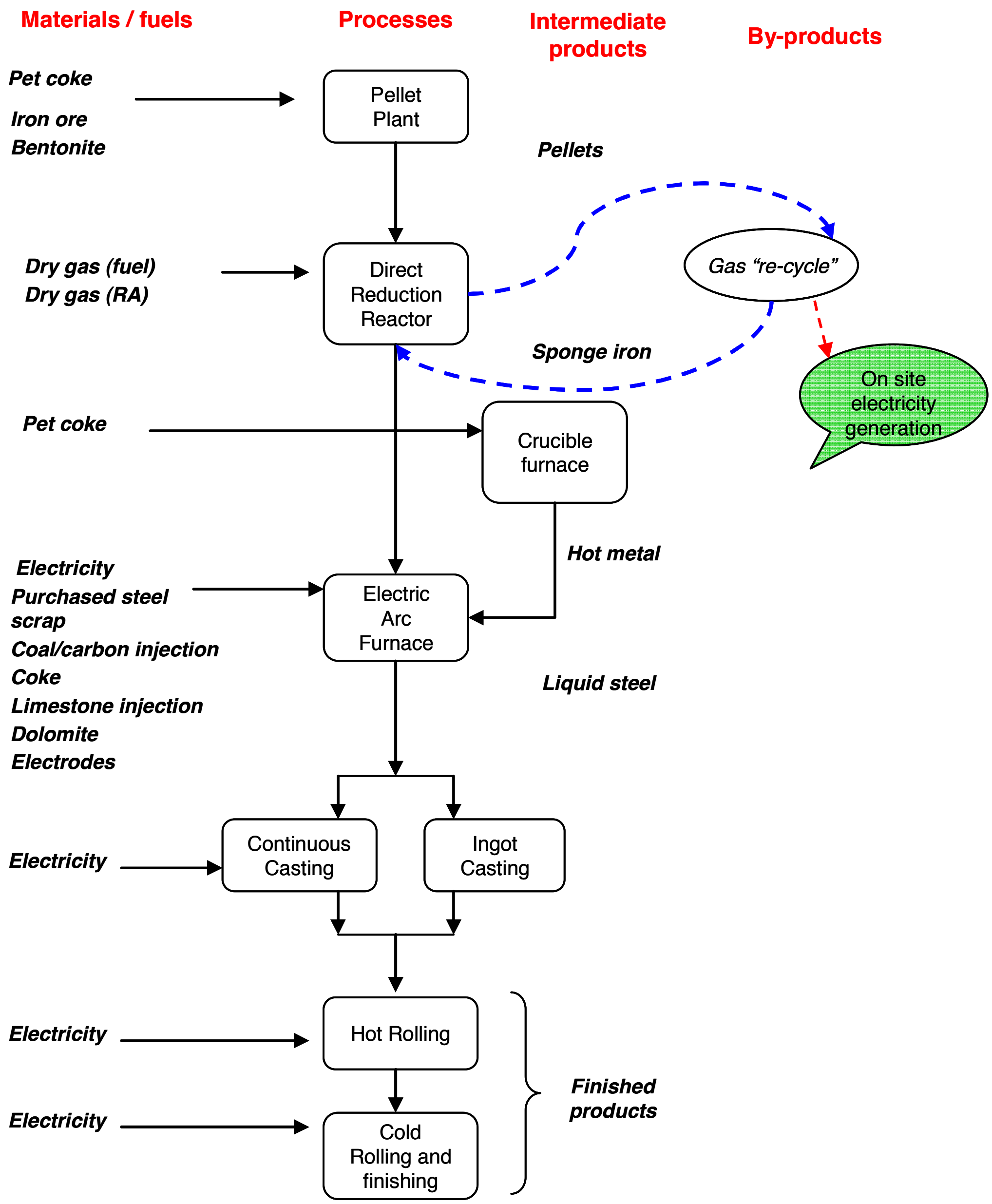

Figure 2.2 – Integrated Secondary Steelmaking in Mexico, 2007-2008

Steel production in Mexico corresponds to the following three main technological routes:

1) Blast furnace – basic oxygen furnace (BF – BOF)

2) Direct reduction reactor – electric arc furnace (DRI – EAF)

3) Steel scrap – electric arc furnace (SP – EAF)

Technology route (3) is part of as a sub-category of DRI – EAF because, in practice, some facilities mix sponge iron (DRI) and steel scrap into the charge of an EAF. Until 1992, steel production in Mexico also relied on the operation of open hearth furnaces (i.e. also regarded as Siemens Martin technology). However, production of steel with open hearth furnaces was closed down by 1992 as part of a process of privatization and modernization of the sector (Guzmán, 2002). In general, the selection of a technology steelmaking route is dependent on: historical circumstances on the industry in Mexico, the availability of basic raw materials and energy inputs, and the quality of steels in terms of their chemical and mechanical attributes. In general, different applications of steels (for instance, steels for automobiles, rods for construction, or plain sheets for electrical appliances) determine the specification of steel quality standards. The availability of raw materials does not only concern the physical supply (i.e. if domestic or imported) but the relative cost of these commodities. For instance, importing steel scrap rather than steel scrap procurement in domestic markets may result into economic savings for a steel manufacturer. More importantly, the selection and development of some particular techniques in Mexican plants have been motivated by a relative shortage of quality products and/or variations in energy prices.

Chapter 3

Drivers and Barriers to Industrial Energy Efficiency

Introduction

This chapter discusses the relative significance of energy efficiency in relation to growth in overall economic efficiency. This present chapter consists of six sections:

1) Section 3.1 revises the traditional attribute given to energy as a commodity.
2) An alternative approach of energy as an ecological resource is brought to this discussion in section 3.2. This second approach represents a critical principle which guides the direction of the research presented in this thesis in view of its associated relevance for climate change mitigation strategies.
3) Section 3.3 discusses the distinction between the institutions of markets and the institution of a firm in which initiatives for energy efficiency improvements appear to be implemented.
4) Section 3.4 provides an indication of the opportunities to exploit the potential for energy efficiency growth if a particular form of governmental prescription is applied.
5) Section 3.5 compares the main purpose of policy approaches which are framed with and energy conservation and market paradigm. This section incorporates previous theory developments which suggest that both approaches formulated in either paradigm are not exclusionary but complementary.
6) Section 3.6 presents a summary of the key aspects of this chapter

3.1 Energy as a Strategic Commodity in Production

The discussion in this section starts with a review of the fundamental differences in concepts which are intrinsically related when addressing the sustainability attributes of energy resources. Energy efficiency and energy intensity are related parameters which provide quantifiable indication of energy consumption profiles in different organizations (i.e. not only industrial plants but also households, energy systems such as transportation, and so on). However, one cannot ignore the fact that efficiency as a principle is also at the core of Economic analysis but the term efficiency used in such analysis may be at variance with the definition used in energy and a clear definition is needed:

a) Efficiency in a transformation process concerns the outcome of work output as compared to energy inputs. This concept is nested in a positivist approach which relates to the work that can be accomplished as a result of a force being applied to a machine or device (i.e. *force times distance efficiency*, Jollands, 2006).

b) Energy efficiency within a thermodynamics discipline consists of the ratio of useful energy output to energy inputs (Op. Cit). The formalization of this concept is as follows:

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

c) Economic energy efficiency is indicative of the number of economic units (measured in GDP) that are achieved by the consumption of units of energy. There are two main refinements on the interpretation of economic efficiency. On the one hand, efficiency is related to productive efficiency in the standard economic theory of production (i.e. units of GDP per energy consumption); on the other hand, efficiency in the allocation of (natural) resources (i.e. allocative efficiency) concerns the achievement of a maximum attainable welfare in society (Op. Cit).

Two related terms of energy conservation and energy intensity are frequently used in the literature and these are defined as:

d) Energy intensity is a measure of the energy used per unit of output. This concept is intrinsically related to efficiency as framed within thermodynamics. Energy efficiency measures will normally lead to an improvement in energy intensity. A decrease in energy intensity is indicative of a reduction in the amount of energy requirements to produce a unit of physical output. On the contrary, an increase in energy intensity suggests growth in energy requirements to produce a unit of physical output over time.

e) Energy conservation is the saving of energy and though energy efficiency is a necessary pre-requite for energy conservation the latter may not necessarily lead on from the form. Thus a new process which is more efficient will improve the energy intensity. However, if as a result of this improvement an opportunity is taken to increase output, then conservation of resources will not occur unless there is a simultaneous and corresponding closure of an older inefficient plant.

Economic analysis is mostly concerned with efficiency in the allocation of resources (Gowdy & Erickson, 2005). In some instances the efficient allocation of resources (i.e. allocative efficiency including energy) may not reach optimal results and factors accounting for inefficiency are regarded as market barriers which may arise from the role of public policies aimed at enhancing the working of markets (Sutherland, 1992). The notion of efficiency in the allocation of resources in indicative of experimenting with arrangements of inputs to production, and share of output in such a way that is not possible to further increase the welfare of every economic agent because a combination has reached optimality (Common & Stagl, 2005). The mechanism by which this outcome is attained is related to the functioning of markets and this state of optimality due to allocative efficiency is only theoretical.

Mainstream Economics looks at energy as a production factor and assigns a monetary value to the magnitude of energy consumption. In opposition to this view, early work on economic modelling questioned the validity of considering energy as a production factor (Denison, 1979). In this respect, coal, oil, gas or uranium consist of *energy carriers* or energy storage mediums, and it is only when energy is released from energy carriers that it becomes a production factor (Kümmel et al., 1985).

When energy is released it can take the form of thermal energy or reducing agent in chemical combustion processes in manufacturing.

The conceptualisation of energy as a production factor is not unique since the concept of energy holds four different scientific perspectives: energy as a commodity, energy as an ecological resource, energy as a social necessity, and energy as a strategic material (Stern & Aronson, 1984). The properties of each view of energy are summarised in table 3.1. Energy as a commodity may be subdivided into two sub-categories: (a) as a commodity to be used directly as energy or to be transformed into a secondary energy source, (b) as a commodity used as a raw material in the chemical industry such as in the manufacture of plastics, etc. Typically the consumption of energy within a country will be split approximately 95% for direct energy use (including secondary energy conversion) and 5% for non-energy use as raw materials.[3] For instance, the total amount of direct energy use in Mexico accounted for 92% whereas this figure in the United Kingdom represented 94% in 2007 (IEA, 2010).[4]

View of energy	Important properties of energy	Central values emphasized	Interests emphasized
Commodity	Supply, demand, price	Choice for present buyers and sellers	Energy producers, consumers with sufficient resources
Ecological resource	Depletability, environmental impact, effect on other sources	Sustainability, frugality, choice for future citizens	Bystanders to market transactions, future generations
Social necessity	Availability to meet essential needs (distribution)	Equity	Poor people, poorly funded public services
Strategic material	Geopolitical location, availability of domestic substitutes	National military and economic security	U.S. energy suppliers, military

Source: Stern and Aronson, 1984, Energy use: the human dimension.

Table 3.1 – Alternative Views of Energy from a Societal Perspective

The commodity view of energy is coherent to the concept of energy efficiency within a Neoclassical Economics framework. The commodity view gives

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[3] This information is based on personal communication with Keith Tovey in the School of Environmental Sciences at the University of East Anglia (UEA) during 2009.

[4] International Energy Agency, statistics by country, energy balances, 2007, access at http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=MX, =GB, 28/june/2010, 8:08 hrs.

primacy to the value of election between current producers and consumers (Op. Cit). In this particular approach, energy efficiency is part of a more general concept regarded as productive efficiency (Cabral, 2000; pp. 27-28). Issues on waste in production and election of production techniques (i.e. technological choices) are inherent to productive efficiency (Op. Cit). Within research work conducted in the commodity perspective, energy inputs and labour are given the same conceptual status and both production factors enter the specification of a production function in the conceptualisation of a firm. Making an expenditure on higher energy efficiency devices is compensated by reduction in operation costs in industrial facilities which suggests that the value for capital is traded for monetary savings arising from lower energy consumption levels per unit of output (Steinmeyer, 1998). Economic efficiency also aims at maximizing output value with respect to a given amount of inputs (Sutherland, 1992). In this respect, the traditional role given to environmental (energy) conservation analysis does not pursue profit maximisation on the basis of output but increases in energy savings.

3.2 A Conservation and Environmental Approach of Energy Requirements

An alternative approach to that discussed above is the ecological resource view of energy which is more in tune with conservational purposes or environmental goals. The ecological resource view of energy focuses attention on social concerns of which the commodity view does not give account. There are several issues here:

- Firstly, the release of pollutants into the atmosphere is the upshot of consumption of energy sources and, more specifically, chemical reactions due to combustion of fossil fuels (i.e. hydrocarbons) in productive transformational processes. In the research reported in this thesis, emphasis is made on carbon dioxide emissions as a precursor of climate change.
- Secondly, in the analysis of the iron and steel industry, some hydrocarbons (e.g. natural gas) enter a particular production process as a reducing agent and not as a thermal energy source (IPCC, 1996; USEPA, 2003). In this respect,

specification of the functions of hydrocarbons by process segmentation in manufacturing can be modelled using a bottom-up approach (Chapter 10).

- Thirdly, it is generally accepted that proven and unproven reserves of fossil fuels are finite or non-renewable (Costanza et al., 1991; Stern & Aronson, 1984). The ecological resource approach of energy addresses environmental sustainability principles since it encompasses the renewable and non-renewable properties and raises the issues on the speed of resource depletion.

Industrial manufacturing as in every economic activity is permeated by a social mindset of enhancing industrial competitiveness at a global scale. Currently, the top six priorities for Mexican top management in industry are according to a survey of PWC, (2006):

1) Market positioning;

2) Organizational growth via mergers and acquisitions;

3) Nurturing of human capital as a differentiated organizational resource;

4) R & D on products and services (including continuous watch of production processes);

5) Reliance on information technology (IT) and documentation; and

6) Risk management.

What is striking from these survey findings is that no energy efficiency or environmental measure is enunciated among the actions taken by companies in order to be competitive, either by temporary or long term actions (Op. Cit). For instance, personnel and production cost reduction; customer service; and innovation of productive processes are, in order of importance, the three out of ten most mentioned actions stated by a hundred leading companies in Mexico in order to be competitive. Likewise, closing plant/offices and reducing labour are the two out of thirteen most cited temporary actions whereas developing performance improvement programs and implementing expansion projects are the two out of thirteen most cited long term actions (figure 3.1).

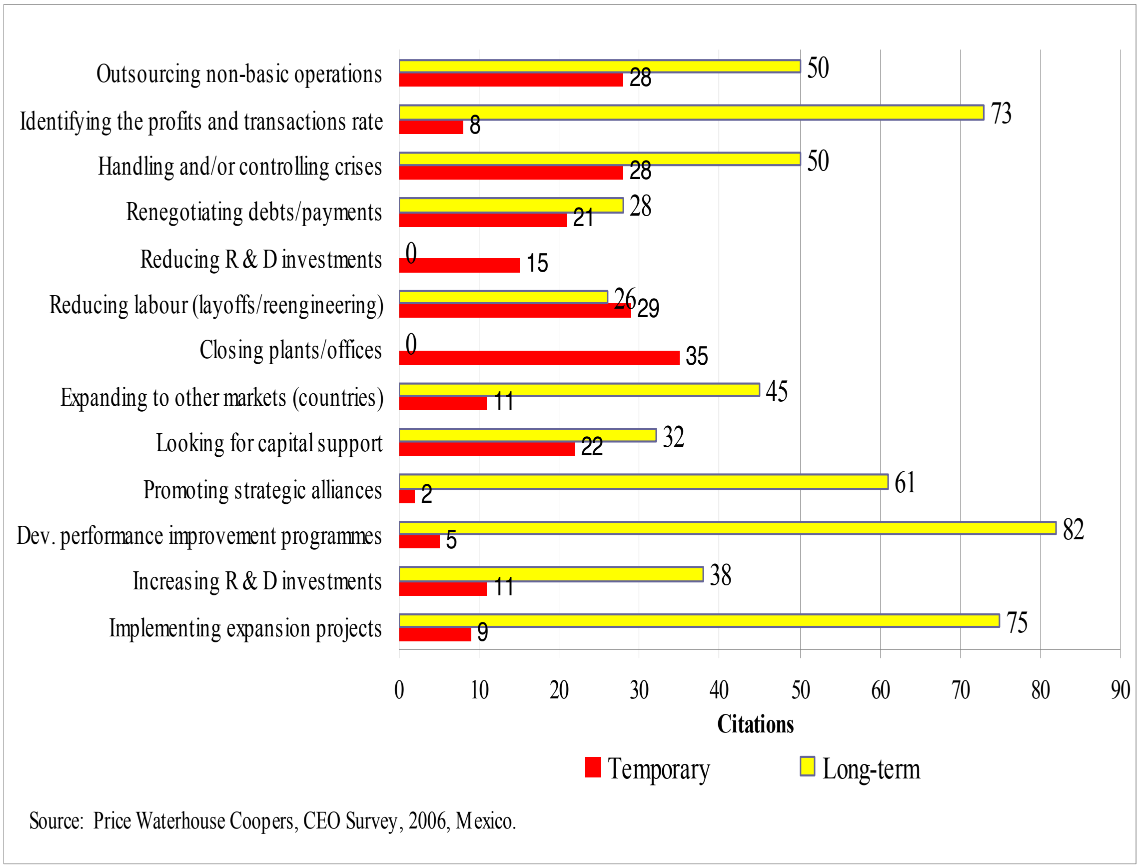


Figure 3.1 – Temporary and Long-term Actions by CEO's Mexico, 2006

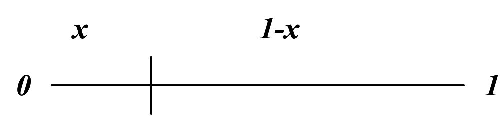
These findings become relevant if we take into account that companies taking part in the survey account for 16% and 13% in industrial products and consumer products category, respectively.[5] For a purely business minded executive these findings may make perfect sense in a global competitive world but they may not do so for a conservationist or social actor whose an important concern consists of reversing the trend of global warming. Yet, at the operational level, there are implicit opportunities for energy efficiency and environmental management improvements (or at least these opportunities may be speculated) while tackling continuous revision of production processes (priority number 4) and possibly organisational growth

[5] Companies by industry sector are arranged in 15 categories with the following distribution: 1) Industrial products (15%); 2) Consumer products (13%); 3) Banks (9%); 4) Automotive (8%); 5) Engineering & construction (8%); 6) Retail (7%); 7) Insurance (7%); 8) Technology (7%); 9) Telecommunications (7%); 10) Entertainment & media (4%); 11) Transportation (4%); 12) Energy & mining (3%); 13) Government (3%); 14) Pharmaceutical (2%); and 15) Tourism (2%). Total sample is the sum of categories 1-15 = 100 %; Source: *Price-Waterhouse Coopers, Actions for business consolidation and growth, Mexican CEO Survey, 100 leading companies specify their key business challenges, Mexico, 2006.*

(priority number 2) if it comes along a process of organisational (corporate) change favouring a proactive environmental stance. These survey findings are important at the aggregate industry level. In particular, the role of organisational change with respect to energy efficiency is explored in two case studies in the iron and steel industry (chapters 6 and 7).

A conceptual difference between the commodity and ecological resource view provides opportunity to state the following postulate:

> ***Proposition 1:*** The Mexican industrial community relates energy usages much more to an economic domain than to an ecological resource referential system. The dominant view of energy as a commodity (axiom 1 from Stern & Aronson, 1984) is largely influenced from pragmatic stances among industry participants which rely on specific paths of knowledge accumulation thorough time. This postulate is represented in formal terms as follows: $1 - x > x$, where (x) stands for ecological resource view and (1-x) for economic view (figure 3.2). For many in the industrial community the postulate is probably more accurately shown by 1 – x >> x, i.e. ecological resource issues are small in comparison with other views.



Domain 0 – 1: Energy efficiency criteria

Figure 3.2 – An Industrial Corporate View on Energy Efficiency

The second part of the above proposition (axiom 1) was first analysed and proposed more than two decades ago bearing on the reality of the American Economy (Op. Cit). This proposition is placed in the context of Mexican industrial competitiveness at the present time where the dynamism of a number of industrial activities is driven by exports to foreign markets, mostly those related to the North American Free Trade Agreement (NAFTA) area. For example, a set of predictions were made on the coming into effect of NAFTA, in particular, an environmental externality was said to be materialised on pollution reduction in Mexico due to further specialization and trade (Grossman & Krueger, 1991, in Stern, 2007). Among the predicted consequences of increasing levels of trade in an open economy is the adoption of best practice technologies and changes in public policy in two directions:

1) Enforcement and compliance of environmental standards are seen as hindering increasing volumes of trade; and
2) Homologation of environmental standards as to reach best practice (Op. Cit).

3.3 Barriers to Energy Efficiency and Imperfect Information in Organisations

An operational question in the research reported in this thesis is under what circumstances energy efficiency practices should be undertaken by the direction of the management of a given company (i.e. a firm) or delegated to external parties (i.e. a consultancy firm or a public entity)? For example, improvements in energy efficiency could be delegated to a group of experts by subcontracting. However, technical complexity of tasks involving energy efficiency practices may set some managerial barriers to subcontracting mechanisms.

It would appear that sub-contracting appears to be effective in a subgroup of energy services in some organizations whereas it is ineffective in end-use energy services at small sites and process-specific energy requirements at large establishments (Sorrell, 2007). In this respect, exploring organisational patterns in industry by which energy efficiency practices are implemented in manufacturing facilities has hitherto not been explored systematically in the Mexican experience, and this is one of the key aspects which this thesis attempts to address.

The conservation and market paradigms are two positions often encountered in the study of energy efficiency (Sutherland, 1992). A first concern on the disagreement of both paradigms is a clarification on the existence of barriers or market failures to energy conservation (Jaffe and Stavins, 1994). Early research work on social and institutional barriers to energy conservation identifies six generic barriers based on fieldwork targeting the housing sector: misplaced incentives; lack of information; regulation; market structure; financing; and custom (Blumstein et al., 1980). For example, in an empirical study on the drivers and barriers to energy efficiency in Commerce and Services sectors in Germany, Schleich and Gruber (2008) find that lack of information on energy efficiency measures represents a barrier in approximately 1/3 of the sectors under study (i.e. banking and insurance, public administration, and schools). In addition, a case study into the Swedish foundry industry suggests that limited access to capital constitute the major barrier to increases in energy efficiency (Rohdin et al., 2007). Generic barriers are also found to arise in the implementation of projects oriented to upgrade energy efficiency such as (Taylor et al, 2008):

1) lack of trained personnel or technical/managerial expertise;
2) low long-run marginal cost price;
3) regulatory disturbances;
4) high initial capital cost or lack of access to credit;
5) high customer discount rates;
6) mismatch of the incidence of investment costs and energy savings;
7) high transaction costs;
8) lack of information; and
9) higher perceived risks of superior efficient technology.

Integration of energy efficiency practices can be viewed as increasing the burden of already overloaded tasks in a firm when actually implementation of energy efficiency programs can have an attractive pay back when considering a series of transaction costs that a firm incurs when searching for information (Schleich & Gruber, 2008). In other words, projects aimed at implementing energy efficiency tasks are cost-effective in industrial facilities (Taylor et al., 2008) though the benefits, either financial and those conservational ones, may not be fully appreciated by the management and top executives in a company.

In industrial manufacturing energy efficiency cannot enter the definition of product quality but in the quality of a manufacturing process. In other words, energy efficiency is a concept more related to process and not product standards in manufacturing. Some approaches propose a change in a corporate culture by incorporating energy efficiency standards, training, and policy as part of a system optimization linking ISO 9000 quality and ISO 14000 environmental management systems (McKane et al., 2005). However, in a study of non energy intensive manufacturing companies in Sweden, Rohdin & Tollander (2006) find that the introduction of environmental management systems does not appear to have an effect on the rate of implementation of energy efficiency measures.

The amount of information on energy efficiency which is transmitted to firms is assumed to have an effect on the decision making process of agents (Tonn & Martin, 2000; Anderson & Newell, 2004). Top management and even bottom-line production engineers may not be capable to foresee the complete dimension of benefits accruing from an energy efficiency project. This capability may be dependent on their degree of specialisation and training. The occurrence of imperfect information in organisations is identified as a critical barrier in order to achieve optimal levels of investment in energy efficiency. In turn, the role of audits is crucial in order to partially remediate the situation of incomplete information (Goitein, 1989).

3.4 Market Failure in the Diffusion of Energy Efficiency Technologies

Most of the literature on energy conservation traditionally points out the economic potential from energy efficiency measures. A set of technologies of superior performance in terms of energy conservation became gradually available in the market. However, a group of studies report on the slow diffusion of already available energy efficiency technologies in spite of proven higher economic and technical potential. This observed phenomenon has been addressed with the concept of the energy paradox which indicates the existence of an energy-efficiency gap between estimated cost-effective levels of investment in energy efficiency and inferior levels of investments actually taking place (Golove & Eto, 1996; Jaffe & Stavins, 1994; Hirst & Brown, 1990).

Some authors (Howarth & Andersson, 1993; Jaffe & Stavins, 1994; Metcalf, 1994; DeCanio, 1998) advance the early work on barriers to energy conservation

(Blumstein et al., 1980) by introducing a classification of market and non-market failures as factors accounting for the occurrence of the energy paradox. A main market barrier concerns the availability of information and the spill-over information effect among external parties which benefit from an agent (i.e. a first mover) adopting an energy efficiency technology (Jaffe et al., 2005). In this context, a market barrier emerges because the agent who possesses critical information faces restrictions when delivering the right message to the adopter in order to convince this agent (a firm) on the benefits that will derive due to the adoption of higher energy efficiency techniques (i.e. *investor/user or landlord/tenant dilemma*, Schleich and Gruber, 2008). The fact that a firm is not capable to foresee in a complete dimension the benefits of energy conservation measures is also proposed to be the result of limited cognition of social actors (Blumstein, 1987). Limited organisational cognition also supports the claim that firms not always take the most economic efficient decisions (Paton, 2000).

Non market explanations of the energy efficiency paradox give account of the observed behaviour as being optimal from the stance of energy consumers. One of the main factors in this category of barriers consists of the relative magnitude of the discount rate which is employed in the net present value calculation of energy saving measures (Jaffe & Stavins, 1994). There are three factors which are not under the control of a firm determining the magnitude of the discount rate (Op. Cit):

a) Uncertainty in future energy prices,

b) Observed savings derived from implementation of energy efficiency technologies, and

c) A capital non recovery property of energy efficiency investments.

These factors are approached in this current research as contextual and transcending the boundaries of the firm. These factors are located in a sort of *"sea"* or institutional-economic landscape where industries operate. This discount rate is generally higher that that one of which calculation theorizes on the occurrence of the energy paradox. A further issue regarding the choice of discount rates which is often overlooked is the fact that a particular discount rate can favour a specific energy strategy. Thus in the case of electricity generation, high discount rates tend to favour fossil fuel generation, intermediate rates will favour nuclear whereas low discount rates favour conservation and renewable generation.[6]

3.5 Energy Efficiency Initiatives under the Conservation Paradigm and Economic Efficiency in the Market Paradigm

In the industrial sector conservation measures are aimed at adopting energy efficiency technologies or inducing organisational change as expressed in a new pattern of practices (Sutherland, 1992). In this respect, changes in relative prices with increases in energy costs are assumed to motivate a search of new production techniques which economise on the use of otherwise cheap energy sources – i.e. the induced innovation hypothesis in relation to energy saving technologies (Newell et al., 1999).

A goal of public policy obtained from economic analysis is to achieve economic efficiency and income redistribution for what it resorts to the framework of market failures and imperfections (Sutherland, 1992). Market barriers as discussed above may, in some circumstances, hinder higher investments in energy efficiency. However, in many situations economic efficiency and not energy efficiency is the issue of central concern. The framework of market barriers attempts to explain why an optimal level of economic efficiency is not achieved. Within this framework energy efficiency is a resource which contributes to overall efficiency. It may also be the case that an excessive level of energy efficiency may diminish and not increase overall economic efficiency thus alerting on the optimal level of energy efficiency. That is, an uneven allocation of resources toward higher energy efficiency may divert resources for other strategic priorities. In this respect, it is suggested that energy efficiency comes along with overall economic efficiency (Nadel et al., 2000) and increasing levels in energy conservation are justifiable as far as they do not compromise growth in economic efficiency (Sweeny, 1993 in Golove & Eto, 1996, p. 13).

In support to the above position, a study on small scale foundry and brick and tile clusters in India finds that entrepreneurs in both industries assign top priority to

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[6] The observations regarding the discount rates are based on personal communication with Keith Tovey in the School of Environmental Sciences at UEA during 2009.

impacts of barrier removal on economic performance as compared to impact of barrier removal on energy efficiency (Nagesha & Balachandra, 2006). The authors argue that managers find logical to attribute more significance to improvement of overall economic performance of a company than energy efficiency improvements.

Barriers, either market or non-market ones, represent a precursor in having a direct effect on the relative amount of greenhouse gas emissions that could otherwise be avoided if proper measures on energy conservation had been taken. Alteration of energy prices through the use of subsidies or pricing based on average costs (particularly in the case of electricity) may disincentive energy conservation efforts up to a social optimal level. Likewise, cost accounting for environmental pollution (i.e. abatement costs) are not included in the computation of energy prices thus consumers may not be aware and may therefore not behave proactively in order to achieve social optimal levels of energy conservation (Jaffe & Stavins, 1994).

Increasing energy prices are politically unpopular because they are said to reduce the overall net social welfare. Industry and households will not share the believe that an increasing long term trend in energy prices is the best response from policy intervention in order to promote conservation measures and control techniques for greenhouse gas emissions. In contrast, it is suggested that declining energy prices over long periods discourage industrialised economies from energy conservation practices thus pushing the slowdown of the overall productivity (Hickman, 1992). Both approaches suggest a possible trade-off between economic efficiency (in the market paradigm) and environmental conservation objectives (in the conservation paradigm).

In addition, public policies designed to intervene in energy efficiency markets can take the form of voluntary agreements in order to encourage cost-saving decisions in industry. Examples of this type are found in programs such as *The Green Lights* and *The Energy Star Office Products* (Howarth et al., 2000); or direct subsidies, wholesale buy-downs, bulk procurement, give-away, education, and consumer financing mechanisms. These approaches demonstrate adequacy to deliver a targeted amount of energy efficiency, for example, in compact fluorescent lamps (CFL) to customers with different cost-effective impacts according to a study conducted in eight countries (Brereton et al., 1998). Energy efficiency voluntary programs, if correctly implemented, suggest a positive outcome on both technical efficiency of energy requirements and economic efficiency of resource allocation (Howarth et al., 2000).

Governmental intervention can also take the following forms (Blumstein et al., 1980; Golove & Eto, 1996):

- By creating demand in the public sector which has a large potential to create a multiplier effect pulling the dynamism of energy efficiency markets,
- By acting as an agent while undertaking demonstration projects on energy efficiency,
- By taking on the responsibility of loans in order to promote energy conservation measures.

More recently, the role of government such as in the United Kingdom and the United States has been as a catalyst or mediator in order to connect suppliers of energy efficiency technologies and low end users (Blumstein et al., 2000) including the industrial sector. Since the beginning of the 1990's a similar trend in policy approach has been evolving in Mexico through the Electricity Power Saving Fund Trust (FIDE) and the National Commission for Efficient Energy Use (CONUEE).

Inadequate diffusion of knowledge is thought to affect the behaviour of industry agents during the different stages of an energy efficiency life cycle decision making process (Tonn & Martin, 2000). In other words, knowledge is a conceptual axiom in order to process information (Cohen & Levinthal, 1990; Zhang, 2005; Badamas, 2009) and not the other way around. Behaviour of various social actors within an industry organisation (i.e. a company) is said to affect the decision making process towards energy efficiency investments (Sardianou, 2008). This behaviour is affected and reinforced by the current domain of knowledge.

The stickiness (i.e. the magnitude of cost of transferring information from one "localised" setting to another) of a particular technical expertise can be reduced by working on a process of knowledge conversion from tacit to explicit knowledge which is readily transferable among economic agents (Von Hippel, 1994; Weber &

Von Hippel, 2000; Lüthje et al., 2005; Nonaka 1994; Nonaka et al., 2006). The transaction costs of disseminating and processing large amounts of information (for example, on energy efficiency practices) are lowered considerably the greater the knowledge base in an organisation.

The above line of argument can be formally represented with the following implicit functions:

Expectations on investment recovery of energy efficiency initiative (E_A) are reflected in the rate of return of an energy efficiency project (r_{eef}) (i.e. a non-market barrier). Standard economic theory suggests that, among other factors, transaction costs (C_{TT}) arise as a consequence of the effort to do searches and acquire information on energy efficiency measures (i.e. Golove & Eto, 1996, pp. 16-17; Rohdin et al., 2007),

$$C_{TT} = f(D) \quad \ldots (1)$$

where D stands for market data which is a proxy of information and assumed to be incomplete i.e $0 \leq D < 1$.

Energy efficiency measures may be contained in projects both as already available technologies and also as energy efficiency services. In this respect, $C_{TT} = f(D)$ should be read as the amount of effort in order to process and use information on energy efficiency measures in the most productive application. The higher the transaction costs involved in energy efficiency implementation, the lower the expectations about obtaining economic benefits from energy conservation projects. In other words, the higher the transaction costs, the lower the expected rate of return from an energy conservation stance:

$$r_{eef} = f^{-1}(C_{TT}(D)) \quad \ldots (2), \qquad \textit{remark 1.}$$

A proxy for knowledge accumulation in a firm (ΔH) consists of organisational cognition (IQ_A) which is defined as the outcome of the interaction effect of the agents' production core competences (i.e. engineers and managers) who work on behalf of organisation A. The more developed organisational cognition due to a process of knowledge accumulation in the firm, the smaller the effort (i.e.

searching costs) to acquire and process information on markets for energy efficiency technologies,

$$C_{TT}(D) = f\left(1/_{IQ_A} \right) \quad \ldots (3), \qquad \textit{remark 2.}$$

Substituting equation (3) into (2) yields

$$r_{eef} = f(IQ_A) \quad \ldots (4)$$

Equation (4) suggests that a process of knowledge accumulation over productive functions inclusive of energy efficiency in industrial plants has the effect of reducing transaction costs thus increasing the expected rate of return of energy conservation related investments. Attention given to an expected rate of return by industry leaders has a large weight in the decision making process thus affecting the likelihood of realisation of an energy efficiency initiative. In other words, a critical mass of productive knowledge on energy conservation influences the decision making process proactively towards conservation measures. In this respect, Golove & Eto (1996) report there are often hidden costs which are associated to managerial/technical expertise in specific domains of an industrial plant:

1) installation of new equipment
2) training operators and maintenance technicians
3) maintenance associated with energy efficiency equipment, etc.

3.6 Summary of the chapter

This chapter reflects on the distinction between energy efficiency and economic efficiency and the inter-relation between both concepts. Energy is seen both as a commodity and an ecological resource and while improvements in energy efficiency contribute to improvements in the efficient economic allocation of resources, such improvements may be in conflict with considerations of energy as an ecological resource. This chapter explored these issues and the associated barriers and drivers are summarised in the following sub-sections.

3.6.1 Market barriers

Economic efficiency is guided by factors such as the maximization of output value and the relative cost of energy commodities. Such factors counter-act each other as barriers or drivers towards optimum energy efficiency growth.

3.6.2 Institutional barriers

The availability of information as part of institutional drivers for energy efficiency growth and access to capital and financing are critical issues in overcoming barriers. Thus an organisation holding and using a critical mass of information on energy alternatives may also have a good command in the decisions regarding energy efficiency.

3.6.3 Technological barriers

Technological barriers can be complex and limit technological progress from the inertia of current production techniques and the associated aspects of energy efficiency such as the thermal conversion efficiencies in specific production processes and the energetic aspects associated with the chemical properties of materials acting as reducing agents.

3.6.4 Managerial barriers

Implementing energy efficiency improvements can be constrained by managerial barriers which also can be quite complex ranging from the degree of technical knowledge through access to already available technologies, and how suitable any current sub-contracting practices are for energy efficiency.

3.6.5 Priority strategies

Firms in the industrial sector in Mexico often focus on other priorities and not environmental ones in the quest of market positioning as has been discussed in section 4.2. Thus the relative importance placed on the priorities of treating energy as a commodity with conservational or environmental functions as second order purposes can create barriers to effective strategies within an organisation.

3.6.6 Non market barriers

In terms of optimal economic efficiency investment for energy production/conservation projects, the simple choice of the relative magnitude of the discount rate will affect the optimum strategy and can be a critical barrier towards effective further investments in energy efficiency. While it might be seen that since all projects would be tested as the same discount rate, it is this choice of rate which can lead to unexpected consequences. Thus a high discount rate choice will make fossil fuel conventional technologies more attractive while moderate discount rates will favour nuclear options and low or zero discount rates will favour renewable technologies and energy conservation.

3.6.7 Governmental led intervention

In infant industries sometimes public intervention is seen as desirable in laying down the foundations for enhancing the functioning of markets. Where a sub-optimal level in the diffusion of energy efficiency technologies is observed, a lack of governmental lead can be seen as a barrier due to inaction and coordination among stakeholders.

Chapter 4

Organisational and Technological Patterns in Industrial Energy Efficiency

Introduction

In this chapter two theory approaches are discussed in relation to critical drivers for energy efficiency growth:

1) the Resource-based View (RBV)

and

2) an extension of the former, the Natural Resource-based View of the Firm (NRBV).

The chapter attempts to give a meaningful interpretation from a resource-based perspective to engineering practices on the shop floor of which effects relate to changes in the intensity/efficiency of manufacturing processes. In particular, it assesses the existence of firm-based capabilities for energy efficiency practices which hinge on productive/technical knowledge as one of the most critical resources for energy efficiency performance. The chapter comprises the following sections:

1) Section 4.1 presents the content of the Resource-based View of the firm.
2) Section 4.2 draws on the explanation of the Natural Resource-based View.
3) Section 4.3 discusses how energy requirements are specific to each stage of the production process and to a particular organisation (i.e. plant, factory, firm).

4) Section 4.4 discusses the way environmental management strategies may be implemented and redefined as part of a process of organisational change. Furthermore, the role of voluntary programmes for reporting greenhouse gases as a driver for a organisational change is brought into the discussion.
5) Finally, section 4.5 assesses the extent to which knowledge on energy efficiency is strategic in relation to the attributes in the Resource-based approach.

4.1 Resource-based View

In the long run, a firm which enjoys a margin of revenues above the rest of competitors is said to accomplish *sustained competitive advantage* (Hoopes et al., 2003; Barney & Zajac, 1994; Barney, 1991; Mahoney & Pandian, 1992). In this respect, a firm with above normal economic rents in an industry is said to outperform the rest of competitors. This is a phenomenon defined as superior firm performance regarding the generation of value and economic rents. In this respect, the central concern of the *Resource-based View literature* (RBV) is the identification of the origins and sources of variability (i.e. heterogeneity) in firm performance in the medium and long term (Barney, 1996; Montgomery, 1995; Grant, 1991).

In the theoretical model of the Resource-based View, sustained competitive advantage can be maintained to the extent that resources are different (i.e. heterogeneous) and not mobile among firms (Barney, 1991). These conditions can be observed whereby organisational resource exhibit the following attributes (Op. Cit):

1) Resources are valuable (i.e. they make the most of available opportunities in order to increase efficiency and effectiveness)
2) Resources are rare (i.e. only some firms have certain attributes which give them an advantageous position among other competitors)
3) Resources are difficult to imitate or replicate by other firms

4) Substitutes of resources cannot be equivalent in the sense that another resource provides simultaneously the same value, rareness and non-imitability (i.e. some resources are unique to an organisation)

These attributes are commonly grouped and referred as a VRIO framework[7] (Barney & Clark, 2006; Knott, 2003; Irwin et al., 1998; Barney, 1991).

Companies may find a strong incentive (i.e. a driver) to increase energy efficiency to the extent that growth in energy efficiency is strategic for the overall performance. Otherwise, firms will focus on more strategic resources and opportunities elsewhere and thus giving energy efficiency relatively less attention.

Among firms as previously explained by (Verhoef & Nijkamp, 2003; 1999), improvements in energy efficiency are assumed to partly explain differences in the economic performance. This observation is a central assumption considered in the research presented in this thesis. On the one hand, improving energy efficiency is a business opportunity in terms of the revenue streams of a company. On the other hand, improving energy efficiency represents a medium term environmental strategy to prevent climate change.

4.2 A Natural Resource-based View of the Firm

Environmental management strategies as sources of competitive advantage have been incorporated in a framework known as the *Natural Resource-based View (NRBV) of the firm* (Aragon-Correa & Sharma 2003; Sharma & Vredenburg, 1998; Hart, 1995). This framework is indeed a derivation of the Resource-based View and strategic management presented above. This last approach is selected as the guiding framework of the research presented in this thesis. The advantages of using this theory approach respond to the following features:

a) Energy efficiency is part of an environmental strategy to control climate change

[7] (V) stands for valuable; (.R) stands for rareness; (I) stands for non-imitability; and (O) stands for organisation.

b) Practices on energy efficiency are enabled by the accumulation of organisational resources

c) There is a business orientation given to the goal of increasing energy efficiency in production processes

During the last decade the fields of strategic management and Resource-based View of the firm have incorporated the constraints set by wider environmental issues into the discussion of the sources of sustained competitive advantage. The discussion, which has centred on a redefinition of corporate approaches and the nurture of critical capabilities for environmental management practices, is known as the Natural Resource-based View of the firm (NRBV) (Hart, 1995; Sharma & Vredenburg, 1998; Aragon-Correa & Sharma 2003).

It commences with a discourse of a well documented recognition of the pressure that growing populations and currently available technological infrastructures are exerting on the stability of the global ecological system. Current patterns of production (i.e. including organisational practices) and consumption are considered components of the global ecological system. The conceptual framework of the Natural Resource-based View is based on the study of accumulation of firm-based capabilities. These capabilities allow the implementation of three related strategies as part of a new business paradigm calling for a change in organisational approaches:

1) Pollution prevention
2) Product stewardship, and
3) Sustainable development (Op. Cit)

The attributes of each strategy and the corresponding environmental factors of social concern are summarized in table 4.1.

Strategic Capability	Environmental Driving Force	Key Resource	Competitive Advantage
Pollution Prevention	Minimize emissions, effluents, & waste	Continuous improvement	Lower costs
Product Stewardship	Minimize life-cycle cost of products	Stakeholder integration	Pre-empt competitors
Sustainable Development	Minimize environmental burden of firm growth and development	Shared vision	Future position

Source: Hart, Stuart L., A Natural-based View of the Firm, 1995.

Table 4.1 – A Natural-resource-Based View for the Study of Energy Efficiency in Industry

The investigation of organisational resources allows the identification of endogenous driving forces (i.e. as created within the firm) which may have a positive effect on observable growth in energy efficiency. In the framework of the research presented in this thesis, re-configuration of resources and emerging capabilities are part of a process of endogenous change which may not necessarily correspond to strictly evolutionary change as defined by Gray et al., (1995). A firm which implements strategies to reduce the effect of its operations on environmental degradation develops specific capabilities which can give this firm a potential competitive advantage (Hart, 1995).

A voluntary environmental initiative and specially energy efficiency if effectively implemented, can lead firms to differentiate products on the premises of higher energy efficiency in the way they carry on manufacturing (Op. Cit). A corporate strategy addressing pollution prevention leads to the formation of a capability for managing energy efficiency practices. The value placed on skills of energy efficiency management with respect to sustained competitive advantage may be expressed in the form of waste and energy flux minimisation, and the consequential control of atmospheric emissions.

The Natural Resource-based View of a firm advances our understanding of environmental management practices as direct sources of competitive advantage by identifying specific capabilities. It also recognizes the existence of inefficiencies attributed to the organisational process in the form of materials utilisation and allocation of human resources (Hart, 1995). Managers perceive strengths which are built up while implementing environmental management measures and provide an indication of organisational capabilities such as:

1) Stakeholder integration
2) Higher order learning, and
3) Continuous innovation (Sharma & Vredenburg, 1998).

Companies and industries which develop the capability to deliver the same products [and services] with less energy and consequential carbon dioxide emissions are said to enjoy more flexibility of operations in a regime characterized by future carbon constraints or quotas (Baron et al., 2007).

An observed group of energy efficiency practices can be viewed as an expression of a particular path of firm-based capability accumulation. Within a company, capabilities for energy management involve internal communication among staff, current executive procedures, and personal accountabilities in relation to a job position (Russell, 2006). Energy management capabilities are the expression of the attributes of an organisation (i.e. technical skills in people; ethics; communication; beliefs; and respect) and the properties of a management system (i.e. multi-year planning; benchmarking; leadership; information systems; and cooperation among departments, Op. Cit).

In the Top-1000 Energy-Consuming Enterprise Program, large scale Chinese industries are encouraged to meet the objective of a 20% energy saving (around 2.9 Exajoules (EJ)) by 2010 as compared to 2005. Activities organized as part of this program require firms to implement good energy management within the organization. These activities include benchmarking, energy audits, development of energy saving action plans, information and educational workshops, and annual reports for energy consumption (Price & Xuejun, 2007). In these instances, capabilities for energy management need to respond to and/or initiate:

1) effective coordination and establishment of energy efficiency objectives
2) the definition of an energy utilization reporting system
3) the implementation of energy audits and training

4) the design of an energy conservation plan and adoption of incentives

5) energy and greenhouse gas management tools

6) energy performance contracting practices

and

7) Opportunities for investment in energy efficiency enhancement (Op. Cit).

4.3 Specific Energy Requirements within Organisations

The use of energy in manufacturing establishments is specific to the organisation and to the stage of the production process. In a production plant, energy is only one among many inputs that enter the production process in order to carry on with the manufacturing of goods and services. Differences in energy requirements across organisations arise depending on the relative weight of energy along a number of production lines. More importantly, the way energy requirements are managed and treated reveal the very contextual character of energy uses.

Environmental sustainable alternatives for delivering an energy service to different sectors of the economy can be viewed as distributed across a 'value chain' which comprises the extraction, processing and integration of different energy sources. A holistic approach is required when identifying a combination of possibilities for a sustainable use of resources in different segments of an energy system (Williams, 2008). More importantly, energy efficiency good practice is also proposed as a basic component incorporated in a holistic approach in order to implement environmental sustainable measures in terms of rational resource deployment and climate change mitigation strategies (McKane et al., 2008; Pye & McKane, 2000). A production line often relies on many different energy systems which combine motor driven systems (compressed air, fan, pump, motor/drive) with, thermal driven systems (i.e. steam), and process heating systems (McKane, et al., 2007a; 2007b). It is thus important to explore holistic approaches incorporating integrated analysis of all aspects of an energy system rather than focus on just one specific aspect.

Particular operational procedures when managing energy requirements are idiosyncratic not only to an organisation but also to different facilities which belong to the same company. A fraction of energy (δ) in the form of heat which is released to the environment may originate from inefficiencies of a particular type of managerial practice (Gillet, 2006). Also, unrealised opportunities for energy efficiency improvements are embedded in operational and organizational practices (McKane et al., 2007b).

Executive reactions to energy efficiency and the manner in which energy efficiency is understood vary across the maintenance, operations, procurement, and finance personnel in a company (Russell, 2006). Depending on the area of the organization in which these functions are performed, energy efficiency can be directly related to technological change over a production process, adjustment of plant layouts, and manufacturing designs. Some of these practices may be simple tasks while others are complex (Taylor et al., 2008).

4.4 Environmental Management Strategies and Organisational Change

Persistence of observed patterns of energy requirements in manufacturing establishments can be conceived as the outcome of the specific workings in every company, in other words, they relate to organisational processes. This suggests an effect of a managerial dimension accounting for variability in energy requirements with respect to physical output (Stern & Aronson, 1984; Lutzenhiser, 1993; Sorrell et al., 2004).

Long term variability in energy intensity and the corresponding efficiencies along the process of each industrial plant may be explained in some instances by organisational change in a firm. In other instances, persistence of observed practices may represent a barrier to further improvements in energy efficiency within an organisation.

The role of corporate accounting practices including the interaction of the firm with the natural environment can be a potential driver or barrier within an organisation undertaking organisational change (Gray et al., 1995; Bebbington &

Gray, 1993). This interaction consists of the by-products which are the outcome of a production process discharged in the form of water, solid, and air pollutants. These authors (Gray et al., 1995) draw on early research on organisational change (Laughlin, 1991) and share the view of companies as entities characterized by resistance to change (Montalvo, 2002; 2003).

External factors to the organisation (i.e. a growing complexity in environmental regulation, introduction of energy efficiency standards, or economic cycles) which are defined as disturbances or ‘shocks’ can provide an incentive to question the effectiveness of current corporate approaches on the domain of environmental management and thus create a process of change (Gray et al., 1995). A new organisational paradigm can develop a family of practices, rules and routines which can have the attribute of adding value along the production process in a company. When a new managerial model is endogenously reconfigured and new practices, rules and routines are institutionalised as a result of external ‘pressures’ the firm is said to experience morphogenic change as opposed to morphostatic change (i.e. external factors to the firm have the effect to make things look different when actually the generic code of a managerial process remains unchanged, Op. Cit).

A firm which embarks on a process of evolutionary change will have lasting effects when members related to an organisation (i.e. top and senior managers, and middle and bottom line engineers) reach consensus on a particular path of growth (Gray et al., 1995) which is envisaged to add value to the realm of production within their specific spheres of influence. Improvements in energy efficiency practices can emerge as part of a group of rules and routines in a new organisational paradigm.

Environmental regulation which is currently characterized by voluntary approaches in Mexico is encouraging firms to report inventories on their GHG emissions as a premise towards making a transition towards best environmental management practices. Firms reporting GHG emissions under the Greenhouse Gas Program in Mexico may have to reconsider a definition on the organisational limits for relevant corporate reporting when disclosing information on atmospheric releases as potential precursors of global warming. While reporting GHG inventories, managers within firms can receive training and technical assistance provided by the

Mexico Greenhouse Gas Programme for the preparation of greenhouse gas inventories and the elaboration and submission of Clean Development Mechanism (CDM) projects.

The Ministry of Environment in Mexico (SEMARNAT), periodically organises a forum as part of the Mexico Greenhouse Gas Programme. This forum enables representatives of industrial firms to participate in presenting their results on corporate inventories in greenhouse gas emissions and exchange ideas of control of GHG emissions in relation to corporate environmental strategies. For a comparison of carbon dioxide emissions across firms reporting in the Mexico Greenhouse Gas Program see table 4.2.

A driver for growth in industrial energy efficiency may or may not be a component part of a process of organisational change. This process is understood as a response to the constraints in the manufacturing activity set by a growing complexity in environmental regulation. In the medium term, these constraints may be represented by a tolerance level of GHG concentration in the atmosphere in order to remain well below the point at which positive feedback will accelerate the process of global warming (sometimes known as a “tipping point”).

	Company	Industry Sector	Emissions
1	Pemex	Energy	42,678,514
2	Cemex México*	Cement	14,647
3	Holcim Apasco*	Cement	5,182,221
4	Coorporativa Crfuz Azul, SCL	Cement	3,514,000
5	Cementos Moctezuma	Cement	2,406,567
6	Grupos Cementos Chihuahua	Cement	1,308,000
7	Cementos Lafarge	Cement	108,000
8	Altos Hornos de México*	Iron & Steel	7,666,754
9	Mittal Steel Lázaro Cárdenas	Iron & Steel	3,577,633
10	Sicartsa	Iron & Steel	3,174,070
11	Siderúrgica Tultitlán	Steel	68,726
12	Industrias Peñoles	Mining	1,812,439
13	Mineral Autlán	Mining & Alloys	756,595
14	Grupo Modelo	Beverages	665,591
15	Simeprode	Public Agency	597,135
16	Grupo Bimbo	Food	231,890
17	Grupo Porcícola Mexicano*	Food Processing	228,414
18	NHumo	Engineering	207,695
19	Cervecería Cuauthémoc Moctezuma	Beverages	164,495
20	Ford Motor Company	Automotive	115,452
21	Caterpillar México	Engineering	61,252
22	Hitachi GST México	Electronics	35,477
23	Industrias John Deer	Engineering	19,910
24	Honda de México	Automotive	17,208
25	Tetrapak	Food packing	11,096
26	Amanco México	Building & Infrastructure Services	9,863
27	Boheringer Ingelheim Vetmédica	Pharmaceuticals	3,230
28	Itesm Campus Guadalajara	Education	3,531

Source: Centro Mario Molina, October, 2007; Company Reports on the Mexico Greenhoue Gas Programme, SEMARNAT, 2006.

Table 4.2 – Firms Reporting Greenhouse Gases in the Mexico GHG Programme, 2007 (tonnes CO_2)

4.5 Relevance of Energy Efficiency Improvements within Corporate Strategies

Knowledge of energy efficiency practice consists of an idiosyncratic way of doing things (i.e. a practice) when managing energy requirements and deploying energy efficiency technologies.

The higher the revenues obtained due to energy efficiency growth, the larger the relevance of knowledge on energy efficiency management. According to the Resource-based approach (described in section 4.1), this knowledge has to be:

- valuable,
- rare (i.e. their availability is restricted to a few industrial plants),
- difficult to imitate, and
- imperfect strategic substitution of resources.

The aspects listed above are now discussed in more detail:

a) Valuable

Knowledge of energy efficiency is valuable insofar reductions in energy intensity in the manufacturing of steels reduce the cost structure. Knowledge of energy efficiency best practices is also valuable in terms of greenhouse gases emissions reduction.

b) Rarity

Knowledge of energy efficiency management is available among specialised engineers and operators. If it is assumed that there is a shortage of expertise in energy efficiency within an industrial facility, there is still the role of governmental and private agencies in facilitating knowledge dissemination. In the Mexican case, knowledge dissemination of energy efficiency practices is supported by the Electricity Power Saving Fund Trust (FIDE) and the National Commission for the Efficient Use of Energy (COUEE).

c) Difficulty of Imitation

There are both arguments which support that knowledge for energy efficiency can be relocated into different industrial facilities and that relocation is temporarily restricted to some plants. There are two instances which suggest that relocation and imitation is not a barrier to increasing energy efficiency.

Firstly, the Industrial Technologies Program (ITP) in the United States follows a strategy of replication in the implementation of available energy efficiency technologies and energy management practices with the purpose of disseminating best practice in industry (USDOE, 2008).

Secondly, lessons from the Chinese Motor Systems Energy Conservation Program suggest that the transference of system optimisation techniques across languages and cultures in different industrial plants is possible to some extent (Williams et al., 2005).

On the other hand, emphasis can also be given to the strategic attribute of technology (i.e. a physical device) and not productive knowledge (Irwin et al., 1998). Relocation of technology from one plant to another plant (or incorporating a new device) may not be a barrier or a factor based on replication (Hayes & Wheelwright, 1984). However, if the operation of this technology requires intense training, replication in using the same technology may be a barrier in instances where training is not readily available.

d) Resources are Imperfect Substitutes

When a corporate approach is adopted, members of an organisation may put into operation a formula prescribed by practices which only exist implicitly in the collective memory of the organisation due to lack of codification and explicit standards. In this respect, a charismatic leader (i.e. an energy champion) in a firm or a codified (i.e. standardized) planning system may be two alternative ways (i.e. mechanisms) which can be beneficial and strategically substituted one for another (Barney & Clark, 2006).

Barney & Clark, (2006) take the argument of the strategic attribute of firm resources further and argue that imitation of firm resources by other companies is dependent on: 1) exceptional historical circumstances; 2) causal ambiguity; and iii) social complexity. The first two attributes are discussed in the remaining of this section.

i. Exceptional Historical Circumstances

The Clean Development Mechanism framework for climate change mitigation strategies represents an external factor with the potential to increase the value of resources on energy management within firms. Those firms taking early action on the control of GHG may have a temporary advantage over other firms that may follow at a later stage similar environmental strategies. For instance, CDM can be seen in a historical setting which is delimited by binding commitments of the Kyoto Protocol 2008-2012 and post Kyoto negotiations. This mechanism has allowed some firms to identify a window of opportunity because they already had the primacy to possess a critical mass of information on alternative energy efficiency techniques.

ii. Causal Ambiguity

In some instances members of a company may not understand exactly how the manipulation of resources for energy efficiency management yields both higher economic efficiency and better environmental performance with regard to the control of greenhouse gases. The most revealing example is provided by Whirlpool internal corporate meetings. In this case, the company felt more comfortable when addressing the issue in terms of energy efficiency even though climate change is part of the long term corporate concerns (Hoffman et al., 2006).

4.6 Summary of the Chapter

The Resource-based View is concerned with the ultimate sources in a firm explaining how they can be exploited for a sustained competitive advantage. Resources are strategic in a firm when the following attributes are observed: resources are valuable, rare, difficult to imitate, and some resource are unique (idiosyncratic) to an organisation.

Energy efficiency is a resource in an industrial organisation (i.e. a firm), and a significant extent to which it contributes to sustained competitive advantage is suggested as a central notion in this chapter. Hence a competitive or market-driven component (i.e. a driver) is observed in those organisations where energy efficiency plays a central role in the overall performance of a company.

In the Natural Resource-based View firms are assumed to implement environmental strategies as part of an organisational paradigm leading to competitive advantage. Using this latter framework, practices on energy efficiency are understood as part of environmental management strategies in a firm. Resources are endogenous to the firm in the sense that while implementing energy efficiency improvements, firms develop specific technical and organisational capabilities. These capabilities support the implementation of environmental strategies as it has been documented with specific examples in the literature in section 4.2.

The uses of energy are specific to each stage of the production process, by type of firm, and by idiosyncrasies in each organisation. Hence implementing energy efficiency best practice requires specific knowledge (i.e. know-how) which is relatively strategic. The overall specific energy requirements within an organisation may be explored in an integrated, holistic energy analysis approach by examining the energy requirements in the specific stages (or domains of the production process).

Organisational change in a company may affect further increases in energy efficiency. In some instances, corporate accounting practices in the environmental domain may represent a significant driver for organisational change and further increases in energy efficiency. In this respect, it is suggested that a potential impact of programmes such as the Mexico Greenhouse Gas Programme (section 4.4) will encourage participating firms in assessing and making a transition towards implementation of best environmental management practice. This is the case for some of the most important iron and steel firms in Mexico. In the context of the Mexico GHG programme, energy efficiency represents a strategy and there is a strong environmental driver (i.e. control the amount of GHG) to increase energy efficiency.

Finally, there is some indication that knowledge supporting energy efficiency practices is strategic in the sense of sustaining competitive advantage. This has been assessed in terms of the Resource-based approach in section 4.5. The more the knowledge of energy efficiency meets these attributes (i.e. valuable, rare, difficult to imitate, and idiosyncratic to an organisation), the more strategic this organisational/technical know-how becomes. Hence the strategic attributes of energy efficiency best practice represent a strong driver towards improvements of energy efficiency with a positive impact on the control of GHG.

Chapter 5

Methodology

Introduction

This chapter elaborates on the combination of both a qualitative and quantitative methodology in the study of industrial energy efficiency. The goal of this chapter is to describe in detail the research design process and the reasons supporting the selection of the current research design. The research presented in this thesis is inter-disciplinary. It combines both a social science approach and an energy modelling approach in the study of drivers and barriers to industrial energy efficiency. The use of a qualitative methodology is explained in this chapter whereas a fully exposition of a quantitative methodology is given in chapters 8, 9, and 10.

5.1 Choice of a Research Paradigm

In this thesis, a methodological framework is used with the purpose of mapping out a process of change within organisations in order to identify drivers and barriers to energy efficiency growth. Drivers and barriers are understood in terms of *industrial practices* conducive or inimical to growth in the energy efficiency of steelmaking processes.

A process of change is characterised by actions implemented within companies. A central aspect about a process of change consists of a response from organisations to changes in external conditions in which they operate. While identifying external conditions related to the steel sector, this research maps out how organisations respond to external '*impulses*'. In those cases where a process of change is identified, an attempt is made to elucidate the way these changes affect energy efficiency growth. A second critical aspect of a proposed methodological framework in this thesis is to assess the impact of energy uses and efficiency in the current amount of CO_2 emissions in the overall steel industry in Mexico.

The research of this thesis is developed with the use of a mixed methodological framework and a pragmatic position as a researcher. Pragmatism, in the context of this research, is indicative of combination of qualitative and quantitative methods as a mode of investigation. In particular, daily experience and solution to a specific problem is central in pragmatism (Maxcy, 2003). This research intends to give a meaningful interpretation to engineering practices in the context of Mexican steel plants which facilitate energy efficiency growth. It attempts to *'capture'* people's understandings of their own activities in the organisation as expressed through views and opinions on energy efficiency. It attempts to produce descriptions of people's productive practices (routines, capabilities, *rule-of-thumb*) in industrial organisations and energy and environmental institutions related to the iron and steel sector in Mexico.

There is one basic cultural assumption shared between the participants (i.e. industry informants and the researcher) during this research. This relates to a shared common language (i.e. the problem of study relates to a Spanish speaking industrial community in which the participants and the researcher share the same language). This facilitated the interview process and the understanding of a particular language (i.e. a jargon used in the steel industry) during the interview process. Both the participants and the researcher have spent part of their lives directly exposed to a factory work environment. This fact provides with a cultural shared assumption and prompts a high motivation for industry related processes.

5.2 Research Goals and Questions

This research focuses on the drivers and barriers to industrial energy efficiency in the iron and steel industry in Mexico in the last fifteen years. There are two goals in the research of this thesis. Firstly, to assess the potential to reduce carbon emissions through an integrated energy system the definition of which is given in chapter 1 (figure 1.4). Secondly, to explore and understand energy efficiency practices the relevance of which is used to characterise current and future carbon industrial emissions in the steel industry. The following research questions are pursued through the research of this thesis:

1) What are the relevant drivers and barriers to energy efficiency accounting for a process of change in the Mexican iron and steel industry?
2) What is the significance of fugitive emissions in energy production and delivery as compared to the emissions in the iron and steel industry?
3) What is the significance of carbon emissions in electricity generation in terms of electricity requirements in the steel sector?
4) What is the overall contribution of carbon emissions in the Mexican iron and steel industry?
5) What are the potential opportunities to reduce carbon emissions in the steel sector from electricity uses and other energy requirements?

The type of research presented in this thesis is exploratory because it identifies a range of drivers and barriers to energy efficiency and attempts to arrange them into categories. It also identifies relationships underneath a process of change in which energy efficiency is part of.

The *research strategy* is based on the elaboration of *case studies* which appear suitable for the analysis of a phenomenon in a specific context. Yin (2003a; 2003b), for instance, suggests that the use of case studies as a research method is desirable when the problem of study and the context are not disentangled at first glance. Within the iron and steel industry in Mexico which is the focus of this research, there are two embedded units of analysis which correspond to two company case studies in the iron and steel industry in Mexico.

5.3 Data Sources and Industry Layout for Energy Analysis

The original research design targeted specific production lines of an industrial plant as the unit of analysis for a case study. However, this changed during the research process to include a company (i.e. a firm) as the unit of analysis. The following main primary data sources were used in this research:

1) Interview material by means of semi-structured questionnaires.
2) Quantitative data obtained from official statistics, governmental ministries, and personal communication with industry informants.
3) Technical and company reports.
4) Public official documents and archival data,
5) Technical literature on industrial processes.

Interview written material and the use of documentary data are the most important data sources in the qualitative analysis and use of case study research method. On the other hand, access to specific energy data was obtained from the Ministry of Energy (SENER), the Ministry of Environment and Natural Resources (SEMARNAT), and National Economic Official Statistics (INEGI).

Both the qualitative and quantitative data were used in an iteration process in this research as follows. First, a section of the questionnaire used in exploratory fieldwork aimed at obtaining data on energy consumption by major fuels in steel facilities. However, it was not possible to obtain comprehensive quantitative data on energy consumption using a questionnaire. Energy consumption at company level is seen as proprietary data and there may be commercial purposes in their use. This limitation was resolved at a later stage with official data on energy consumption by industry establishment and this is treated as confidential information. On the other hand, interviewees talked openly about the production process and described the corresponding energy requirements. While doing this, it was possible to build a layout of the operations of each of the visited plants and the specific technology. A trend was identified during the observation of the properties of a group of plants in different companies in terms of steelmaking processes. Mexican steel plants operate under the three following technological routes:

1) Blast furnaces (BF) – basic oxygen converters (BOF)
2) Direct reduction reactors (DRI) – electric arc furnaces (EAF)
3) A combination of direct reduction reactors and/or steel scrap – electric arc furnaces

These different routes provided a framework for energy analysis at a later stage. A detailed observation of the technology configuration in each steel plant consists of the bottom-up approach in the context of this research. In some instances, general parameters of energy consumption were indicated by some managers in steel plants. These specific parameters were only used for validation purposes since the majority of quantitative data came from governmental bodies.

5.4 Methodological Framework

Mapping out practices on energy efficiency is a research endeavour looking at *actions* or *activitie*s. Observed energy consumption and the corresponding carbon emissions are understood *de facto* as a consequence of a collection of activities in industry (inclusive of energy efficiency practices). This is not a simplistic assumption but a pragmatic approach to research. In view of the variety of research questions defined in section 5.2, a combination of research methods is necessary. A qualitative method is used to tackle the more qualitative question 1 whereas a quantitative method is used to address the research questions 2 to 5. The use of both qualitative and quantitative methods appears to be gaining wider use in organisational and management studies. Combining qualitative and quantitative methods represents a mode of triangulation which will result in a more comprehensive knowledge (Currall & Towler, 2003) or maximum theoretical advantage (Denzin, 1970).

On the one hand, the qualitative approach is based on the extraction of information on the energy efficiency views and opinions from industry practitioners. This was achieved through interviews in industrial firms with the use of semi-structured questionnaires in two fieldwork periods in 2007 and 2008. Afterwards, written interview material was analysed and organised into categories with the use of coding strategies.

These categories represent the outcome of a process of organising information and afterwards this information was structured in two case studies. A process of change was documented in case studies based on a comparison of anecdotal evidence given by industry informants. While reporting on a process of organisational change in two steel companies, the most relevant drivers and barriers playing a role on energy efficiency are identified in the exposition of each case study. Also, improvements in energy efficiency practices and changes in technology are addressed as part of a more general process of organisational change.

On the other hand, the quantitative methodology consists of an application of a lifecycle analysis of carbon industrial emissions consisting of fugitive emissions in energy industries, efficiency in electricity generation and the steel industry. An overview of a holistic approach to energy is presented in chapter 1. The quantitative methodology is fully explained in chapters 8, 9, and 10 the exposition of which consists of a group of equations and the corresponding calculations.

Figure 5.1 is used to elucidate the combination of both qualitative and quantitative methodologies. Energy efficiency practices and a process of organisational change affecting energy uses are part of a social process. In the context of this research this process is addressed in relation to technical and organisational capabilities which are related to energy decisions in industrial firms. These energy technology-based skills and the decisions around energy uses form a fundamental part of the organisation of anthropogenic activity the growth of which puts on a pressure on carbon industrial emissions.

The social analysis presented in case studies is used as *prima facia* to characterise firm-based capabilities and the energy related decisions in relation to the observed amount of carbon industrial emissions. This latter is part of a carbon accounting approach in this research. The use of a social analysis to characterise carbon industrial emissions offers a more comprehensive or holistic approach which is used to indicate what different organisations can do. Thus oil and gas producers as compared to power facilities and steel plants, in the use of strategies to mitigate climate change. It is not only the identification of carbon emissions and potential opportunities but also the social aspects of energy that are an analytical strength in the mixed methodology of this research. In this regard, mixed methodological frameworks are used in a social environmental related phenomenon. Christensen (2007) developed a similar and comprehensive mixed methodological framework in the analysis of fishermen’s tactics and strategies in Danish fisheries and European Union fleets.

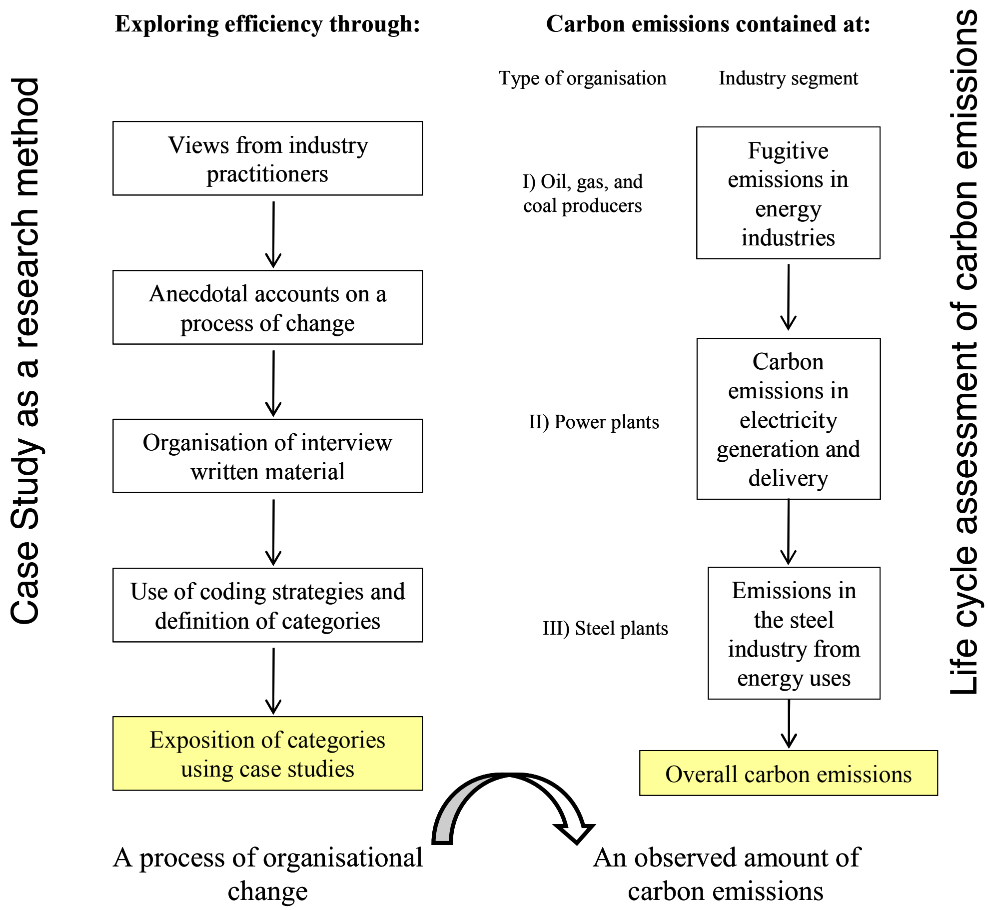

Figure 5.1 – A Methodological Framework for the Study of Drivers and Barriers to Energy Efficiency in Industry

5.5 Research Design and Procedure

A point of departure in the research presented in this thesis was formulated from the observation of a specific trend: i.e. a continuous drop in the energy intensity of the overall steel industry in Mexico during 1994-2005.According to a growth index in which 1993 is used as a reference year, the energy intensity index for the iron and steel industry reduced from 99.5 to 74.6 over the considered period.[8] This former observation prompted a large research interest in finding out what was explaining

[8] This index measures the growth in both the manufacturing activity (in tonnes of steel) and the energy uses (in PETA Joules) taking 1993 as a reference year.

this energy intensity trend. The general research questions consisted in finding out the overall drivers and barriers to energy efficiency.

The research procedure developed through the following three major inter-related stages (figure 5.2). The first stage consisted in doing exploratory fieldwork in Mexico during the spring and summer of 2007 with the use of a former questionnaire looking at general and climate changes aspects. This provided a first primary source of qualitative data the analysis of which aided in laying down a 'dialogue' between empirical data and the construction of a theory framework. At this stage a preliminary theory was sketched and this guided a further design of case studies. The formulation of a theory framework was more the outcome of inductive analysis, that is, it was based on observation during exploratory fieldwork and through an iterative thinking in relation to the available literature.

A first theory framework was proposed on the notion of market transformation, market, organisational and other institutional barriers regarding the diffusion of energy efficiency technologies. This opened a discussion of a wide array of aspects pointing out the drivers and barriers to energy efficiency in an industrial organisation though the problem of study at this stage was static. In other words, no allusion was made to a process of change in industry at this stage of the research process.

With the opinions thrown up by industry informants over the first fieldwork the critical problems and needs the steel industry was facing were indentified. Also, a first exploratory revision of qualitative data helped in cross-checking if the collected evidence was shedding some light on the key insights already written in the existing literature.

Two things became apparent from this first exercise. Firstly, economic and technical aspects of energy efficiency appeared very often in the accounts given by industry informants. Secondly, though some barriers documented in the literature were very close to the accounts from industry informants, it was very noticeable energy issues were discussed in relation other aspects in industry. Views on energy uses and efficiency were also associated to energy regulation and voluntary programmes on greenhouse gases as these were gaining importance in the managerial approaches of the companies. This opened a new conceptual angle on how the organisations were responding to new approaches to energy uses from an environmental management standpoint which were of particular concerns among the governmental sector.

Stage 1

- Definition of a general research question on the main drivers and barriers to energy efficiency.
- Use of a semi-structured questionnaire to explore general energy efficiency and climate change aspects (fieldwork 1).
- First interview transcription and content analysis.
- Comparison of the interview written material with energy related concepts in the existing literature.
- Identification of critical needs in the steel industry in relation to energy uses.
- Identification of technical and economic attributes of energy efficiency.
- Identification of voluntary environmental programmes and climate change initiatives.

Stage 2

- Refinement and definition of the main research questions including quantifiable effects on carbon industrial emissions.
- Inclusion of organisational aspects of energy efficiency as a key research concern.
- Definition of main steelmaking technological routes (i.e. BF-BOF and DRI-EAF).
- Full documentary revision for company case study selection.
- Use of a semi-structured questionnaire looking for organisational changes in the two selected companies (main fieldwork).
- Access to specific energy consumption data provided by governmental organisations.

Stage 3

- Second interview transcription and content analysis.
- Integration of qualitative data from both fieldworks into a single project using NVIVO.
- Analysis of the organisational aspects of energy efficiency in the two selected companies.
- Use of coding strategies in the identification of a process of change in relation to energy efficiency (qualitative analysis).
- Calibration of energy parameters and quantitative analysis on the calculation of carbon emissions.
- Writing up central chapters on:

-Company case studies on industrial energy efficiency.

- Estimation of carbon industrial emissions.

Figure 5.2 –Research Process

In the second stage of the research process, an extended angle of the views of energy uses including environmental aspects in industry allowed a refinement of the research question. In particular, the latter research questions were more interested in measuring the effect of energy uses on the carbon industrial emissions and organisational changes affecting energy uses. This stage of the research process also allowed the identification of the main steelmaking technological routes using the accounts given by industry informants (stage 2 in figure 5.2).

At this second stage the main fieldwork study period incorporated a set of targeted questions in order to map out a process of change in the iron and still sector. This main fieldwork at manufacturing plants in Mexico was carried out during the summer and autumn of 2008 but before this was done, an in-depth review of the available documentary material was done in order to select two companies for case study research (section 5.6). At this stage, a clear notion on the drivers and barriers to be investigated in the research was incorporated in second semi-structured questionnaire. A central aspect of this second questionnaire was to also include items inquiring about organisational changes playing a role on energy efficiency.

In this main fieldwork, it was also possible to obtain information on specific energy consumption data by industrial establishment (stage 2 in figure 5.2). This was facilitated by direct communications with representatives of the Ministry of Environment and Natural Resources in Mexico (SEMARNAT). This latter data was used to calibrate energy parameters using a life cycle assessment of carbon industrial emissions.

In the third stage, all the available qualitative data was integrated into a single analysis and this provided a rich source of information of a number of facilities in the iron and steel industry (stage 3 in figure 5.2). This information was incorporated into a single project using NVIVO software for qualitative analysis. The main focus of collecting this second strand of data was to assess the group of research questions stated in section 5.3

Two critical outcomes were reached at this stage of the research process:

1) The organisational aspects of energy efficiency were studied more in detail. The analysis consisted of characterising the selected two

companies by looking at the attributes of energy uses. Changes in technology and the role of environmental programmes were tracked down through the use written accounts and how this affected changes in fuels, energy uses, and efficiency. Also, the attention was placed on the decisions and organisation of energy activities in a company. This allowed assessing the extent to which energy efficiency improvements were part of a more general process of organisational change.

2) With access to specific quantitative data at plant level, it was possible to obtain specific energy parameters. These parameters are often regarded as specific energy consumption (SEC). More importantly, this data allowed the incorporation of the following three components as part of the key methodological contribution in the energy analysis of this thesis:

   2.1 An improved life cycle assessment of carbon emissions incorporating fugitive emissions in energy generation, electricity loses, and efficiency in three types of industrial organisations: energy producers-distributors, power stations, and steel plants.

   2.2 The definition of energy scenarios through changes in the mix of energy sources and how this impacts carbon emissions in Mexico.

   2.3 The effect of a specific carbon emission factor for electricity uses in the steel industry as a result of alternative energy scenarios in point b above.

The final chapters of the thesis deal with the specification of a methodology and results of the proposed energy holistic model. These chapters were organised in relation to the type the strategies in each industrial organisation to reduce greenhouse gases as follows:

1) The significance of fugitive emissions in oil, gas, and coal producers (organisation type I) the purpose of which is to estimate an emission factor of each fuel allocated to electricity generation (Chapter 8).
2) Carbon emission factors in electricity generation by type of power plant (organisation type II) the use of which is to elaborate on alternative energy scenarios (Chapter 9).

3) Carbon emission factors by main type of steel plant (organisation type III) the use of which is to estimate overall carbon emissions in the steel industry taking into account:

   3.1 Changes in the emission factor of electricity generation by scenario.

   3.2 Changes in the amount of steel production.

   3.3 Changes in the relative importance of main steel technique (i.e. technology diffusion if BF-BOF or DRI-EAF).

   3.4 Changes in energy intensity by main steel process.

These aspects are highlighted in the research process. Firstly, a description of the technology configuration with the use of a qualitative description validates the definition of a holistic energy model. Secondly, an inductive approach is followed in stage 1 because it is the understanding of the research context during the exploratory fieldwork which aided in the identification of relevant energy related concepts.. Thirdly, the results arrived at are used to assess the the research questions at stage 3 of the research process. This stage consisted of the writing of latter chapters on the case studies and the carbon emissions results.

5.6 Exploratory Fieldwork (2007)

5.6.1 Interviews in Industrial Plants

Companies and organisations were initially contacted by telephone. Most of my inquiries were transferred to the environmental, energy, and maintenance department. Each interview took a substantial time from the date of establishing a first contact with an organisation. Several phone calls and e-mails were sent to an organization two months in advance an interview date was appointed. This implied a negotiation process where I explained the research project and what the expectations from the research were. Most organisations refused to give specific data on energy consumption but provided with some general figures. Unfortunately, a group of companies ignored completely the request for an interview. Overall, the process of contacting organisations and obtaining an interview was lengthy and a substantial networking was involved.

A large amount of information was provided by people in charge of the maintenance department clarified energy efficiency aspects. During the exploratory fieldwork on-site plant interviews were conducted in eleven companies. The largest integrated steel producers, a large glass company, and companies in the engineering sector were visited at this stage. Only one large steel company denied access to interviews.

5.6.2 Interviews in Private and Public Institutions

Eight interviews were conducted at governmental institutions of energy and environment (sections 6.6.4 and 6.6.5). The majority of interviews were recorded with the aid of a digital recording device (IC Recorder ICD-P110/P210 Sony ®).[9] In other cases, where those interviewed declined to be recorded, detailed handwritten notes were taken. In cases where no recording was taken, the notes taken in the interview were expanded to a full context immediately after the interview was completed. The following institutions were visited during exploratory fieldwork and in most cases an interview was conducted in each visit:

1. Pemex Gas y Petroquímica Básica.
2. Pemex Finanzas.
3. Procuraduría Federal de Protección al Ambiente.
4. Secretaría de Medio Ambiente y Recursos Naturales - Programa Gases de Efecto Invernadero México.
5. Presentación Oficial del Programa Gases de Efecto Invernadero México.
6. Instituto Nacional de Ecología.
7. Cámara Nacional de la Industria de Aceites, Grasas, Jabones y Detergentes.
8. Reporte de la Transición Energética.
9. Fideicomiso para el Ahorro de Energía Eléctrica.
10. Comisión Nacional para el Ahorro de Energía.

A specific semi-structured questionnaire was prepared according to the competence of each institution. In most cases, the questionnaire contained up to ten

[9] SONY IC Recorder, Manual, Operating Instructions, bar code 234823711, (2004) SONY Corporation.

questions. There is no such homogeneity in the type of questions compared to the case of interviews in industrial plants. Unlike the more specific information which was obtained from personnel in firms associated with the Steel Industry, the information obtained from Government and other agencies will always tend to be of a general nature and not specific to particular circumstances. Nevertheless the information provided by the government and other agencies, provided a useful counterpart to that provided by the Industry.

5.7 Company Case Study Selection

During the first stage of research design, companies in the engineering and glass sectors in Mexico were targeted for exploratory fieldwork. However, at a later stage, it became clear that although engineering companies employ steel in their manufacturing processes, the amount of energy requirements and the specific technologies differ significantly from the steelmaking process. In the case of glass companies, although the production process requires similar energy inputs such as natural gas and electricity, the glass sector is largely concentrated in a single company. It became evident that access to steel plants was easier than in the case of plants in the glass sector.

Contacts with an ex-representative of National Iron and Steel Association in Mexico (CANACERO) contributed to the decision to select the steel sector. This decision was also supported by the fact that some steel companies showed large interest in cooperating with this research. It appeared that large companies had designated channels of communication which facilitated the interview process.

As result, the research focused on exploring in detail the energy efficiency change in steel facilities instead of comparing processes across different industrial sectors. The selection of the iron and steel industry as a case study was also based on the fact that this sector was the most important consumer of electricity (7.3% of total nationwide) and natural gas (26.3% of total nationwide) in Mexico in 2005.[10]

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[10] CANACERO, Perfil de la Industria Siderúrgica Mexicana, April, 2005.

In this stage, it was also possible to identify firms not only implementing energy efficiency activities but also taking preliminary action on climate change mitigation. This was the case of the companies taking part in the Mexico Greenhouse Gas Programme since 2005. This criterion was used to screen for possible candidates among industrial firms in order to build a case study research.

After the exploratory fieldwork, a diversity of views on energy among industry informants depending on the type of steel facility was found. For instance, energy and/or environmental managers in rolling mills referred mostly to the uses of electricity whereas energy managers in integrated steel plants discussed on a larger number of fuels and electricity (i.e. metallurgical coke, blast furnace gases, natural gas, and so on). At this stage of the research process, it was clear that the demand for fuels varied significantly according to each stage in steelmaking. The diversity of views on energy uses according to the stage of the steelmaking process was taken into account in the selection of company. Hence it appeared appropriate to choose a company with a integrated steelmaking process.

In view of the role of technology in lowering the energy consumption it appeared adequate to compare two steel companies operating in different technological routes. With the use of this criterion it was possible to compare the energy intensity of specific steelmaking processes and the associated carbon emissions. Hence one company was selected of which operation is based on secondary integrated steelmaking and another one based on primary integrated steelmaking.

A review of the documentary material and news on the steel industry was crucial. From the revision of the documentary material it was found that the steel industry in Mexico experienced a re-organisation process based on acquisitions and mergers since 2000. Not only large companies were part of a wave of acquisitions and mergers but also mini-mills and non-integrated rolling mills. This fact provided a fertile 'ground' in the exploration of organisational processes affecting energy efficiency. Hence a diverse use of energy sources and materials, different technological routes, and changes in the organisation of industry were the critical aspects in the decision of selecting two companies as case studies.

5.8 Main Fieldwork (2008)

The main fieldwork was conducted between July and August, 2008. Two steel companies visited during the exploratory fieldwork were contacted again and interviews were appointed. A third integrated steel company was also contacted and in this case, one of the respondents accepted a phone call interview. A plant in the glass industry was also appointed for an interview. However, in this case, the information obtained from the glass plant was only used to compare some points in relation to the steel sector. Also, an office of the Ministry of Environment on Industrial Inspection, the Electricity Power Saving Fund Trust, an environmental NGO, and two suppliers of energy efficiency technologies were contacted and interviewed.

In the first company, three energy managers were interviewed during the main fieldwork and a fourth maintenance manager guided a tour in the facilities of the integrated steel plant. In the second company, an environmental and an energy manager were interviewed. All the information obtained in the main fieldwork was integrated and compared with data obtained during exploratory fieldwork.

The design of the questionnaire considered 1.5 hours for interview application. The three energy managers in the integrated steel company were interviewee simultaneously. The interview followed the format of a discussion round table with a multimedia projector showing the attributes of technology and plant layout. During this interview, each manager expressed their views openly and discussed on the points considered in the questionnaire. The way this specific interview took place was chosen by the energy managers since this was not planned in advance.

5.9 Coding Strategies and Use of NVIVO

Most of the qualitative data was extracted with the use of semi-structured questionnaires through the use of recorded interviews. The transcription of the recorded interview material was assisted with the use of a digital voice editor (Sony

® version 2.3.1, 2005).[11] A single source Word file of each transcription was created for every interview and exported to NVIVO 7.0 which is the preferred software currently in use for qualitative data analysis which allows linkages in ideas to be effectively associated. The answers to the semi-structured questionnaire by respondents from different organisations were given a label to keep their identity as confidential.

A first step in the analysis consisted in doing a general reading of each interview to get a grasp of the main ideas thrown up by the industry informants. Not all the questions received an answer as each interviewee was led to openly talk on the relevant information. A former question led the interviewee sometimes to talk on other important aspects not considered in the questionnaire. In view of different responses the content of each interview was grouped into sub-topics allowing a thematic comparison of a group of responses.

The organisation of responses into sub-topics followed many steps. The revision of the existing literature was a very first step in selecting relevant ***concepts*** such as ***process of change*** and ***organisational resources***. In what follows I use these two concepts as examples to explain the qualititative analysis. While reading each interview instances and key words indicating a change in the organisation were flagged out. Changes in the organisation referred to many different aspects which were coded with specific words. The following examples are used to explain the iteration of coding strategies:

Example 1:

> [II.A2] *Now I don´t have a figure at hand because we have gone through a re-organisation process since the company changed of ownership. Since then we have been optimizing our resources, haven´t we? Unfortunately I do not have the latest figure of the number of workers per tonne of liquid steel. But I would say we are very, very competitive as compared to NUCOR and BRITISH STEEL, and steel mills of the like. And I remember when we started up our continuous [casting] line that I described to you; we were 10% below as compared to the best [steel mill] in the United States.*

[11] SONY ®, Digital Voice Editor, Manual, Operating Instructions, SONY Corporation (2004).

Example 2:

> [II.A9B] *Well, as I told you about this... the integration took place last year, didn´t it? And the process of change is slow, isn´t it? Because... well there were some changes in the structure that were quick, for instance, in our case... well, formerly we were three companies, weren´t we? The two big ones were company X and Y and in between a service company. Then we particularly... the energy group, we have the command of the three plants [formerly referred as companies], that is, we are in charge of them. Therefore the integration took place immediately in this case.*

Example 3:

> *[II.A3] Now, in relation to carbon… regarding carbon, there is a culture, we here in company X, we have been managing it [the culture] many years ago. We struggled to convince our own operative people [the staff] about the benefits of using high carbon content sponge iron.*
>
> *[II.A2] Look… we… for us it was still a business to substitute natural gas when the price rose above four dollars per million of BTU even when the metallic [as in the price of steel] was very low. Now that the price of natural gas is ten dollars per million of BTU... I think that an investment of 12 million dollars is recovered easily... a higher investment is clearly not. But this is a cultural change. It is a cultural change for the people who operate the systems, isn´t it? Natural gas is very clean, it is easy to use.*

In the first example, the interviewee is linking the concept of productivity to give an account that something has changed since a new company ownership. He is also pointing out to improvements in the use of resources. In this case, ***productivity*** is marked as code which is related to a process of change in the organisation. He is also noting ***competition in international markets*** of steels so we have another key word associated to a process of change.

In the second instance, the informant is explicitly talking about a process of change which he relates to the structure of different companies which he later refers as plants. He also talks about the energy group which is coded as ***energy management***. The third example talks about a culture of energy uses and the difficulty of energy investment recovery, something which is related to the return rate in the literature. In latter case, the word ***culture*** is used as a code. Culture is used as code to make part of organisational resources affecting the use of energy.

.The use of codes is part of a purposive reading of the interview material and these codes were associated to more general concepts obtained from the revision of the literature. The purpose was to identify aspects which were grouped into the thematic concepts. In this case, words such as competition in international markets, productivity, and energy management are codes the use of which gives an indication of an organisational change as a concept of analysis.

After coding the written interviews, a query in NVIVO was used to list all the codes grouped into a concept. These queries yielded a text output of the codes related to organisational change across different interviews. Sometimes a code was complemented with documentary revision, for instance, in the case of competition in a market of steels, this data was cross-checked with shipments of the same company from industry reports. In effect, growth in steel exports validated the notion of change registered under the code competition. Also, a comparison of text output for a group of codes guided the search of additional data from technical reports and industry news. For instance, in the qualitative results presented in case study 2, it is possible to document the lowering of energy consumption based on the analysis of interview material. This was validated with the comparison of specific energy consumption (kWh per tonne of steel) of this company with parameters obtained for other plants.

Sometimes the reading of the text outputs helped to change the code of an interview text and in most cases the codes were obtained from original words as they were narrated by industry informants. In other instances, the accounts given by the interviewees were not enough as to use a code to make part of a category.

The grouping of these codes into relevant concepts or categories is a form of organising and comparing views based on written accounts. This allowed the structure of qualitative data and the exposition of the analysis with the use of case studies. For instance, in view of the variety of interview responses pointing out to technical aspects of energy efficiency, it was possible to document several stages of steelmaking on the improvements of energy consumption in case study 1. Overall, coding strategies helped to reflect on the content of written interviews and organise the data to make part of relevant concepts previously sketched in a theory framework.

5.10 Validity and Consistency

During the research process, a check was made to see how close the accounts given by interviewees were to reality. This was addressed with the review of documentary data (i.e. corporate and technical reports); press releases and news; and interviews conducted in public institutions which could inform on some actions related to the steel industry in Mexico. Views and accounts on environmental activity obtained during the interview process were compared to company data contained in the Emissions Registry and Transference of Pollutants in Mexico (RETC). This represents a form of triangulation technique in order to gain validity and reliability during the research process.

A second case study strategy applied during the research process was the use of semi-participant observation. This aided in gaining a closer insight into general factors and situations affecting energy efficiency in a plant. A diary with drafted descriptions about the way the visited place looked like, the main ideas thrown out during the interview process and my observations were summarised after each field visit.

Chapter 6

The Contribution of HYL-III Technology to the Energy Efficiency of Steel Making Processes: the Case of Company Centaury

Background

This case study shows how technological progress based on in-house R & D has led to dramatic reductions in the energy intensity of secondary steel making in a Mexican company. The integration of direct iron making processes (DRI) with electric arc furnace technology (EAF) appears to re-enforce a decreasing trend in energy intensity. The integration of HYL-III DRI process with EAF technology in some Mexican steel plants has led to the establishment of the direct reduction iron – electric arc furnace steelmaking route.[12] The case of company Centaury is unique because the former R & D activity of this company is atypical in the steel industry in Mexico. In addition, in-house R & D activity appears to provide support to energy efficiency practices in company Centaury. Technical improvements implemented in daily operations and the implementation of eco-efficiency principles in the steel plants of company Centaury appears to play a central role in the reduction of energy requirements. The relevance of this case study hinges on a trajectory of energy intensity reductions with a direct impact on the control of greenhouse gas emissions in industry.

[12] See chapter 2.

6.1 Financial and Organisational Attributes Of Company Centaury

6.1.1 Financial Performance

Company Alpha Centaury is an integrated steelmaker of plain and long steel products with facilities in Argentina, Guatemala, Mexico, and the United States. Volume sales accounted for 8 millions tonnes of steel in 2008. Sales of steel products in this company increased from 4,484.9 to 8,464.8 US current million dollars between 2006 and 2008, respectively, and this represented a 23.6% growth. The majority of steel production corresponded to Mexico and the United States (5,230. 1 tonnes of steel accounting for 62%), South and Central America (3,107.5 tonnes of steel representing 37%), and Europe and other countries (127.2 tonnes accounting for 2%). Growth in steel production in this company is partly attributed to acquisition of a group of Mexican steel facilities[13] and this represented a strategy to trade steel products in Mexico and the United States.[14]

6.1.2 Corporate Structure

The company Centaury was founded in 1942 in order to supply tin plate for the manufacturing of bottles and bottle tops in the Mexican beer industry. The company started up operations with 149 employees and capital valued at three million current Mexican pesos as of 1942.[15] The company aimed at supplying tin plate during a shortage of steel as most steel requirements had been allocated during the Second World War (Guzman, 2002). By the end of the War, company Centaury faced a growing competition from imported tin plate which was of better quality than those produced domestically. The company embarked on R & D motivated by a shortage of energy sources and steel scrap (Op. Cit). Innovation consisted of the development and commercialisation of the HYL-I and HYL-III ® direct reduction technologies.

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[13] Company Centaury, El Acero de México, Resultados al Tercer Trimestre 2005, Hechos Sobresalientes, Octubre 28 2005.
[14] Company Centaury, Annual Report 2005, 115 pp.
[15] Gobierno del Estado de Puebla, (2009).

The corporate structure of Alpha Centaury consists of four major organisational units: GRUPO Pegasus which controls 59.06% of total shares; Company Orion (11.46%); Company Ursa Major (14.25%); and the remaining of the shares are under the control of the public sector (15.23%) as of 2009. After a process of acquisition, Centaury became a subsidiary of Alpha Centaury with operations in Mexico which has financial control for 89% of total shares in the company (71% of these shares represent direct control whereas 19% represent indirect control, figure 6.1).

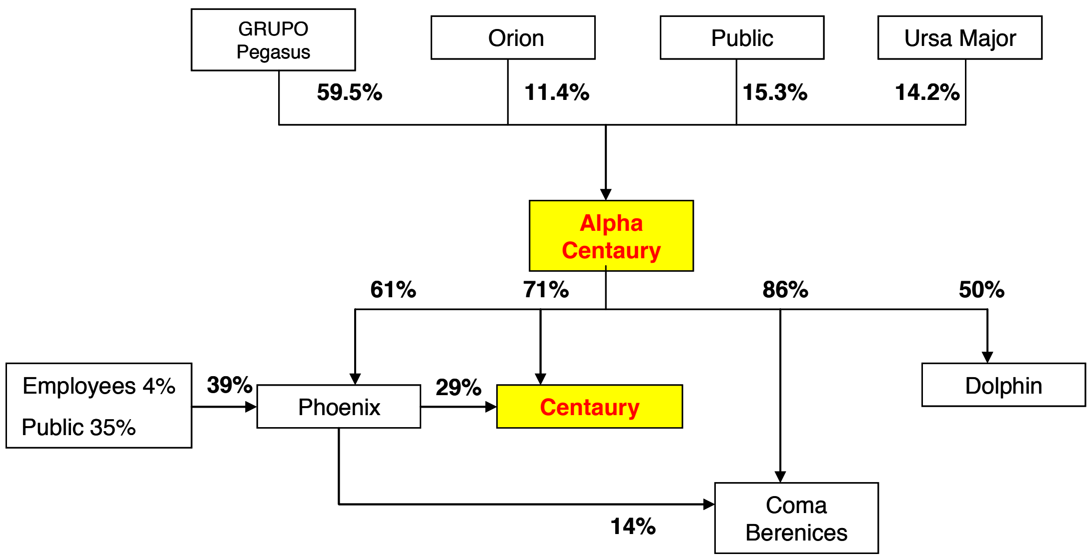

Figure 6.1 – Corporate Structure of Company Centaury

Re-organisation and integration of productive operations took place in this company after the acquisition in 2005. Some of the implemented changes aimed at harmonisation of accounting and financial operations based on the corporate policy of GRUPO Pegasus.

The integration also consisted in the abandonment of an organisational scheme based on business units and divisions in favour of a functional scheme.[16] GRUPO Pegasus also acquired another steel facility in Mexico in 2007 and in this case the major concern was to integrate this facility (GRUPO Dorado) into the

[16] Company Centaury, El Acero de México, Resultados al Tercer Trimestre 2005, Hechos Sobresalientes, Octubre 28 2005.

supply chain in Mexico and the United States[17].[18] Plans after the acquisition comprised greenfield investment in steel production capacity accounting for 4,200 US million dollars. This consist of a compacted hot rolling mill with expected production capacity of two million tonnes of flat steel and a tandem cold rolling mill and an immersion galvanizing line[19],[20].

6.1.3 Market Orientation

Steel production in company Centaury consists of four major products: 1) semi-finished products (slabs); 2) flat carbon steels (i.e. applications for electrical appliances; components and external body of cars, trains, and/or ships); 3) long steels (i.e. reinforced steels or re-bars, railroad tracks, structural steels in buildings and bridges, and wires); and 4) metal spring supports for automobiles. A market diversification strategy in this company includes a technology and trademark license agreement with VARCO PRUDEN BUILDINGS INC in order to supply steels for metal building systems.[21]

6.1.4 Description of Operations

Company Centaury is an integrated steel producer using direct reduction reactors and electric arc furnaces. The major raw materials used by this company consist of iron ore, pellets, coke, direct reduction iron, granulated steel slag, and ferro-alloys. Natural gas and electricity are the most important energy inputs in steel facilities of company Centaury. There are five steel plants in the operation of company Centaury:

1) Long steels plant 1
2) Long steels plant 2
3) Flat carbon steels plant (CSP)

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[17] Press Manager, Luxemburg, 30th April 2007, Alpha Centaury Obtendrá el Control de la Mexicana GRUPO Dorado, Alpha Centaury – Relaciones con Inversionistas, Press Release.
[18] Press Manager, Luxemburg, 26th July 2007, Alpha Centaury Obtiene la Totalidad del Capital Accionario de GRUPO Dorado, Alpha Centaury – Relaciones con Inversionistas, Press Release.
[19] ALFA EDITORES TECNICOS, Alpha Centaury, uno de los mayores proveedores de acero, construirá dos plantas en México, September, 2008.
[20] EL SEMANARIO, Alpha Centaury invertirá US $ 4,200 en México, construirá dos plantas, 8th Septermber 2008, 12:48 pm ©
[21] Alpha Centaury, Annual Report 2008, 128 pp.

4) Galvanizing plant
5) GRUPO Dorado coil plant and galvanizing plant

There are 23 distribution centres and one service centre for the commercialisation of steel products of company Centaury nationwide. The long steels plant 1 produces corrugated rod, billets, and metal spring supports whereas the long steels plant 2 produces low and high carbon rods; alloys; forge pieces and welded seams; billets and corrugated rod.[22] The CSP mini-mill produces high quality coils. GRUPO Dorado plant produces cold and hot rolled steels, coil, and galvanized products. The integrated steelmaking in company Centaury consists of the following:

1) Mining operations
2) Materials preparation
3) Sponge iron production
4) Electric arc furnace liquid steel
5) Finished steel products
6) Distribution/commercialisation

Uses of pellets represent a major raw material in company Centaury. This is obtained from iron ore extraction in two mines: Santa Cruz mining facilities and Molino Rojo.[23] Santa Cruz contains a pellet plant, Homero iron ore mine and Embarcadero iron ore mine (this mine is currently not in operations). Molino Rojo consists of a two-production line pellet plant and an iron ore mine. Company Centaury deployed intense iron ore exploration activities in the Michoacán, Jalisco, and Colima States of Mexico during 2008 as part of their plans to integrate additional iron ore reserves to steel production.[24]

Investment in iron ore exploration in Mexico was not significant before 2004 because the international prices of this commodity were relatively low. Proved iron ore reserves in Mexico are relatively short. They accounted for 1,100 tonnes of iron ore and this represented 0.5% of world total iron ore reserves in 2008.[25] Production capacity in iron ore mines corresponds mostly to pellet production (figure 6.2). Production capacity in Molino Rojo and Santa Cruz accounted for 5.9 and 1.9

[22] Gobierno del Estado de Puebla, (2009).
[23] Company Centaury, Unidades Productivas, Acerca de Alpha Centaury en México.
[24] Alpha Centaury, Annual Report 2008, 128 pp.
[25] Cámara Minera de México (CAMIMEX), 2009.

million tonnes of pellets, respectively, in 2008. The remaining production capacity corresponds to iron ore concentrate (0.4 million tonnes), fines (0.4 million tonnes), and fines for exports (0.4 million tonnes).

Overall, total pellet production in Mexico decreased from 14,767 to 14,293 thousand tonnes between 2007 and 2008 which represented a -3.2% reduction in output. This decrease was attributed to a demand contraction for plain steels in export markets.[26]

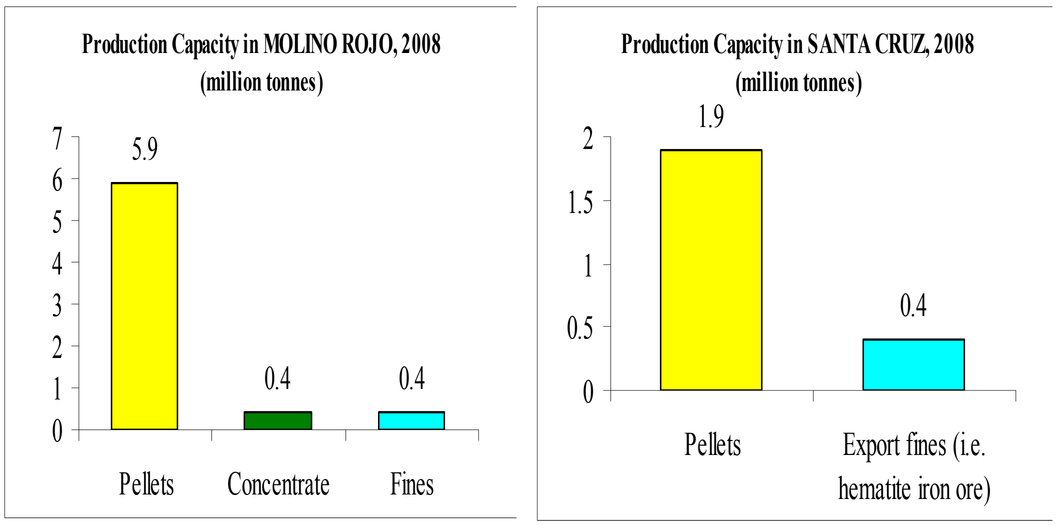


Figure 6.2 – Iron Ore Production Capacity, Company Centaury,[27] 2008

6.2 The Cost of Raw Materials and Energy

The iron and steel industry is significantly energy intensive and requires uses of different raw materials. Among the cost structure of total overall inputs in the steel industry,[28] the cost of raw materials is very significant accounting for 77% in 2007 (figure 6.3). The cost of electricity, maintenance, and fuels and lubricants represented 9%, 4%, and 3% of the total input cost structure, respectively, in the same year. These findings correspond to the overall steel sector but it is important to map out

[26] Cámara Minera de México (CAMIMEX), 2009.
[27] Alpha Centaury, Annual Report, 2008.
[28] The overall input cost structure consists of the following nine items: 1) Raw materials and auxiliaries; 2) Containers and packing; 3) Fuels and lubricants; 4) Maintenance and accessories; 5) Electricity; 6) Transportation hiring; 7) Labour; 8) Advertisement; 9) Maquila 10) Letting services; 11) Royalties; and 12) Other expenditures on goods and services, INEGI, Banco de Información Económica, 2010.

changes in specific energy consumption (SEC) in the case of Company Centaury (see section 6.3).

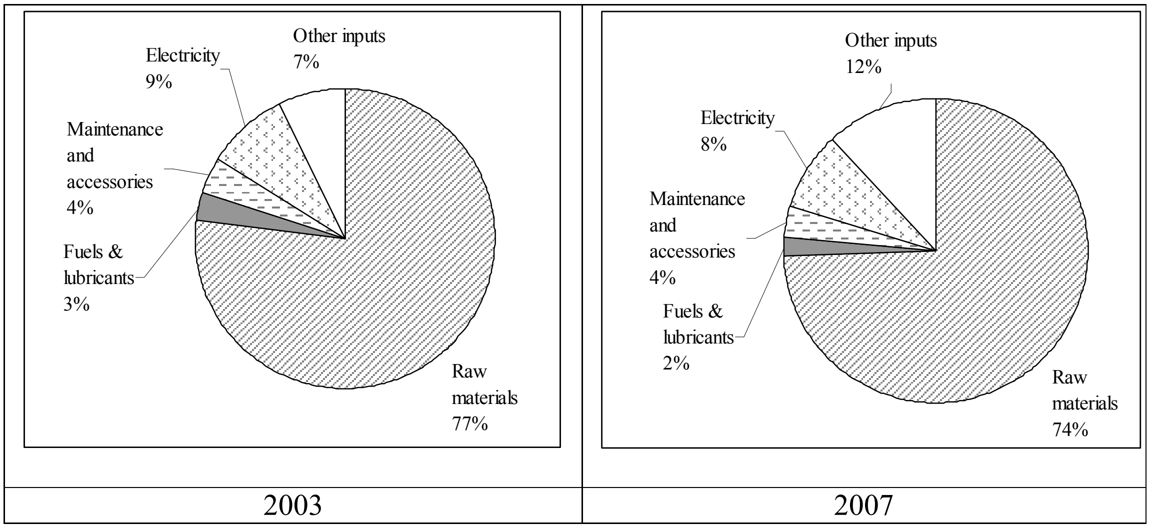


Figure 6.3 – Input Cost Structure in the Iron and Steel Industry, Mexico

(Percentage of total inputs)

Source: Encuesta Industrial Annual, Industrias Metálicas Básicas, 231 Clases (SCIAN), INEGI, BIE, Mexico, 2010.

In monetary value terms, the cost of raw materials increased from 26,583,785 to 42,284,263 thousand current Mexican pesos between 2003 and 2007 representing a 9.7% growth. Similarly, the cost of electricity increased from 3,126,926 to 4,624,275 thousand current Mexican pesos in the same period which accounted for a 8.1% growth (see table 6.1).

	Total inputs	Raw materials	Fuels & lubricants	Maintenance and accessories	Electricity	Other inputs
2003	34,563,813	26,583,785	1,077,158	1,320,135	3,126,926	2,455,809
2004	51,456,308	38,927,281	1,368,606	1,832,687	3,868,020	5,459,714
2005	48,936,161	35,965,539	1,321,922	1,751,485	3,615,412	6,281,803
2006	53,978,975	40,222,734	1,105,092	1,765,874	4,230,605	6,654,670
2007	56,900,629	42,284,267	1,108,830	2,016,548	4,624,275	6,866,709

Table 6.1 – Inputs Used in the Iron and Steel Industry, Mexico, 2003-2007

(Thousand Current Mexican Pesos)

Source: Encuesta Industrial Annual, Industrias Metalicas Basicas, 231 Clases (SCIAN), INEGI, BIE, Mexico, 2010.

Nine raw materials accounted for nearly 98% of the cost of total overall raw materials in 2003. Among these materials, steel scrap accounted for 26%, followed by pig iron (19.5%), coal and related products (16%), iron ore (10.5%), and iron ore concentrates (9.5%) in the same year (figure 6.4).

Figure 6.5 presents a price index for both natural gas and electricity taking as reference year 2003 in which the index has a value of 100. The index shows an increasing trend in the price of natural gas and electricity in the period 1994-2010 (i.e. nearly a two-fold increase in the price index of both energy commodities between 2003 and 2010). Not surprisingly, steel manufacturers have a strong incentive to lower the energy consumption in view of the increasing energy costs as is the case of Company Centaury. This situation indicates the effect of an economic driver to energy efficiency as is the need for steel manufacturers to cushion a long term trend growth in energy costs.

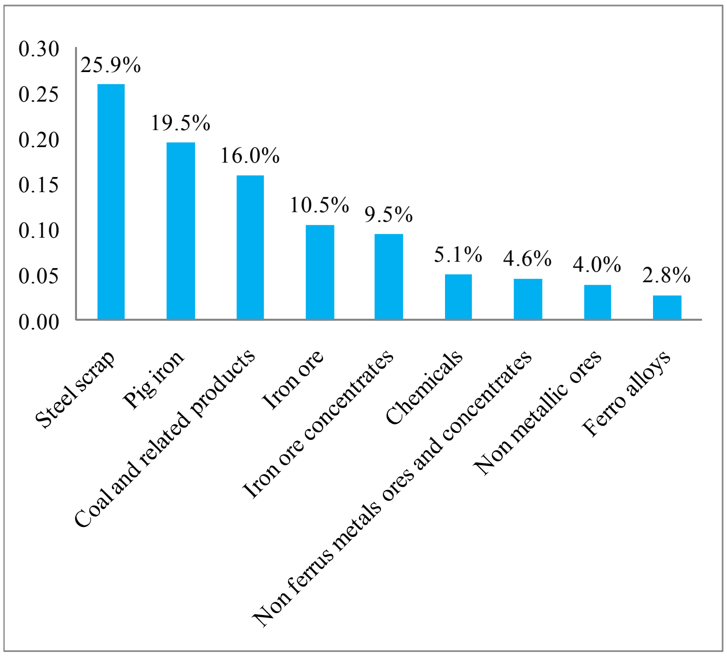


Figure 6.4 – Main Raw Materials Used in Steelmaking, Mexico, 2003 (Percentage of Overall Total Cost of Raw Materials)

Source: INEGI, XV Censo Industrial, Censos Económicos, 1999, Industrias Manufactureras, Subsector 37, Industrias Metálicas Básicas, Mexico.

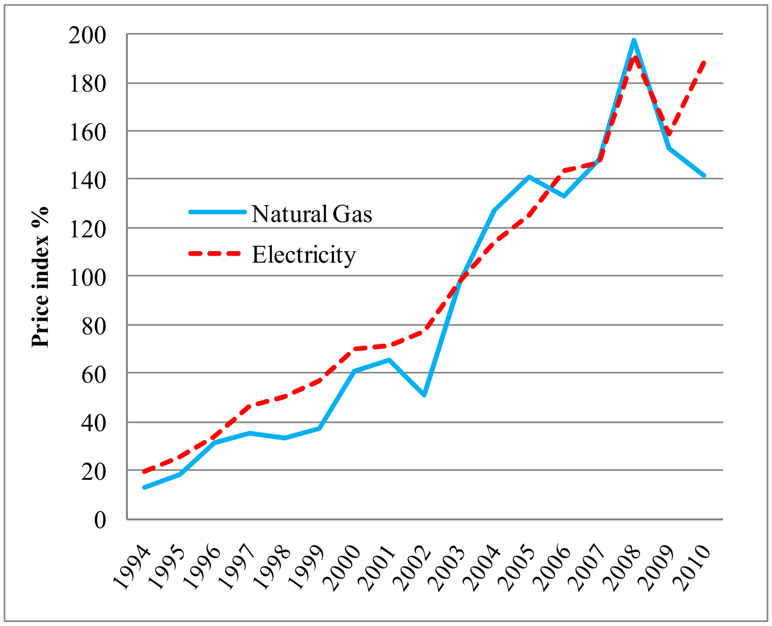


Figure 6.5 - Price Indexes for Natural Gas and Electricity, Mexico, 1994-2010 (Percentage, base year 2003)

Source: Banco de México, Indice de Precios de Productor y Comercio Exterior, 2010.

An increasing cost of energy sources, in particular natural gas (figure 6.5), has led some steel manufacturers to replace the use of materials in favour of more economical choices. This has impacted the energy consumption in some steel plants because sometimes a switch in the use of materials implies a shut down or interruption of direct reduction iron plants. Because pellet is a basic raw material in direct iron reduction plants and production was suspended, mining activities were also suspended.[29] As a result, sponge iron production was replaced by purchased steel crap.

An environmental manager in the long steels plant 2 indicated some flexibility in combining the use of sponge iron and steel scrap for producing liquid steel.[30] In this plant, the content of sponge iron in the load of an electric arc furnace is increased when the price of steel scrap goes up. However, if the price of natural gas raises further, the cost of producing sponge iron is pushed up and, as result, the top management may reconsider the use of steel scrap. This view may be in

[29] [II.A2B.19.06.2008].
[30] [II.A3.13.04.2007].

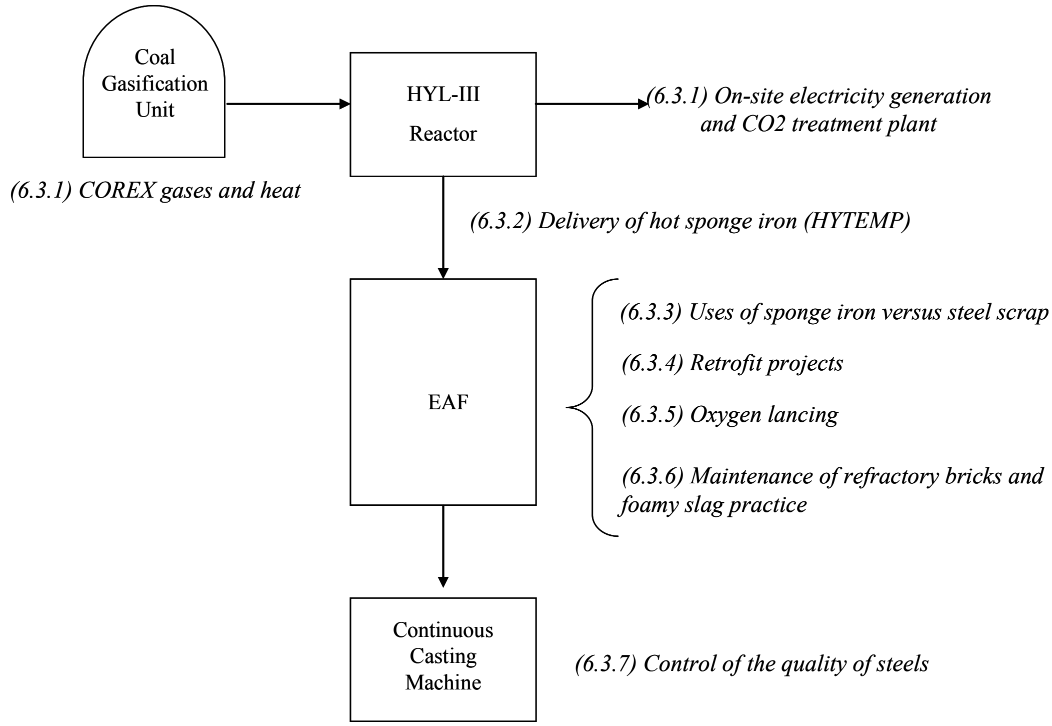
opposition to an alternative view which indicates that the use of raw materials (i.e. sponge iron versus steel scrap) is largely determined by the quality of steel products (see section 6.3.2). Currently, although energy costs are perceived as high in the Mexican steel sector, a recovery in the global market for steels allows the use of sponge iron.[31] This instance shows how the cost of energy commodities and materials affect the energy consumption thus representing a critical driver to energy efficiency.

A major concern in company Centaury was the possibility to put additional steel production in the market. It was also commented by an environmental manager that the incorporation of new technology and investment in energy efficiency projects gain stronger support in instances of growth in steel production.[32] This view was also supported by an energy manager in the long steels plant 1. However, expansion of production capacity is given more relevance as compared to projects of energy efficiency in the investment decisions in this company. It was commented that a period of investment recovery of a production capacity project is shorter that in the case of an energy efficiency project.[33] Thus a priority strategy given to the expansion of production capacity (see a theory sketched in Chapter 3) may represent a barrier to energy efficiency in instances where energy retrofit projects are given insufficient attention.

6.3 Improvements in the Energy Consumption of Steelmaking Processes

Steel production in this company is carried out with the use of direct reduction reactors (DRI) and electric arc furnaces (EAF) the technology of which was described in chapter 2. This section elaborates on the technical changes at different stages of the DRI-EAF route the contribution of which lowered the energy consumption. The order of each measure in the remaining of this section is arranged according to the stage of the steelmaking process as presented in figure 6.6.

[31] [II.A2B.19.06.2008].
[32] [II.A3.13.04.2007].
[33] [II.A2.26.07.2007].



Note: Each number in brackets (6.3.x) indicates a section with the corresponding explanation.

Figure 6.6 – Technical Improvements Lowering the Energy Consumption in Steelmaking

6.3.1 Use of Recovery Gases Obtained from a Coal Gasification Unit

Natural gas is the main fossil fuel used in a direct iron making process in company Centaury. The technology used consists of a HYL-III ® reactor. Natural gas performs both functions a source of thermal energy (i.e. heat) and a reducing agent in an HYL-III ® reformer.

Heat recovery gases from a coal gasification unit are used to provide heat in a direct reduction process. The technology used in coal gasification is a COREX ® direct iron making process. COREX ® gases are mixed with reducing recirculation gases originated in a HYL-III ® reactor. A rich current of gases is used for removing CO_2 during the reduction process in order to produce sponge iron.[34] CO_2 is delivered to a processing plant nearby the direct reduction plant for other industrial

[34] Op. Cit. [27]

applications[35] (i.e. fizzy drinks, preservation of frozen food, control of hydrogen potential, etc).

In addition, steam is generated during a direct reduction process by means of energy obtained in a mixed current of reformation and combustion gases. This steam is primarily used for reformation processes and separation of CO_2. Also, steam is generated at high pressure (63 kg per sq cm) and used for electricity generation through a high efficiency turbo-generator.[36] Two facilities of company Centaury employ this scheme for self electricity generation. According to public data reported by the Regulatory Energy Commission in Mexico (CRE), the long steels plant 1 has a declared capacity of 50 MW whereas the long steels plant 2 has a declared capacity of 5.6 MW.

6.3.2 Delivery of Hot Sponge Iron to Electric Arc Furnaces

In an integrated steel plant, sponge iron produced in a direct reduction reactor can be delivered directly to the load of an electric arc furnace. There are three main classes of sponge iron: 1) direct reduction iron (DRI); 2) hot briquetted iron (HBI); and 3) hot sponge iron (HYTEMP).

The main difference between DRI and HYTEMP is that this latter is transported by a pneumatic system and loaded directly into an electric arc furnace. Heat and carbon is contained in hot sponge iron (HYTEMP) and this contributes to lowering the electricity uses in the operation of electric arc furnaces. The carbon content in hot sponge is around 2.2% to 4%.[37] In an integrated steel process electricity requirements in electric arc furnaces can be reduced in the following cases (figure 6.7):

- High temperatures of sponge iron (600 °C circa) lower the electricity consumption in electric arc furnaces.
- High content of sponge iron (60% circa) in the load of an electric arc furnace reduces electricity consumption.

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[35] ENERGIRON, (2008): Advantages of the HYL III DRI Process.
[36] Op. Cit [29].
[37] Technology Division Manager (name omited), Presidente, HYL, División de Tecnología, Company Centaury, Avances en el Proceso HYL III de Reducción Directa, Congreso Latinoamericano de Siderurgia ILAFA-36, Cartagena de Indias, Colombia, 17-20 Septiembre, 1995, 16 pp.

- Steel of high carbon content (4% C circa) reduces electricity consumption in electric arc furnaces as compared to steels of low carbon content.

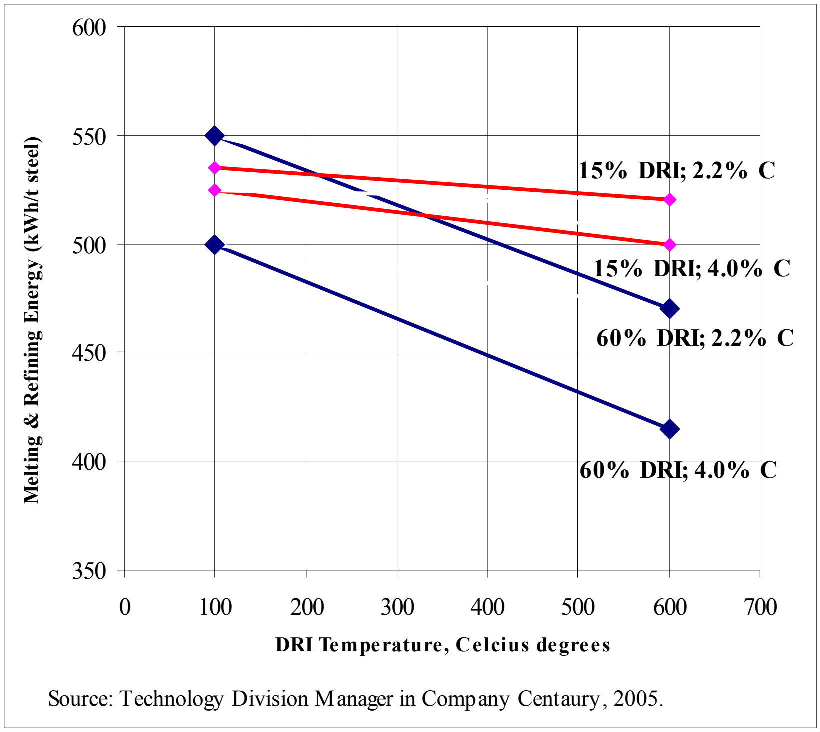

Figure 6.7 – Effect of Sponge Iron Temperature and Carbon on Electricity Consumption in EAF (kWh/tonne steel)

The quality of steels is specified in terms of the percentage of sponge iron, carbon content, and degree of metallisation. These properties taken in combination affect the electricity consumption in an electric arc furnace. Hence depending on the demand of a certain steel quality there is specific energy consumption (SEC). In integrated and semi-integrated Mexican EAF plants, SEC can be as high as 660 and as low as 341 kWh/tonne of steel.[38] Clearly, this focus on the quality of steels indicates a critical market driver on the demand for quality affecting the energy consumption.

The implementation of HYTEMP is regarded as a concept developed by company Centaury. During the first quarter of 1999, the installation of a HYTEMP system started up operations which resulted in a decrease of around 70 kWh/tonne of liquid steel. An energy manager in the long steels plant 2 documented a decrease

[38] Data for 1998.

from 800 kWh/tonne of liquid steel to around 460 kWh/tonne of liquid steel as part of the improvements in a ten year period which included the installation of a HYTEMP system.[39]

Lowering the energy consumption was partly attributed to the implementation of a concept known as *continuous fed of sponge iron at variable speed*.[40] The velocity of transportation of sponge iron is adjusted to power increases in an electric arc furnace. The speed of delivery of hot sponge iron varies from 50 to 300 kg of sponge iron per kWh as the power in an electric arc furnace goes up.[41] HYTEMP is transported by reduction or inert gases generated in a direct reduction reactor. In 1997 a finger shaft furnace of company Centaury showed a SEC of 432 kWh per tonne of steel (vrg. 55% sponge iron and 45% steel scrap).[42]

6.3.3 Uses of Sponge Iron versus Steel Scrap

An energy manager in the long steels plant 1 indicated two parameters considered in the production of high quality steels. Firstly, high quality steels contain high percentages of sponge iron or direct reduction iron (60% or above it) and the rest consists of steel scrap. Secondly, a large content of iron (Fe) in liquid steel is desirable in the production of high quality steels (a concept regarded as metallisation in section 6.3.2).[43] High quality steels in company Centaury correspond to metallisation levels between 93% and 95% in the market. On the other hand, this manager also indicated that a traditional use of steel scrap is attractive for steel manufacturers because the melting process requires less electricity. This is an economic measure suggesting the cost of electricity as representing a critical driver to energy efficiency. In opposition to this view, it was indicated in section 6.3.2 that some believe that the quality of steels and not the costs of energy commodities affecting the energy consumption in steelmaking.

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[39] [II.A2.26.07.2007].
[40] Technology Division Manager (name omitted), Presidente, HYL, División de Tecnología, Company Centaury., Avances en el Proceso HYL III de Reducción Directa, Congreso Latinoamericano de Siderurgia ILAFA-36, Cartagena de Indias, Colombia, 17-20 Septiembre, 1995, 16 pp.
[41] Op. Cit [26].
[42] De Beer et al., 1998.
[43] [II.A2.26.07.2007].

6.3.4 Retrofit Projects in the Operation of Electric Arc Furnaces

The useful life of an electric arc furnace is within a range of 20-30 years. Electric arc furnaces are replaced in a situation of production capacity expansion or when better technologies become available.[44]

A DANIELLI ® direct current electric arc furnace[45] started up operations at the flat carbon steels (CSP) plant of company Centaury at the end of 1998. Production capacity was 0.81 metric tonnes of steel per year before the installation of a DANIELLI ® furnace. With the new furnace production capacity was expected to reach 750,000 metric tonnes per year. A learning curve of around five weeks was documented after the start-up of a DANIELLI ® DC electric arc furnace.[46]

The DANIELLI ® DC design considered the use of HYTEMP ® in the load of the electric arc furnace (i.e. 100% sponge iron). Collaborative links were in place between the DANIELLI design team and company Centaury team in order to integrate the production of HYTEMP sponge iron using HYL-III ® technologies into the load of a new DC electric arc furnace.[47]

The operation of this furnace is based on a concept of 'twin' electrodes for reducing electrode consumption as compared to alternate current electric arc furnaces. Efficiency during the melting of HYTEMP is attributed to the design of a twin electrode system in view of the fluid dynamics and the configuration of the electrical arc.[48] By the time of fieldwork visits in Mexico during 2007, an energy manager in company Centaury commented on three major energy components in an electric arc furnace:[49]

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[44] [II.A2.26.07.2007].

[45] DANIELLI ® is a registered trademark in steel making technologies of which original equipment manufacturers (OEM) are based in Italy.

[46] Name ommited., name ommited, name ommited, and name ommited, (2000): Tecnología: Nueva Generación de HEA de Super Potencia a Corriente Continua, Company Centaury – Division de Productos Planos – México, DANIELI CENTRO Met.-Italia, Acero Latino Americano, No. 458, pp. 35-40.

[47] Op. Cit [36].

[48] Op. Cit [36].

[49] [II.A2.26.07.2007].

1) A focal point between an electrode and an arc. Some practices have been implemented in company Centaury which aim at rotating the arc in order to increase the stock of heat.

2) Reflection of light emitted from the electric arc furnace with temperatures of 5000-7000 °C circa.

3) Practices which cover the arc with steel slag and not scrap. This practice allows over-heating of slag which, in turn, provides heat for melting the iron.

6.3.5 Oxygen Lancing in Electric Arc Furnace

Around 30-40% of total energy inputs in an electric arc furnace are achieved with the use of oxy-fuel burners and oxygen lancing.[50] Combustion is created by oxygen injection and carbon dissolved in a bath of molten iron. Using sponge iron with high carbon content (4% C) and oxygen injection provides additional heat and this reduces the amount of electricity requirements.[51]

A second alternative is carbon injection in the electric arc furnace. However, with the use of this latter practice, only 40% of the carbon injected remains in the bath whereas the remaining 60% is lost. Also, the overall melting process is enhanced with the use of sponge iron because this material dilutes the residuals in steel scrap.[52] It appears that more electricity is required in the melting of compacted scrap (i.e. steel scrap of a low grade).[53] Steel scrap contains an amount of nickel, chrome, molybdenum, and manganese which are considered impurities in the production of high quality steels.[54]

6.3.6 Maintenance of Refractory Bricks and Uses of Foamy Slag

Electric arc furnaces in company Centaury are given maintenance work during two or three days once a month. Minor adjustments of the refractory bricks are also

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[50] Jones, Jeremy A.T., (2002): Understanding Energy Use in the EAF, NUPRO Corporation, Electric Furnace Conference Proceedings, pp. 141-154.
[51] [II.A2.26.07.2007].
[52] HYL Report, (1998): The Direct Reduction Quarterly, Winter, Vol. 12, No. 4, pp. 1-11.
[53] [II.A3.13.04.2007].
[54] HYL Report, The Direct Reduction Quarterly, Winter, 1998.

implemented in every shift. Slag is produced during liquid steel production in an electric arc furnace. Refractory bricks are eroded due to a chemical reaction of slag and the refractory bricks. Additives are employed to adjust the chemical reaction of slag in order to avoid a damage of the refractory bricks or otherwise a continuous replacement of the bricks. On the other hand, slag has the function of making the arc of a furnace longer and thus providing additional heat to the melting process of an EAF by means of a practice known as foamy slag.[55]

The amount of gangue present in iron ore (i.e. the grade of pellets) defines the chemistry of slag. Iron ore has large quantities of silicon in the form of silicon oxide which is an alternative to lime in terms of chemical reactions. The main chemical compounds in slag are oxides, silicon, lime, magnesium, and manganese. The formation of slag takes place in the production of pig iron in a blast furnace; the production of hot metal in a cupola furnace; the production of liquid steel in both electric arc furnaces and basic oxygen converters; and ferroalloy production by means of submerged arc furnace.[56] The following represent typical average values of slag per tonne of steel in Mexico:[57]

a) 250-300 kg of slag per tonne of steel in a blast furnace.
b) 100-250 kg of slag per tonne of steel in a basic oxygen furnace.
c) 100-250 kg slag per tonne of steel in an electric arc furnace (i.e. this is the technology used in Company Centaury).
d) 900 kg of slag per tonne of silicon-manganese in a submerged arc furnace.
e) 1000 kg of slag per tonne of ferro-manganese in a submerged arc furnace.

A common practice in company Centaury was the use of acid refractory bricks in EAF reacting with silicon and not with lime. This practice has been changed for the use of alkaline refractory bricks reacting with lime and magnesium and not with silicon. In the latter case, the alkaline composition of slag is adjusted to the chemical reaction of slag with the refractory bricks. Additives are also used the

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[55] [II.A2.26.07.2007].
[56] Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), Diario Oficial de la Federación DOF-SEMARNAT 04-07-06, Segunda Sección, 23rd April 2006.
[57] Camara Nacional de la Industrial del Hierro y el Acero (CANACERO), Escorias, Comisión de Desarrollo Sustentable, 2006.

purpose of which is to adjust the chemical properties of liquid steels in view of the end use steel applications.

An energy manager in the long steels plant 2 commented on the desirability of using refractory bricks with a more chemical stability and resistance to high temperatures of around 2000 °C (average temperatures in steelmaking in company Centaury are between 1600-1650 °C). This was regarded as a technological barrier to further energy savings.[58]

6.3.7 Continuous Casting and Control in the Quality of Steels

The most relevant aspect in the design of a production line in company Centaury is the quality of steels. The flat carbon steels plant (CSP) of company Centaury consists of a continuous casting machine (1.5 millions tonnes of steel production capacity) and a rolling mill (2 million tonnes production capacity). The most critical stage in the CSP is localised during the continuous casting process.[59] The chemical properties of steels are modified at this stage and the quality of steels (i.e. the content of niobium, vanadium, aluminium) cannot be modified afterwards unless steel is recycled. Re-uses of steel are considered as 'second-class' and this is not currently a practice in company Centaury.[60]

Company Centaury obtained certifications for total quality management in different divisions during 1997 (table 6.2) and this covers the following aspects: 1) design for conceptual engineering; 2) laboratory tests; 3) commissioning and start-up; 4) warranty tests; and 5) training on a direct reduction plant.[61] Company Centaury has further enhanced its product differentiation capabilities towards the design and marketing of a line of steel products for the building sector. This latter consisted of a certification from the Accreditation Criteria for Manufacturers of Metal Building Systems in North America in 2008.[62]

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[58] [II.A2.26.07.2007].
[59] [II.A2.26.07.2007].
[60] [II.A2C.20.06.2008].
[61] HYL Report, (1997): HYL Receives ISO 9001 Certification, The Direct Reduction Quarterly, Vol. 11, No. 4, 11 pp.
[62] Press manager, (2009): Alpha Centaury, la Primera en Norteamérica en Lograr Acreditación en Calidad de Ingeniería y Estructuras para Edificios Metálicos, Relación con Medios, Alpha Centaury en México, CANACERO Informa, No. 34.

Company Centaury's Divisions	Certification
1) Bar & Rod Division – plant 2	ISO 9001
2) Bar & Rod Division – plant 1	ISO 9002
3) Flat Products Division – CSP	ISO 9002, QS 9000 ISO 14000 in process
4) Tabular Products Division	ISO 9002
5) x – Service Centre	ISO 9002 QS 9000 in process
6) y – Galvanizing Division	ISO 9002
7) HYL – Technology Division	ISO 9001

Source: HYL Report, Vol. XI, No. 4, Winter 1997.

Table 6.2 – ISO-9001 Certification in Company Centaury's Plants

Personnel in company Centaury are committed to satisfying customer's needs in the delivery of steels. Commitment consists of maintaining continuity and regularity in the supply of steel products. In particular, the supply of steel products to the automobile industry is characterised by *just-in-time* deliveries. A bar coding system is assigned to steel casts according to specifications and tailor made to customer orders. An order of steels is identified at the stage of continuous casting.[63]

6.4 HYL-III Technology Leadership in Direct Iron Making Processes

Since the early days of company Centaury, innovative activity was driven by the need to survive in the market. The need to undertake innovative activities was referred by an energy manager as part of a process of competitiveness.[64] The company was very proactive in the development and improvements of steel processes till the end of the 1990's. Technological innovations on integrated steelmaking took place along a trajectory of direct iron reduction processes.[65] Company Centaury successfully commercialised the first HYL-I technology at the

[63] [II.A2.26.07.2007].
[64] [II.A2B.19.06.2008].
[65] Op. Cit [3]. Guzman Alenka, (2002): Las Fuentes del Crecimiento en la Siderurgia Mexicana. Innovación Productividad y Competitividad, Universidad Autónoma Metropolitana, Iztapalapa-Miguel Ángel Porrua, México, D.F.

end of the 1970's. This was followed by a wave of exports of the HYL-I and, subsequently, HYL-III technology to the Middle East, Russia, Southeast Asia, and South America (table 6.3 and figure 6.8).

Plant	Location	Capacity (Mt/y)	Modules	Product	Start-up	Status
PT Krakatau Steel 1	Cilegon, Indonesia	0.56	1	DRI	1978	I
PT Krakatau Steel 2	Cilegon, Indonesia	0.56	1	DRI	1978	I
Sidor H2	Matanzas, Venezuela	1.4	3	DRI	1981	0
Ternium Hylsa 3M5	Monterrey, Mexico	0.5	1	DRI	1983	0
ArcelorMittal Lazaro Cardenas 1	Lazaro Cardenas, Mexico	1	2	DRI	1988	0
ArcelorMittal Lazaro Cardenas 2	Lazaro Cardenas, Mexico	1	2	DRI	1991	0
Vikram Ispat	Raigad, India	0.75	1	HBI/DRI	1993	I
PT Krakatau Steel	Cilegon, Indonesia	1.35	2	DRI	1993	0
Khouzestan Steel (ASCO)	Ahwaz, Iran	1.03	3	DRI	1993	0/I
Perwaja Steel	Kemaman, Malaysia	1.2	2	DRI	1993	0
Usiba	Salvador Bahia, Brazil	0.31	1	DRI	1994	0
Ternium Hylsa 2P5	Puebla, Mexico	0.61	1	DRI	1995	0
Ternium Hylsa 4M	Monterrey, Mexico	0.68	1	DRI	1998	0
Lebedinsky GOK	Gubkin, Russia	0.9	1	HBI	1999	0
Hadeed D	Al-Jubail, Saudi Arabia	1.1	1	DRI	1999	0
Tenaris Matesi	Matanzas, Venezuela	1.5	2	HBI	2004	0
Vikram Ispat 2	Raigad, India	0.6	1	DRI	2007	0
Gulf Sponge Iron (Al Nasser)	Abu Dhabi, UAE	0.2	1	DRI	2009	C
Sidor	Matanzas, Venezuela	0.8	1	DRI	2009	C
Emiriates Steel Industries (GHC)	Abu Dhabi, UAE	1.6	1	DRI	2009	C
Suez Steel	Egypt	1.95	1	DRI	2010	C
Emiriates Steel Industries (GHC)	Abu Dhabi, UAE	1.6	1	DRI	2011	C

Source: MIDREX, World Direct Reduction Statistics, 2008. 0 - Operating; I - Idle; C - Construction

Table 6.3 – World Direct Reduction Plants, HYL / ENERGIRON Process,[66] 2008

Most of the R & D activity in this company continued to reap technological vintages all through the 1990's. Innovative activity formerly motivated by necessity was, at a later stage, driven by commercialisation of direct reduction iron technologies in export markets. Currently, the innovative activity of company Alpha Centaury has focused on the development of steel products.

In-house R & D in company Centaury led to a *'family'* of patents regarding the production and delivery of sponge iron from the stage of direct iron making to the stage of production of liquid steel. A trajectory of technical change in company

[66] MIDREX, (2008): World Direct Reduction Statistics, 12 pp., www.midrex.com.

Centaury took around twenty years as it was the case of the concept of continuous fed of sponge iron at variable speed (table of patents in Annex I). The first patent concerning the transportation of hot sponge iron was issued in 1984 whereas the last patent related to this improvement was issued in 2001.[67]

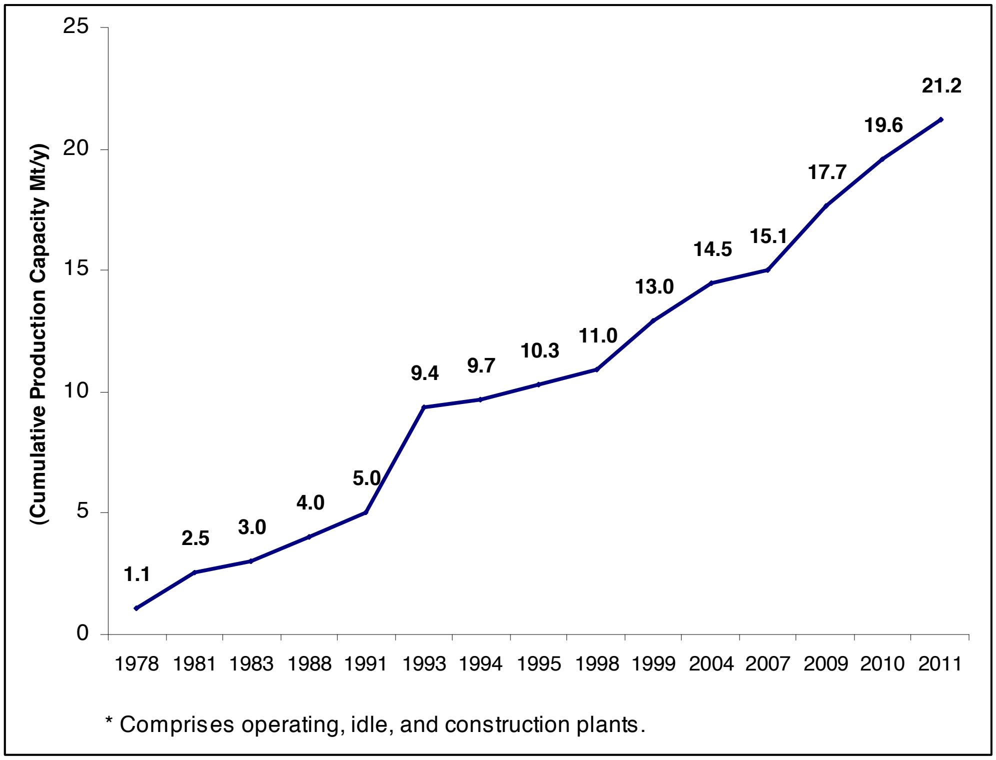

Figure 6.8 – World Direct Reduction Plants, HYL / ENERGIRON ® Process, 2008 Cumulative Production Capacity* (million tonnes per year)

In-house R & D in company Centaury led to a *'family'* of patents regarding the production and delivery of sponge iron from the stage of direct iron making to the stage of production of liquid steel. A trajectory of technical change in company Centaury took around twenty years as it was the case of the concept of continuous fed of sponge iron at variable speed (table of patents in Annex I). The first patent concerning the transportation of hot sponge iron was issued in 1984 whereas the last patent related to this improvement was issued in 2001.[68]

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[67] United States Patent & Trademark Office (USPTO), Search Patents, Advanced Search, accessed on June 2009, www.uspto.gov.

[68] United States Patent & Trademark Office (USPTO), Search Patents, Advanced Search, accessed on June 2009, www.uspto.gov.

Inventive activity and the corresponding patent output are very significant with regard to energy efficiency of steelmaking processes. The ownership of a patent is part of a commercial strategy in this company. An energy manager in the long steels plant 1 indicated that the technology registered as is the case in the patents of this company incorporates two critical parameters. This consists of investment and energy consumption.[69]

> *"Well… our patents… always were obtained due to the need of commercial purposes… from the stance that we sell the process. And the ownership title of a technology is a patent. In the majority of competition in the world of direct iron reduction technology… there is a very important parameter: investment and energy consumption. Therefore, our patents… most of them already pursue both objectives. If one accesses the patent database and checks, for instance, our patents to move hot sponge iron, pneumatic transport, then it is essentially about energy, it is about productivity. It is, instead of cooling down sponge iron, to pass it from a silo to the load of an electric furnace. It is to pass it hot and load it into an electric furnace. Therefore, there is a significant saving in electric energy consumption in the furnace. If one looks at the patent on the reformer process, then it provides energy efficiency because we do not have to use energy for gas reformation. In addition, we reduce investment because we do not longer rely on the like. Hence you are essentially pursuing both aspects.[70]"*

Involvement of personnel along the production lines is crucial in the implementation of technical improvements. It appears that the innovation process in company Centaury was largely informed and guided by accounts on the needs expressed by operators in daily activities. Cooperation among people is identified as very important for the success of technical improvements. Training among operators was identified to be very useful in implementing an innovation project in a shorter time.[71] Energy consumption is viewed as a controlled process in which operators

[69] [II.A2B.19.06.2008].
[70] Op. Cit. (69).
[71] [II.A2B.19.06.2008].

participate and have awareness of efficient uses of energy.[72] The top management is highly concerned of keeping energy consumption within certain limits and not incurring in economic loses.

An environmental manager in the long steels plant 2 commented that practices are not possible to homologate or replicate across plants. On the other hand, work teams in this company are constantly looking for successful cases in other plants of the company. The concepts arisen from successful improvements can be copied or transferred into a specific area. Replication of improvements takes place at a conceptual level.[73] As an example of a successful concept is a self sufficiency scheme in electricity generation of the HYL-III reduction process. This concept is used in the HYL-III VIKRAM ISPAT-GRASIM plant in India for electricity exports[74] and in regions where the supply of electricity is less reliable. The same self-sufficiency scheme is used in two plants of company Centaury in Mexico.

6.5 Firm-based Capabilities and Environmental Performance

6.5.1 Environmental Responsiveness

Currently, company Centaury is in a transition towards a fully implementation of an integrated management system which incorporates the organisation of environmental, safety, and health procedures. The organisational model of company Centaury centres on the development of productive foundations and the consolidation of efficiency and synergy of processes.[75] The environmental policies in company Centaury are consistent with the claims of the World Steel Association and the Occupational Health and Safety Administration's 18,000 and ISO 14,000.[76] The significance given to the environmental aspects in company Centaury is transmitted to the operations staff in environmental training courses.

During fieldwork conducted in 2007 and 2008, it was identified the promotion of a culture of environmental conservation as part of total quality

[72] [II.A3.13.04.2007].
[73] [II.A2C.20.06.2008].
[74] HYL Report, (2005): 2004 Plants Review, Spring, Vol. 19, No. 1, 7pp.
[75] Alpha Centaury, Reporte de Gases de Efecto Invernadero, 2007, Company Centaury Mexico, S.A. de C.V.
[76] Alpha Centaury, Annual Report 2008, 128 pp.

management in the production of steels. Environmental managers in company Centaury conceive sustainability as preservation of resources for the next generations. In this respect, the company guidelines[77] state commitment and promotion of the following:

1) Health preservation
2) Risk minimisation of work related accidents and environmental impact
3) A more efficient use of resources

An integrated management system indicates an inter-relationship of different aspects of production in this company. For instance, good maintenance guarantees the performance of production lines and minimisation of waste. This, in turn, affects favourably the environmental and safety performance of the company. Safety and environment are two domains of the company included in the total risk management.[78] In the organisational culture of company Centaury, knowledge management is seen as a fundamental resource and conducive to market leadership. The most important aspect of knowledge management relates to the continuous improvement of steel processes and retrofit projects inclusive of capital investments.[79] Company Centaury relies on a rotation programme in which personnel from different departments gain knowledge of the overall steelmaking process.[80]

Eco-efficiency is a central concept in the corporate environmental, safety, and health policy of company Centaury. This includes a continuous revision of operations in order to guarantee an efficient use of energy sources, a re-utilisation of by-products, and an appropriate disposal of air emissions and water discharges.[81] Ecology is viewed as part of a business in the sense that recycling materials, minimising leakages and spills reduces monetary losses. Some of the eco-efficient opportunities already implemented are the use of water treatment plants and oil recycling.[82] Uses of water correspond to the following treatment processes:

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[77] Alpha Centaury, Politica de Ambiente, Seguridad y Salud Ocupacional.
[78] [II.A2C.20.06.2008].
[79] Name ommited, (2007): Administración del Conocimiento, Caso de Éxito,
[80] Alpha Centaury, Asociación Mexicana de Directivos de la Investigación Aplicada y el Desarrollo Tecnológico, p. 7.
[81] Alpha Centaury, Annual Report 2007, 114 pp.
[82] [II.A2C.20.06.2008].

1) Water for steel processes of which function is to cool down the flux of gases generated in a direct reduction iron process.
2) Machine-water of which function is to cool down machinery such as compressors of a DRI reactor, panels of an electric arc furnace, and machinery in rolling mills.
3) Boiler house-water of which controlled chemistry is suitable for steam generation.

An energy manager in the long steels plant 2 indicated that efficient uses of energy are also part of the activities included in the eco-efficiency guidelines. In addition, lowering in the consumption of energy was already considered in the retrofit of steelmaking technologies as was the case of heat recovery systems in the furnaces; replacement of high efficiency motors; and improvement of HYL-III reformers.[83]

Environmental management activities in company Centaury include the following:

1) Preparation and assessment of a system of environmental indicators by plant.
2) Internal environmental audits by plant conducted once a year.
3) Environmental audits conducted by some customers of steel products.
4) Industrial inspections conducted by the Federal Attorney Office of Environmental Protection (i.e. PROFEPA) in Mexico
5) Adaptation of current technologies for water extraction and discharge plants
6) Oil recycling and treatment for uses in other industrial activities
7) Substitution of oils for natural gas in instances whereby the production process can be adjusted.
8) Steel slag recycling and uses in other industrial activities.

The environmental activity in point 8) above belongs to an environmental scheme known as regulatory technical instruments (ITN). This environmental

[83] [II.A2C.20.06.2008].

scheme[84] was established in 2003 and allows reuses of steel slag in other industrial activities[85] with consequential energy savings, re-utilisation of materials, and cost reductions in industrial processes,[86].[87]

Steel production in some niche-export markets requires an environmental certification process. These environmental standards relate to the specification of cadmium, chromium, and mercury content in alloy steels used in the engineering and automobile sectors and specialised steels merchandised in European markets,[88],[89].[90] Company Centaury confines and disposes steel scrap contained in the body of lamps at the end of the useful life in view of the mercury content not suitable for niche-export markets.

Company Centaury has obtained a certification of clean industry by the Federal Attorney Office of Environmental Protection in Mexico (PROFEPA). This certification is based on a systematic inspection of the procedures in the company in order to comply with environmental norms defined in the Mexican legislation. The purpose of this certification is to detect at an early stage contingent risk situations in order to implement a preventive approach to environmental pollution. The company is continually screening for potential irregularities in plant operations. Afterwards, the company elaborates on a programme by which corrective environmental practices are scheduled.

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[84] ITN CVSC-ITN02-2003 concerns the "management of steel slag in iron and steel production, and manganese and silicon-ferroalloys.

[85] Asphalt foundations in motorways, raw materials in buildings, cement and concrete manufacturing, etc.

[86] Cámara Nacional de la Industria del Hierro y el Acero (CANACERO), (2006): Norman SEMARNAT y CANACERO el Uso Industrial de las Escorias Siderúrgicas, Internal Communication.

[87] El Financiero, (2007): En Vigor, Norma Ambiental para Reciclar los Desechos de la Producción de Hierro y Acero, Suplemento Comercial, Industria Siderúrgica, p. 10, México.

[88] European Confederation of Iron & Steel Industries (EUROFER), (2008a): EUROFER Position Paper on Steel Welding Wire, 14th November.

[89] European Confederation of Iron & Steel Industries (EUROFER), (2008b): EUROFER Position Paper Determining the Borderline Between Preparation/articles for Steel and Steel Products, Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) in the Regulation (EC) No. 1907/2006 of the European Parliament and of the Council of 18 December 2006, 28th October.

[90] Op. Cit [50]. Consejo Coordinador Empresarial, (2005), Política Ambiental y Eco-Eficiencia en la Industria: Nuevos Desafíos en México, Internal Document.

6.5.2 The Organisation of Environmental Activities

In total, eight people in company Centaury are directly responsible for the implementation of eco-efficiency guidelines in the five plants. These personnel have the attribution of defining the normative aspect (i.e. the guidelines and procedures) of the environmental and safety corporate policy. Each plant has a work scheme based on a concept which is regarded as *"self-directed natural teams*". This work scheme has been recently adjusted as part of the organisational adjustment in the company and is still an ongoing process. In turn, there is a person in each team who is delegated the responsibility of coordinating environmental conservation and safety activities at the interior of each team in daily operations. Each environmental agent in a team aims at making the rest of the people aware of the procedures of the environmental system.

The implementation of a work scheme based on teams has implied a significant effort. The challenge has consisted of making the corporate environmental guidelines widely accessible to all the personnel in the company. This has entailed a process of cultural change in the work environment. Bringing new ideas into the improvement of environmental activities is conceived in company Centaury as a driver towards best environmental practice.[91]

6.5.3 Opportunities to Reduce Carbon Emissions

The use of a comprehensive energy management; technological innovation in direct reduction processes; and optimal gas recovery systems contributed significantly to lower the energy consumption.[92] However, two environmental managers commented that the requirement of additionality in the Clean Development Mechanisms (CDM) works regressively in view of the energy projects already implemented.[93]. This is an example of an organisational and technical barrier to further lower the energy consumption in direct reductions processes using a CDM project.

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[91] [II.A2C.20.06.2008].
[92] Alpha Centaury, Nuestra Empresa, Medio Ambiente, July 2009.
[93] [II.A2C.20.06.2008] and [II.A3.13.04.2007].

Company Centaury implemented technical improvements in order to selectively remove carbon dioxide in direct reduction reactors at the beginning of the 1980's. Further improvements were made to recover heat in the furnaces in 2005. Carbon dioxide recovery in direct reduction reactors and heat recovery in furnaces were part of retrofit projects driven by financial returns and included in the eco-efficiency activities of the company.[94]

Potential opportunities to curb carbon emissions are identified in the following three areas:

a) Full reconversion of the electrical system (i.e. motors and lights).[95]

b) Electricity savings in the office spaces of the overall steel sector entirely attributed to work on culture.[96]

c) Further improvements in electricity uses in electric arc furnaces[97] with consequential reductions in carbon emissions.

The work on a culture of energy savings of the steel sector as a whole was one of the proposals for a CDM project but a lack of interest by some authorities both private and governmental appears as an institutional barrier.

The company is currently looking for alternative energy sources in the production of sponge iron. Also, the following alternatives are identified as not feasible at the moment:

1. Biomass and tree plantations for wood gasification.
2. Insufficient waste gasification regarding the energy requirements in direct iron reduction.
3. Insufficient gasification from oil recycling regarding the energy requirement in direct iron reduction.

The following alternatives offer some energy potential in the future:

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[94] [II.A2C.20.06.2008].
[95] [II.A2B.19.06.2008].
[96] [II.O2.18.04.2007].
[97] Op. Cit [89].

1. Increasing the capacity of wind energy though the use of renewable energy contracts is not fully implemented..
2. Biodiesel the use of which requires specification of organic crops and cane waste.

The following energy sources are currently attractive for the company:

1. Imports of non-metallurgical coal although this would require the design of logistics for transportation and handling of coal. This would require a coal gasification unit to produce synthesis gas as an input in the direct reduction process.
2. Reconversion of the refinery plants in order to manufacture pet coke in the energy sector in Mexico. Pet coke, in turn, could be used as an alternative energy source in the steel industry via a gasification unit.

6.6 Summary of the Chapter

Company Centaury became a subsidiary of Alpha Centaury in 2005 and new investment was allocated for two millions tones of additional steel production capacity. An acquisition strategy spurred growth in steel production and sales accounting for 23.6% in the period 2006-2008.

Specialized steels are produced in an integrated steel process using direct reduction reactors and electric arc furnaces. Electricity and natural gas are the main energy inputs used for steel production. Pellets are the main raw materials used in direct iron reduction. However, a demand contraction of plain steels also reduced pellet production the decrease which amounted to -3.2% in 2008.

The cost of raw materials and electricity are very significant in the cost structure of the overall iron and steel industry. An increasing trend in the cost of natural gas and electricity is found as a critical economic driver on the need to find alternative energy sources. In the case of Company Centaury, an increase in the cost of steel scrap may motivate the use of higher sponge iron content in the load of an electric arc furnace. However, since natural gas is a basic energy input in the production of sponge iron, an increasing cost of natural gas raises concern on overall energy costs. Hence there is an inter-relationship between uses of raw materials and energy commodities wherein the need to economize on the cost structure is a critical driver to lower the energy consumption.

Another important driver to energy efficiency is the expectation to increase steel production capacity since energy retrofit projects come along with the up-grading of steel processes. However, it was found that return on production capacity investments is faster than energy efficiency retrofits. Thus a priority strategy on the expansion of production capacity may represent a persistent barrier to energy efficiency.

Technological improvements were documented in section 6.3 as key technical drivers to lowering the specific energy consumption. The following technological improvements consist of:

1) COREX ® gases from a coal gasification unit to provide heat in direct reduction processes.
2) Self electricity generation using reformation gases and steam generated in direct reduction processes.
3) Uses of HYTEMP loaded directly into electric arc furnaces.
4) A demand for quality of steels in terms of percentage of sponge iron, high carbon content, and degree of metallization.
5) Implementation of continuous fed of sponge iron at variable speed.
6) Uses of steel scrap in the melting process of a semi-integrated plant.
7) Integration of HYTEMP into the operation of a new DANIELLI ® DC electric arc furnace.
8) Uses of oxygen lancing in electric arc furnaces to provide additional heat.
9) Foamy slag practice to enlarge the arc of an electric arc furnace and thus providing additional heat.

10) Uses of continuous casting as opposed to traditional energy intensive ingot casting.

Company Centaury followed a trajectory of technological innovation in direct reduction processes. This represented a technological driver the contribution of which lowered the specific energy consumption with the energy integration of practices 2 and 3 as listed above.

Also, the technology ownership codified in a patent reduces future investments and lowers the energy consumption thus technology development contributing to raise the energy efficiency of steelmaking processes.

The performance of Company Centaury shows an environmental responsiveness as is the case of the implementation of an integrated environmental management system and the use of a preventive and eco-efficiency approach. In this latter case, lowering the energy consumption is seen as an environmental strategy.

Most of the technical and organizational improvements which lowered the energy consumption cannot be claimed as part of CDM project in view of the additonality principle. However, the following potential opportunities to reduce carbon emissions are identified:

1) Reconversion of the electrical system.
2) Electricity savings in office spaces due to work on culture.
3) Further energy efficiency improvements in electric arc furnaces.
4) Capacity expansion of wind electricity used in steel processes.
5) Uses of biodiesel in niche energy markets.

Chapter 7

Growth in Slab Production and Integration of Energy Requirements: the Case of Company Perseus Mexico Facilities

Background

Perseus Mexico Facilities is a subsidiary of Perseus GROUP. Perseus GROUP is one of the largest steel producers in the world with production facilities in North, Central, and South America; Western and Eastern Europe, and Africa. Perseus Mexico Facilities is currently the largest producer of steel products in Mexico. This company is a subsidiary which consolidated as a result of an acquisition and integration process. This re-structuring process commenced in early 1990's and, along this period, Perseus Mexico facilities capitalised on strength and growth in steel production. This case study shows how this subsidiary company has overcome some inefficiency processes and established a sustainable route of growth in steel production. Energy integration of an overall steelmaking process in this subsidiary company is the result of vertical integration and the restructuring of the steel sector in Mexico. Furthermore, this case study highlights how an "unexpected" technological discontinuity was the origin of an acquisition process and internationalisation of operations.

7.1 Company Acquisition and Integration Process

Solaris I was built as a public owned steel company during the 1970's the purpose of which was to meet insufficient supply of steels in the domestic market. The company started up operations in 1976 as part of a governmental initiative.[98] The design of this plant consisted of a primary integrated steel plant with the use of blast furnaces and

[98] Guzmán Chávez, Alenka, (2002): Las Fuentes del Crecimiento en la Siderurgia Mexicana. Innovación Productividad y Competitividad,Universidad Autónoma Metropolitana, Iztapalapa-Miguel Ángel Porrua, México, D.F.

basic oxygen converters. In addition, the Mexican government decided to invest in the expansion of steel production capacity with the building of a new plant called Solaris II in 1980. The original design of plant layout in Solaris II consisted of:

1) Pellet plant
2) HYL-III DRI plant
3) Four electric arc furnaces
4) Casters
5) A plate mill

Additional steel capacity was planned in order to produce slabs for the manufacturing of plate and pipes. Demand for pipes was growing during the 1970's due to an expanding infrastructure of the oil industry in Mexico. However, growth in the oil industry began to decrease at the beginning of the 1980s. This external factor combined with an economic recession in Mexico in 1982 put pressure on the government to meet the former investment plans for the completion of Solaris II. The government decided to reduce public investment and the building of a pellet plant and rolling mill was cancelled.[99] Two major technological discontinuities appeared as a result of insufficient capital investment:

1) Solaris II purchased pellets in the commodity markets and this increased production costs and created economic inefficiencies in the company (i.e. vertical disintegration in steel production).

2) Production of plates and pipes was truncated due to the unavailability of a rolling mill.

The management in Solaris II decided to produce and sale slabs (i.e. a semi-finished product) to producers of final steel products.

A planned production capacity accounting for two million tonnes of steel never took place and this created operative inefficiencies and economic losses. Under these circumstances, the Mexican government decided to make a public bid and put Solaris II on offer. A downturn economic 'climate' and operative inefficiencies due to technological discontinuities represented the premises of a process of privatisation of the steel sector.

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[99] (Name omitted), The Extraordinary Story of Mycenae, Rediff, Business, Special, March 17th, 2005.

This represented an external factor due to contraction in the oil markets leading to a re-organisation and change of ownership in the company. As it will be shown later in this section, this is a type of morphogenic change (section 4.4 in chapter 4) which took place after the acquisition of PERSEUS Mexico facilities.

After eight moths of negotiation with the Mexican government, Mycenae (now Perseus GROUP) completed the acquisition of Solaris II on January the first, 1992.[100] Solaris II took the name of Galapagos (now Perseus Mexico facilities) after the acquisition process. The acquisition comprised the following auxiliary facilities:[101]

- 50% control of Molino Rojo iron ore mines and pellet plants. The control of these mines is shared with company Centaury (Chapter 6)
- 50% control of captive port facilities (i.e. Balloons Corporation)
- 50% control of an industrial gas/service supplier by which raw materials are purchased at production costs prices
- 50% control of lime-materials supplier

The acquisition included a commitment on expenditure by part of company Irving International (later on known as Mycenae and currently Perseus GROUP) of around 50 US million dollars in capital through a five year period after the acquisition. In addition, 300 US million dollars were invested for the building of a hot rolling mill. As a result of these financial commitments, 525 US million dollars were invested (i.e. Greenfield) by Galapagos (now Perseus Mexico facilities) in the construction of a pellet plant and a direct reduction reactor in 1996 and 1997, respectively.[102] Although the building of hot strip rolling mill went ahead, Perseus Mexico facilities consolidated its position in slab production.

The overcoming of operative inefficiencies and economic loses appeared as a critical economic driver leading to a change in the company ownership and the successive organisational restructuring. The lack of access to capital

[100] Op. Cit [1].
[101] Irving International, Form:20-F/A Filing Date: 4/9/2004, Item 4, Information of the Company, EDGAR® Online.
[102] Op. Cit [3].

financing appeared as a barrier to the expansion of the technological infrastructure in this company and thus hindered the manufacture of finished and high quality steel products.

This financial barrier was overcome with foreign direct investment, and as a result of this, some stages in the production process were up-graded with new steelmaking technologies. Solaris II under the management of Perseus Mexico became the largest slab producer in the world this being more the result of a technological discontinuity (i.e. a historical accident) rather than a plan. This arrangement resulted in two integrated plants located in the same vicinity but managed by different firms: Solaris I plant (i.e. Mexican capital ownership) and Perseus Mexico facilities (i.e. a subsidiary of Perseus GROUP).

This was not the end of a restructuring process and globalisation of the steel sector in Mexico. In effect, the Perseus GROUP made a public announcement of a purchase of Solaris I as of 20th December 2006. The value of this operation accounted for 1,439 US million dollars by which Perseus GROUP acquired 50% control. In addition, GRUPO Oasis in Mexico was a major shareholder in Solaris I. At the end of 2006, GRUPO Solaris made a public announcement of future plans of the company to make a strategic alliance or sell the corresponding share.[103] A final outcome of this process consisted of the acquisition of GRUPO Oasis's shares by Perseus GROUP in April 2007.[104]

Perseus Mexico facilities increased its production capacity to 6.7 million tonnes of steel per year. Part of this production capacity (2.7 million tonnes) corresponded to Solaris I.[105] Hence the growth in Perseus Mexico steel production relied on a strategy of mergers and acquisitions all through the 1990's. A chronology of changes expanding the technology configuration of this subsidiary company in Mexico is presented in table 7.1.

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[103] Económico, Vendería Grupo Oasis participación de Solaris, El Pervener.com 90 Aniversario, Wednesday 4th October, 2006.

[104] Perseus Group, Bold Future, 2007, Building our company with the needs of future generations in mind, Activity Report, 2007, p. 12.

[105] Las 10 mayores compras en México, Perseus Group compra Solaris, Monday 30th April 2007 at 13:34 hrs.

Year	Inflexion Point
1988	The company was born as an expansion to Government owned Solaris I, and this was called Solaris II.
1991	Solaris I was privatised as Irving Mexico, a member of Irving International
1995	Backward (technological) integration – pellet plant
1996	DRI capacity expansion – MIDREX® plant
2004	Steel plant sets a new record of liquid steel production 4 MTPA; MIDREX® plant sets a record of 1.74 MTPA – highest production ever from any single module of MIDREX ® plant world over.
2005	Irving International transformed to Mycenae Company and Galapagos became Mycenae Mexico facilities, Commissioning of Oxygen plant.
2006	Merger of Mycenae and Perseus GROUP; Agreement for acquisition of Solaris I; ISO/TS 16949 certification
2007	Mars Mines, in the SONORA State of Mexico – start-up

Source: Perseus Group in Mexico, Investor's Day, 28th March, 2007.

Table 7.1 – A Brief History of Perseus Mexico Facilities

7.2 Global Presence and Holdings of the Parent Company

The Perseus Group has global operations with production accounting for 116 million tonnes of steel worldwide and sales valued at 105.2 billion US dollars in 2007. Industrial operations cover 20 countries and employ 320,000 people in 60 countries. Steel production is mostly localised in Europe (34%), followed by North America (i.e. United States and Canada account for 21%), Latin America (15%), Central and Eastern Europe (13%), Community of Independent States and Central Asia (10%), and Africa (7%).

Figure 7.1 presents worldwide steel production of Perseus Group during the period 1989-2008. Crude steel production sharply rose from 58,000 to 102,866 thousand tonnes between 2004 and 2005 which represented 77% growth. This change in production was the result of a business strategy of Perseus Group. This consisted in increasing the scale of operations, vertical integration, diversification of products, and continuous product growth with higher value added.[106] In particular, Perseus Group and Mycenae completed a merger in 2006 and production of both companies was integrated into a combined financial operation in 2007.[107]

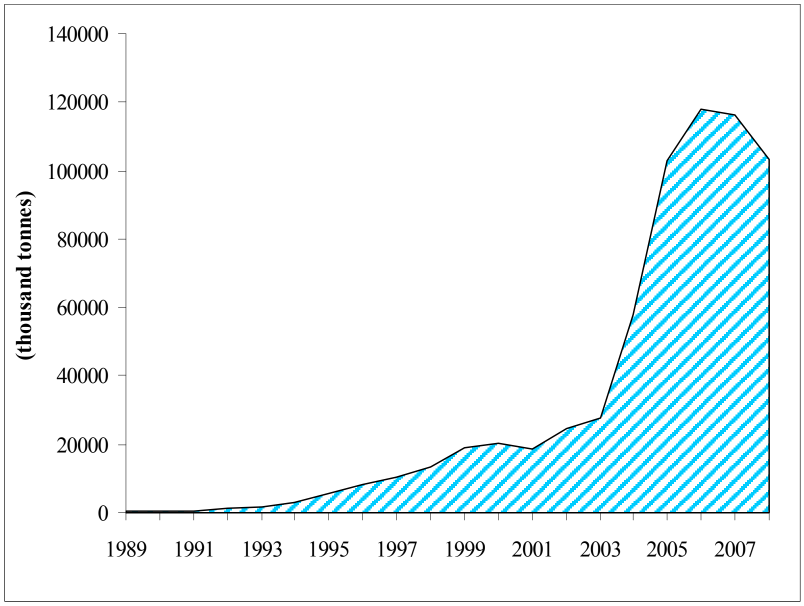

Figure 7.1 – World Steel Production, Perseus Group,[108] 1989-2008 (thousand tonnes)

Source: Perseus Group, Analyst and Investor Day, 2005; Perseus Group, Fact Book, 2007 and 2008.

By implementing a merger and acquisition strategy, the company consolidated a strong path of growth worldwide. A focus was based on consolidating steelmaking operations and the creation of synergies.[109] The Perseus Group is the largest steel manufacturer in the world with 103.3 millions tonnes of steel production in 2008. This accounted for 10% of total world steel output.[110]

Production in Perseus Mexico facilities amounted to 5.2 millions tonnes of steel in 2007.[111] This figure represented 4.5% of overall worldwide steel production

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[106] Perseus Group Fact Book 2006, 67 pp.
[107] Perseus Group, Bold Future 2007, Building our company with the Needs of Future Generations in Mind, Fact Book 2006, 156 pp.
[108] Perseus Group, Analyst and Investor Day, 2005, and Perseus Mexico facilites, Fact book, 2007, 2007, 2008.
[109] Op. Cit [10].
[110] Perseus Group, Safe Sustainable Steel, Fact Book 2008.
[111] INEGI, La Industria Siderúrgica en México, Edición 2008, 149 pp.

of the Group. Mexico steel facilities are strategic in terms of specialised steel products for niche markets in the Americas consisting of flat and long carbon steels.

The list of holdings of Perseus Group consists of the following six operating segments worldwide:

1) Flat Carbon Americas
2) Flat Carbon Europe
3) Long Carbon Americas & Europe
4) Asia, Africa, Commonwealth of Independent States and Balkans
5) Stainless
6) Perseus Steel Services & Solutions

The flat carbon Americas segment is integrated by steel facilities in Brazil, Canada, Mexico, and the United States. In addition, the Mexico facilities include long carbon steel production as part of the long carbon Americas segment.[112]

7.3 Market Performance and Specialisation in Mexico Facilities

Production of iron ore concentrate decreased from 3.4 to 3 million tonnes between 2006 and 2007, and at the same time, production of long steel products also dropped from 1.4 to 1.1 millions tonnes, the contraction of which accounted for -21.4%. On the other hand, production of high quality slabs increased from 3.5 to 3.7 million tonnes, representing a 5.7 growth in 2006 (Figure 7.2).[113] Production of slabs for plate application is very specialised worldwide. In general, plate applications of slabs consist of API Grades X70 and X80; drawing steel; pressure vessels; heat treat; and armour grades.[114]

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[112] Op. Cit [12].
[113] Perseus Group in Mexico, Investor's Day, 28th March 2007.
[114] Op. Cit [16], World's Leading Supplier of Slabs for Plate Application.

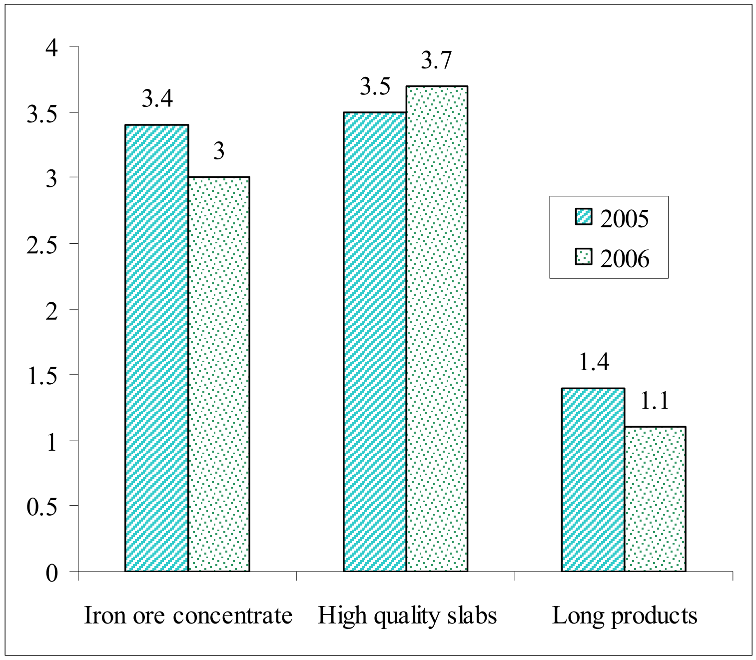

Figure 7.2 – Steel Production in Perseus Mexico facilities, 2005-2006

Source: Perseus Group, Fact Book 2006.

The Mexico facility was the fourth major subsidiary in terms of shipments of flat steels in 2004 (i.e. 4,223 thousand tonnes). The largest amount of steel shipments were attributed to South Africa subsidiary (i.e. 6,835 thousand tonnes), followed by the Polish subsidiary (i.e. 6,654 thousand tonnes), and the Galiti (Romania) subsidiary (i.e. 4,462 thousand tonnes) in the same year (table 7.2). Shipments from the twelve facilities in Perseus Group amounted 36,681 thousand tonnes of steel in total of which shipments from Mexico facilities represented 11.5%. A substantial growth in steel production took place after the year of acquisition in the majority of steel facilities (columns 6 and 7 in table 7.2). Shipments of flat steels in Mexico facilities increased from 526 thousand tonnes to 4,223 thousand tonnes during 1992-2004 which represented annual16% growth in the period.

Operating Subsidiary	Year aquired	Location	Product	Production process	Year before acquisition	In 2004
Point Lisas	1989	Trinidad & Tobago	Long	EAF	395	785
Perseus Mexico	1992	Mexico	Flat	EAF	526	4,223
Hamburg	1995	Germany	Long	EAF	936	1,141
Contrecoeur	1995	Canada	Flat / Long	EAF	1,294	1,493
Termirtau	1995	Kazakhstan	Flat	BOB	2,532	4,146
Ruhrort/Hochfeld	1997	Germany	Long	BOF	1,553	1,479
Gandrange	1999	France	Long	EAF	1,361	1,307
Annaba	2001	Algeria	Flat / Long	BOF	913	964
Galati	2001	Romania	Flat / Long	BOF	3,352	4,462
South Africa	2001	South Africa	Flat / Long	BOF/EAF	5,825	6,835
Ostrava	2003	Czech Republic	Flat / Long	BOF	2,804	3,192
Poland	2004	Poland	Flat / Long	BOF	6,026	6,654
TOTAL shipments					27,517	36,681

Table 7.2 – Turnaround Track Record, Steel Shipments, Perseus Group, 2004

Source: Mycenae Company, Analysis and Investor Day, 23rd February 2005.[115]

7.4 Description of Steelmaking Processes

7.4.1 Primary Integrated Steelmaking

After the acquisition process, Perseus Mexico facilities consisted of an integrated process of primary and secondary steelmaking the process of which are explained in Chapter 2. The technology configuration of primary steelmaking in this company is as follows (figure 7.3):

1) Mine (with a slurry pipeline)
2) Pellet plant
3) Coking plant
4) Blast furnace
5) Cupola furnace
6) Melting shop (basic oxygen furnace)
7) Continuous casting machine
8) Rolling mills

[115] Shipments.

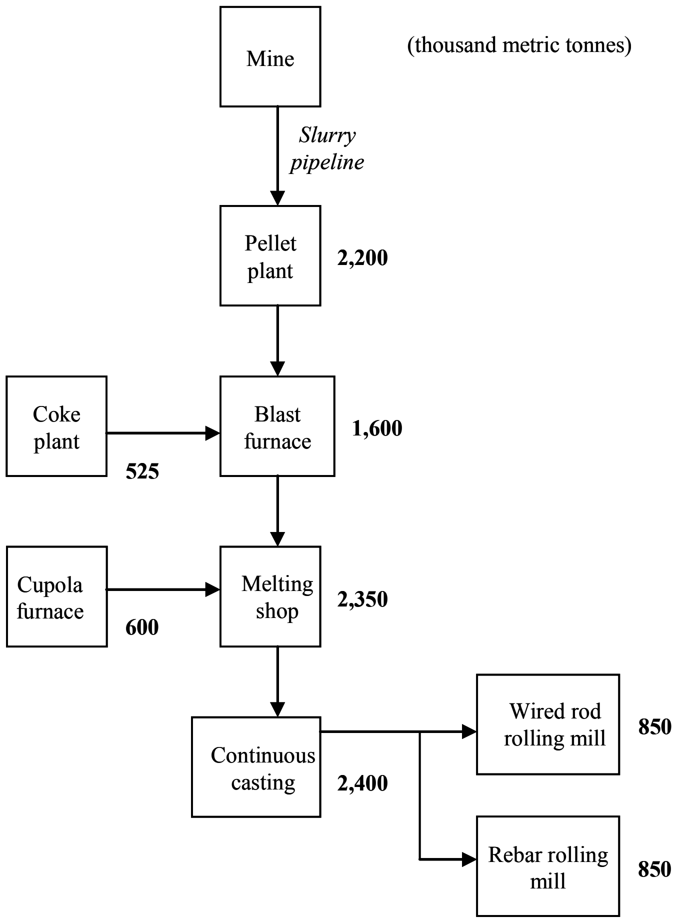

Figure 7.3 – Primary Integrated Steelmaking in Perseus Mexico facilities,[116] 2006 (thousand metric tonnes)

Auxiliary facilities provide iron ore concentrate, pellets, and metallurgical coke to the blast furnace. Upstream operations, i.e. production capacity of the pellet and coking plant accounted for 2,200 and 525 thousand metric tonnes of pellets and coke, respectively, in 2005. These materials are delivered to the blast furnace of which production capacity amounted 1,600 thousand metric tonnes of pig iron in 2005. In addition, pig iron production is complemented with production of hot molten iron in a cupola furnace of which production capacity accounted for 600 thousand metric tonnes in the same year. Both pig iron and hot molten iron are

[116] Perseus Group in Mexico, Investor's Day, 28th March 2007.

delivered to the melting shop. The melting shop consists of production of liquid steel by means of two basic oxygen converters (BOF) of which overall production capacity amounted 2,350 thousand tonnes of liquid steel in 2005.

Downstream operations include liquid steel which is delivered to three continuous casting machines with overall production capacity of 2,400 thousand tonnes of cast steel. Cast steel represents a proportion of slabs which is allocated to shipments for export markets. The final stage corresponds to a wire rod rolling mill (i.e. 850 thousand metric tonnes production capacity) and rebar rolling mill (i.e. 850 thousand metric tonnes production capacity) in 2005.

7.4.2 Secondary Integrated Steelmaking

After investment in additional steel capacity and revamping of the Solaris II plant, the technology configuration is as follows:

1. Port facilities (i.e. raw materials reception and distribution channels)
2. Iron ore mines pellet plant
3. Direct reduction plant 1 (i.e. HYL-III ® reactor)
4. Direct reduction plant 2 (i.e. MIDREX ® reactor)
5. Melting shop (i.e. four electric arc furnaces)
6. Vacuum degassing
7. Two ladle furnaces
8. RH – TL degasser furnace
9. Two continuous casting machines
10. Slab delivery (i.e. distribution channels)

Perseus Mexico facilities control 50% of Molino Rojo mines. The provision of iron ore was further enhanced with the start-up of Mars mines in the Sonora state of Mexico in 2007. Future plans for iron ore operations and expansion include Dessert-by-the-sea and Homero mines. Currently, Santa Cruz mines located in Homero are totally controlled by company Centaury (Chapter 6).

Table 7.3 contains data on estimated reserves for the four mines as discussed above. Molino Rojo mines represent the largest estimated reserve of iron ore as of 2006. The quality of future iron ore from the Homero mines contains around 64% of iron (Fe) in the total overall geological reserve. However, it is expected that the majority of iron ore production will still be supplied by Molino Rojo mines (i.e. 46 millions tonnes). In addition, the last row of table 7.3 compares the investment required for future exploitation of the referred iron ore mines. Mars mines require the highest investment accounting for 64 million current US dollars, followed by Dessert-by-the-sea mines (i.e. 60.7 million US dollars), and Homero mines (i.e. 32.7 million US dollars).

Item / mine	Mars	Dessert-by-the-sea	Homero	Molino Rojo
Geological Reserves Estimated (million tonnes)	28	41	26	110
Mineable Reserves Estimated (million tonnes)	25	37	20	92
Ore Expected Quality in Geological Reserves (Fe total)	55%	57%	64%	46%
Expected Production (million tonnes/year)	2.0	1.5	1.0	2.2
Expected Total Production Concentrate (million tonnes)	17.5	22.2	13.0	46.0
Estimated cost/tonne (US dollars) landed port	30.5	21.9	21.3	21.6
Estimated Investment (million US dollars)	64.0	60.7	32.7	0.0

Table 7.3 – Iron Ore Operation and Expansion, Perseus Mexico facilities, 2006

Source: Perseus Group in Mexico, Investor's Day, 28th March 2007.

Figure 7.4 presents the operations of secondary steelmaking in this company in Mexico. Production capacity of Molino Rojo amounted 2,000 thousand tonnes of iron ore as of 2006. The rest of raw materials (steel scrap) are supplied via deliveries through the port facilities. Production capacity of the pellet plant amounted 3,700 thousand tonnes per year. Pet coke is the main energy input required in the operation of the pellet plant. This fuel is employed in a kiln furnace during a hardening process.

In turn, pellets are supplied from the pellet plant to the two direct iron reduction plants for the production of sponge iron. One direct reduction plant corresponds to HYL-III ® reactor with production capacity of 2,400 thousand tonnes of sponge iron. Another direct reduction plant corresponds to MIDREX ® reactor with production capacity of 1,700 thousand tonnes of sponge iron in 2006.

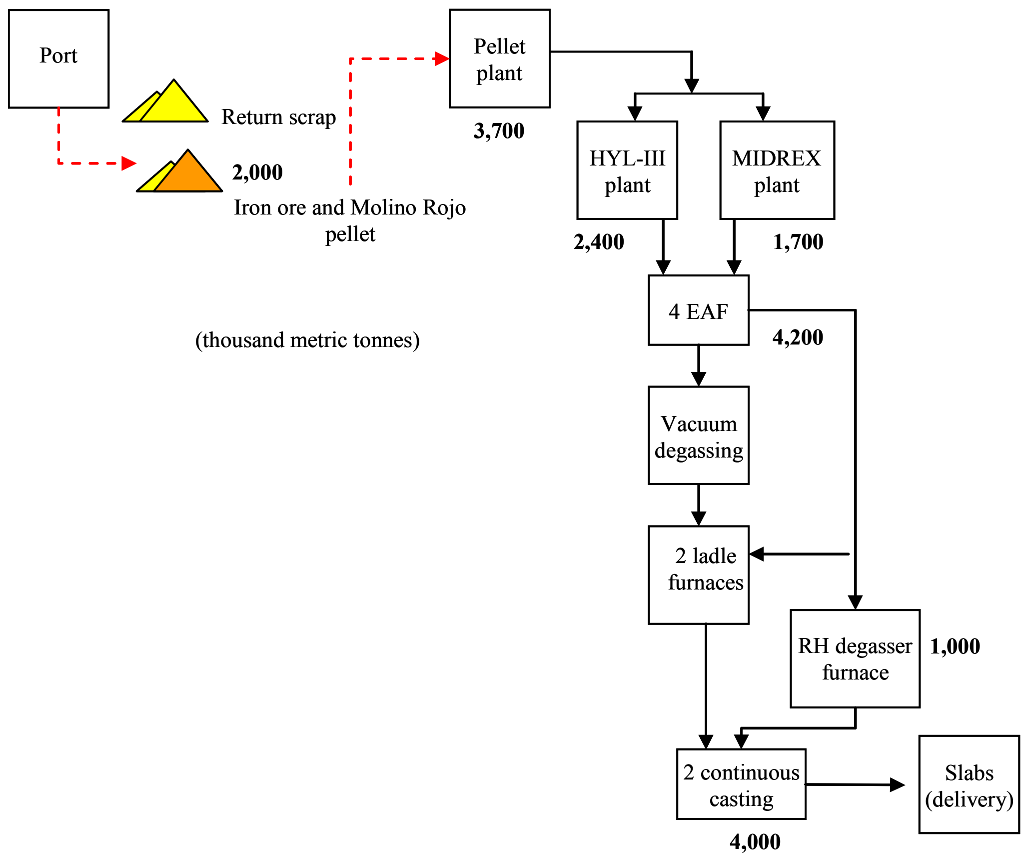

Figure 7.4 – Secondary Integrated Steelmaking in Perseus Mexico facilities, 2005 (thousand metric tonnes)

Source: Perseus Group in Mexico, Investor's Day, 28th March 2007 and Fact Book 2006.

There are several critical issues flagged out at this stage of the integrated steelmaking process. Firstly, it is observed both the production of pig iron via a blast furnace and sponge iron via direct reduction reactors. Production capacity for sponge iron (i.e. 4,100 thousand tonnes) is larger than pig iron production capacity (1,600 thousand tonnes). In other words, sponge iron production is 2.56 times pig iron production in this facility. This is the only facility in Mexico with both primary and secondary steelmaking technologies.

Secondly, both direct iron making technologies HYL-III ® and MIDREX ® coexist in the operation of direct reduction reactors. This is a critical feature because in direct iron making processes, MIDREX represents a technological alternative to

HYL-III. This subsidiary facility does not produce or market direct reduction technologies as was the case of company Centaury. However, some practices which support energy savings as in the case of company Centaury are also implemented in this subsidiary facility.

Thirdly, there is a delimitation of steel products according to the technology configuration observed in this company:

1) Blast furnace – basic oxygen converter for the production of wire rod and rebar (i.e. this last product is also referred as re-enforcing bar used in buildings)
2) Direct reduction iron reactors – electric arc furnaces which are employed in slab production and subsequent shipments for export markets.

Natural gas is the main energy input in the reformers of both HYL-III and MIDREX reactors. Recovery off-gasses as previously explained in chapter 6 (section 6.3.1) are employed in the reformers and boilers of the HYL-III reactor in this plant. Energy requirements and the corresponding intensity are largely related to the operation of these steelmaking technologies in the company.

Downstream operations include a melting shop of four electric arc furnaces with 150 MVA transformers. Overall production capacity of the four blast furnaces accounted for 4,200 thousand tonnes of liquid steel in 2005. Some steel scrap is part of the charge in four electric arc furnaces which affects electricity consumption as explained in chapter 6. Other import raw materials in electric arc furnace operations in this plant are anthracite coke, graphite, and electrodes. In addition, the melting shop is integrated with two ladle furnaces of which heating is achieved by combustion of natural gas and pet coke.[117]

The next stage consists of a vacuum degasser and a new RH (Ruhrstahl-Heraeus) – TL degasser furnace with production capacity of 1,000 thousand tonnes of slabs. A RH degasser furnace was part of a budget allocated for capital expenditures in Perseus Group in 2004 in order to up-grade the production

[117] Reporte de Emisiones de CO_2, Perseus Mexico facilities 2005, Environmental Department, Quality and Technology, September 2006.

capabilities of this facility in Mexico.[118] The purpose of the vacuum degasser furnace consists of injecting calcium and aluminium during slab production. This practice enhances the quality of slab production for specialised steel applications (i.e. automobile manufacturing, line pipe, shipbuilding, and electrical appliances).[119] The final stage downstream manufacturing operations comprises two continuous casting machines with overall production capacity of 4,000 thousand tonnes of slabs. Natural gas is used to preheat the burners in the continuous casting machine and as a gas cutting torch to divide the cast slab in sections at the end of the casting process. Electricity is also used in continuous casting although the majority of electricity requirements correspond to electric arc furnace operations.

This steel facility is also equipped with a thermal power plant with two integrated boilers. Natural gas, fuel oil, and steam are used in a combined heat and power (CHP) plant for electricity generation on site. According to available industry data, the thermal power station consists of two-140-tonnes/hour steam boilers and two steam-driven turbo-generators. Declared production capacity accounts for 40 Mega Watts (i.e. 20 Mega Watts each unit) and reported electricity output amounting 88.24 GWh in 2003.[120]

7.5 Opportunities to Lower Energy Consumption

Electricity and natural gas are the most critical energy sources employed in the production of slabs in this company. The operation of four electric arc furnaces demands the majority of electricity requirements in this integrated steel plant. An energy manager in this company commented that the amount of kWh per tonne of liquid steel in an electric arc furnace depends on the type of raw materials used.[121] In this facility, sponge iron with high carbon content is the main raw material in the load of an electric arc furnace.

[118] Mycenae Company, Analysis and Investor Day, 23rd February 2005, p. 61.
[119] Perseus Mexico facilities., Goliath, Business Knowledge on Demand, 26th June, 2009.
[120] Op. Cit [4].
[121] [II.A9B.06.08.2008]

This loading practice appears also to be implemented in the steel facilities of company Centaury. In this respect, high carbon content embedded in sponge iron offers the resource advantage which consists in reducing the amount of specific energy consumption in electric arc furnaces. The heat contained in sponge iron loaded in an EAF overlaps with the electricity requirements which results in a relatively less amount of kWh per tonne of steel (or specific energy consumption – SEC). A second related improvement consisted in changing the arms which hold up the electrodes in the EAF. Some electricity savings were targeted with the implementation of this device although this was not achieved in 2008.[122]

Unlike the case of the company Centaury, not all the sponge iron requirements are produced on site. Some sponge iron is purchased and also combined with a relatively small proportion of steel scrap. This company produces both high and low quality steels. Low quality steels are produced in integrated primary steelmaking (figure 7.3) whereas high quality steels consists of slabs in integrated secondary steelmaking (figure 7.4).

Sponge iron is purchased, for instance, during maintenance of the direct reduction reactors of which operation is temporarily interrupted. On average, direct reduction reactors are shut down twice a year for around eleven days for maintenance works. Maintenance comprises the replacement of catalysers, repair of compressors, revamping of leakages and refractory(s).

The operation of direct reduction plants represents a critical stage in the steelmaking process. Unlike the case of Centaury, an energy manager in this company identified a critical bottleneck in the operation of direct reduction reactors since they provide the molten iron for the production of liquid steel.[123] On the contrary, another energy manager suggested that pellet production consists of the most critical raw material in steelmaking.[124] Pellet requirements are met with imports from South America when the operation of a pellet plant in this company is interrupted. The operation of a pellet plant relies on the consumption of fuels (i.e. oil, natural gas, and coal) for the pre-heating of gases. Electricity is also required in the

[122] [II.A9B.06.08.2008]
[123] [II.A9B.2.06.08.2008].
[124] [II.A9B.06.08.2008].

operation of a pellet plant. While fulfilling the demand for pellets with imports, the energy intensity of the steelmaking process goes down in this plant.

Coke oven gas is a by-product generated in the production of metallurgical coke which, in turn, is fed into the blast furnace (figure 7.3). Although coke oven gas (COG) can be used as a reducing agent and hence representing an alternative source to natural gas, the quantity of COG is not enough for the requirements in the direct reduction reactors.[125] Two managers in this company shared the view that the physical location of the plants represents a *technical limitation (barrier)* in the use of coke oven gas as a reducing resource in the direct reduction process.[126] Some COG would require to be transported from the coking plant to the direct reduction reactors for producing sponge iron. This does not appear to be happening at present time.

A public relations (PR) manager commented that the original design of Solaris I plant in the production of long steels (i.e. the route BF – BOF) considered the use of coke oven gas (COG) for pre-heating the furnaces. Solaris I plant has a re-distribution network of coke oven gas. Blast furnace gas (BFG) is an exhausted gas from the production of pig iron. It was commented that a relatively low calorific value for BFG (i.e. 700-800 kcal per cubic meter) is not enough to provide with heat in a process.[127]

> The previous examples of different aspects of energy uses in this steel plant indicate some of the technological barriers to energy efficiency thus representing an opportunity to lower the energy consumption and carbon emissions still further. At present time these barriers relate to further reductions in the average SEC of the electric arc furnaces, future recovery of-gases (coke oven and blast furnace gases), and temporary shutdowns of utilities.

As part of the organisational change taking place after the merger, an energy team inclusive of the three energy managers interviewed during 2008[128] was assigned the task of reducing flaring practices of blast furnace gases (BFG). A process of

[125] [II.A9B.06.08.2008].
[126] [II.A9B.06.08.2008] and [II.A9B.2.06.08.2008].
[127] [II.A9B.3.06.08.2008].
[128] [II.A9B.06.08.2008], [II.A9B.2.06.08.2008], and [II.A9B.3.06.08.2008].

change was documented as reducing the volume of BFG flaring practices from 100,000 to 30,000 cubic meters per hour. A goal in the team aimed at eradicating COG flaring. Future plans include a complete COG recovery and delivery for pre-heating in the melting shop.[129]

During fieldwork visits to this facility in 2007, the public relations manager commented that energy consumption parameters were taken into account in the design of Solaris I plant during the 1970's. However, as technology has evolved, so has the additional improvements implemented in this facility. In this respect, automation and the installation of programming logic controllers (i.e. or PLC), among other technical improvements, are viewed as supportive to energy reductions in the plant.[130]

Works on the HYL ® reactor of this company were implemented in order to increase the efficiency of the plant. At a later stage, the company looked for innovative technologies driven by the owner's expectation to increase production capacity. As result, it the decision was taken to set up a MIDREX ® reactor. This technology was indicated to require less energy as compared to HYL but further steps have been implemented to lower the energy consumption in both reactors. Natural gas requirements have been curbed as result of these practices in the company.[131]

> Hence production capacity expansion in response to a growing market demand provided a critical economic driver in this company leading to the up-grade of steelmaking technologies.

These technical improvements need to be seen in a context of privatisation and increasing trade liberalisation of the steel sector in Mexico. A PR manager commented that after the privatisation of the sector, a significant investment was made on the improvement of water treatment plants and cooling water (i.e. in EAF panels, rolling mills, and heating for on-site electricity generation).[132] Overall total investment in 14 companies of the steel sector in Mexico amounted 4,365 US million

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[129] [II.A9B.06.08.2008].
[130] [II.A9.23.04.2007].
[131] [II.A9B.2.06.08.2008].
[132] [II.A9.23.04.2007].

dollars during 1996-2000.[133] The combined investment of Galapagos and GRUPO Oasis in environmental and process improvements amounted 1,509 US million dollars during this period (i.e. 34.6% of overall total investment). Uses of water for absorbing the heat in machinery are part of the maintenance utilities. It was also commented that some iron ore fines are recovered during water recycling which, in turn, are sent back to the blast furnace.

In general four aspects were identified as important needs to improve energy efficiency in this plant:

1) Effective use of all available energy flows including the re-utilisation of blast furnace and coke oven gases[134]
2) Improvements in the handling of water resources, re-utilisation, and use of water disposal from the city adjacent to the plant as part of an energy efficiency project[135]
3) Identification of improvements in natural gas consumption in the reduction process for the production of sponge iron.[136]
4) The need to do R& D into methods to improve energy efficiency. It was suggested that there is a lack of experience and that this might be addressed through establishing strong collaborative linkages with other organisations with the primary aim of promoting improvements in energy efficiency.[137]

7.6 An Organisational Framework for Energy-related Decisions

The management of the Perseus Group consists of a corporate responsibility and governance structure. The structure was designed to be simple and flexible the purpose of which is to respond quickly to new challenges and opportunities. The authority given to the corporate responsibility team (CRT) within this organisation

[133] Iron & Steel Industry in Mexico, CANACERO Report, Internal Document 2005.
[134] [II.A9B.3.06.08.2008]
[135] [II.A9B.06.08.2008]
[136] [II.A9B.2.06.08.2008].
[137] [II.A9B.3.06.08.2008].

structure is significant since there is a straight link between them and the group management board (GMB) – figure 7.5.

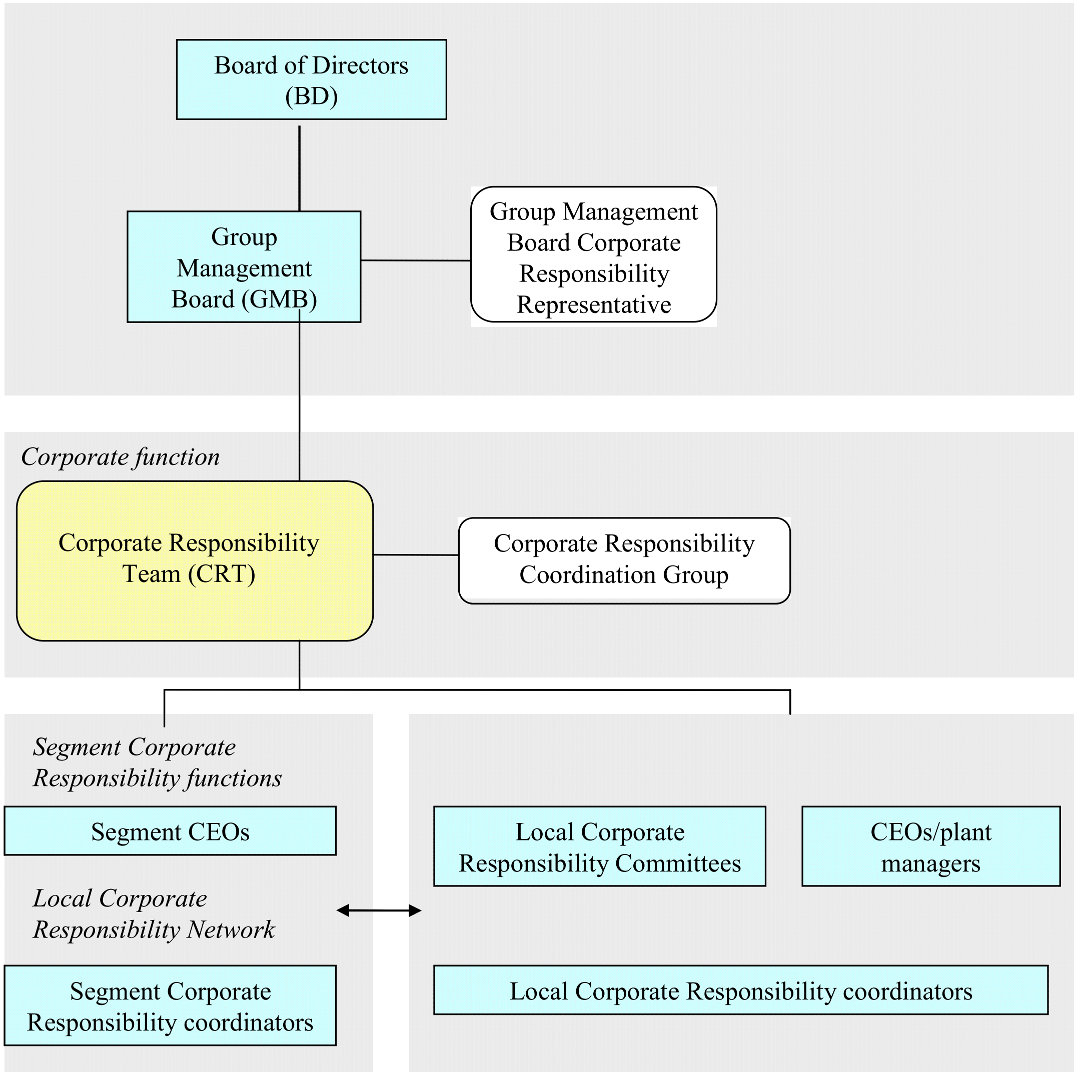

Figure 7.5 – Group Corporate Responsibility Governance Structure

Source: Perseus Group, Corporate Sustainability Report, 2008, How will we achieve safe sustainable steel?

The Board of Directors (BD) at the top of the structure oversees the functions across the company. Decision-making is an informed process wherein reporting activities flow from the operational (bottom-line) to the strategic levels of the organisation before any decision is arrived. A representative of the Corporate Responsibility Team (CRT) reports on several 'domains' of the company to the

GMB and BD every quarter and twice a year, respectively. These domains of the firm concern governance, control, strategy, communications, standards, and policies and thus representing parameters of performance. How the company will achieve sustainable steel production is at the core of the corporate responsibility and thus energy efficiency is given a critical function to mitigate climate change (Perseus Group, 2008). Energy efficiency is pursued in the Perseus Group as a sustainable strategy and this is seen as a way to reassure corporate leadership.

The CRT is also empowered to establish contact with social responsibility related stakeholders and thus having a critical role in any energy and climate change concern expressed by such groups (i.e. NGOs).

At the very bottom-line of the organisational structure operates the segment and local corporate responsibility coordinators. Various coordinators are arranged in local corporate responsibility committees. These committees together with CEOs and plant managers are empowered to establish a management framework according to local conditions. The role of these agents is very critical since they have the responsibility to implement the energy efficiency master plan (in section 7.8) and to ensure the corporate energy policy is implemented in a way that best shows the priorities at the local level.

The executive committee and the energy team are part of the local corporate responsibility committees at Perseus Mexico facilities. They look for a series of opportunities and propose a series of corrective measures to increase the efficiency of production processes and lower energy consumption. They transmit to the CRT what they identify as critical needs to improve energy efficiency and negotiate with the CRT the allocation of a budget to carry on with the current needs in the plant.

The CRT supports both the executive committee and the energy team in building capacity and sharing best practices. At the same time, the CRT receives advice from the corporate responsibility coordination group (CRCG) in the setting of standards, risk assessment, the revision of social and environmental trends, monitoring of strategies, and so on. Ultimately, the CRT authorises the decision of a series of energy efficiency measures to proceed and the corresponding budget allocation.

As an example, the energy team may want to establish a long term relationship with the suppliers of energy efficiency technologies. The energy team may want to start with the measurement of energy consumption within an energy management programme. They may not only want to set up a programme but be responsible for the maintenance over a lifecycle. At an early stage of a programme the plant obtains electricity savings from implementing technology A. However, at a later stage the plant not only achieves energy savings but actually up-grades the facility so they kind of modernise. The CRT assesses the performance of the energy efficiency investment so they authorise over the course of a period if current energy savings can fund subsequent capital improvements.

During the world financial crisis in 2009 the Perseus Group had to take critical decisions thus giving priority to other critical needs. In this latter case, adjustment measures were strongly motivated by reducing the risk of economic loses, clearly an economic driver. This included fixed cost reductions, managing cash, lowering levels of operation, and stopping current projects. Energy efficiency management programmes were affected or delayed at the same time of delaying an ongoing development of a long term corporate responsibility strategy. The priority given to these strategies of operational adjustment in the Group affected the efficiency of some steel processes. For instance, hard decisions were made to temporarily shut down of blast furnaces in some plants of the group and this was seen as a risky operation with significant energy loses.

7.7 Rules-of-thumb in the Procurement of Energy Commodities

7.7.1 Example 1: Provision of steel scrap

The company has a department at the corporate level (i.e. the headquarters) which is searching for market opportunities in order to procure from steel scrap at lower prices worldwide. This purchasing policy is applied in the operations of Mexico facilities which receive shipments of steel scrap in the port facilities.

A relations manager in this company commented that steel scrap represents up to 25% of the raw materials loaded in the blast furnace.[138] However, steel scrap supply is relatively short in Mexico and steel scrap imports turn to be expensive. On the other hand, steel scrap production appeared to increase in Mexico at 6% during 1980-2007. Also, a significant proportion of local steel scrap is exported. The value of steel scrap exports increased from 22.63 to 60.47 US millions dollars (a threefold increase) between 2005 and 2007. The Foundry National Association in Mexico expressed the need of retaining in the country a high proportion of steel scrap in view of expensive imports. The Ministry of Economy indicated that by including a compensation fee in order to retain steel scrap, Mexico could get a penalty by the World Trade Organisation although the need of a programme to assist the foundry sector is recognised.[139]

7.7.2 Example 2: Provision of natural gas

The provision of natural gas is managed in a different way. The price of natural gas is determined by international prices but there is a small margin of flexibility since there is only one supplier in Mexico. A volume of natural gas for this steel company is specified in a contract with an energy supplier. The agreed volume of natural gas is determined according to a programmed activity in steel production in this company.[140]

7.7.3 Example 3: Provision of electricity

In the case of electricity, the industrial sector is charged an electricity tariff depending whether consumption takes place during peak or off-peak hours. The energy policy in Perseus Mexico consists of a partial interruption of the electric arc

[138] [II.A9.23.04.2007].
[139] Chatarreros, Empresarios en Busca de Oportunidades, INFOGAS, Energia hoy, No. 34, January, 2007.
[140] [II.A9B.06.08.2008].

furnaces during peak hours as a measure to cushion electricity costs. A partial shut down does not affect the delivery of just-in-time steels to other industrial sectors.[141]

The publicly available data for Perseus Mexico facilities shows EBITDA[142] cost reductions of 380 current Mexican pesos per tonne of finished steel in 2007 (Perseus Group, 2007). Of the 380 current Mexican pesos, the EBITDA cost structure consists of the following:

- Around 50% of cost improvements correspond to raw materials
- Around 40% of cost improvements correspond to energy (electricity and gas)
- Around 10% of cost improvements correspond to labour, parts and suppliers.

Energy cost reductions were possible by the absorption of CO_2 in the HYL plant (layout is in figure 7.4) while recovering off-gases and the corresponding 14% decrease in natural gas and electricity consumption per tonne of sponge iron. In the case of raw materials, a mining project facilitated a 45% cut in the landed cost of iron ore.

> Overall, Perseus Mexico is a key player in steelmaking since the physical production of steels is concentrated of around 23% in this company. Competition in the international market of steels is a key driver pushing down the production costs of which the cost of energy inputs is largely significant.

7.8 Reorganisation of Productive Operations

Personnel at Perseus Mexico facilities have been working on an energy efficiency master plan. This plan includes training methodologies for workers and operators in order to increase the stock of skills aimed at increasing energy efficiency in the plants. The energy efficiency master plan contains two critical aspects which act as drivers to growth in the energy efficiency. Firstly, the top management has required the energy team in this company to implement specific projects addressing

[141] [GC.A9B].
[142] Earnings before interest, taxes, depreciation and amortization.

commitment to continuous improvement.[143] Secondly, this plan aims at defining better work methodologies for the identification of energy efficiency opportunities along the steelmaking process. The energy efficiency master plan is administered by an executive committee formed by a general director, and operations director, and a technical director. Positions below the executive committee are held by people with an inter-disciplinary background (i.e. inclusive of human resources).[144]

The energy team in Mexico facilities has communication with an energy team integrated by experts in other subsidiary facilities in North America. During fieldwork visits in 2007, it was identified that the Perseus USA energy team visited the Mexico facilities during the end of March 2007. The goal of this visit was to identify areas of opportunity for energy savings along the integrated iron and steel process. The agenda of the energy team included the participation of the energy team in Perseus Mexico facilities, department managers, and process engineers. The energy team visited each area of the plant as depicted in figures 7.3 and 7.4. Also, the agenda included the presentation of steel processes by segment; verification of information; reporting and registration of findings; open discussions between the energy team and the sponsor process of Perseus Mexico facilities; and the definition of commitments according for future energy projects.[145]

The implementation of the energy efficiency master plant consists of three consecutive phases: 1) the first stage consists of a zero-leakage scheme; 2) the second one is on energy efficiency; and 3) the third stage addresses process optimisation.[146] A concrete example about these three stages is given in relation to the operation of burners as follows:

> "*For instance, we talk about a burner. If I have a burner the first thing to avoid is the existence of leakages… there should not be loses. As a second step I would refer to energy efficiency… to do the adjustment of the burner… fuel should be combusted adequately and with no loses.*[147]*"… "Or the use of*

[143] [II.A9B.06.08.2008].
[144] [II.A9B.3.06.08.2008].
[145] Agenda for the Energy Team Visit, PERSEUS internal document, Monday, 26th March; and Verificacion del Uso Eficiente de la Energia, PERSEUS internal document, Monday, 26th March.
[146] [II.A9B.2.06.08.2008].
[147] [II.A9B.2.06.08.2008].

output hot gases. These things were not considered in the past.[148]" "*And as a last step, while looking for a leading technology… in order to optimise the burning, by replacing it [the burner] totally [or] using oxygen injection. That would be [regarded as] optimisation.*[149]"

Although the energy team in the company has been elaborating on the energy efficiency master plan it advanced, this was only authorised as of 2008.[150] Two energy managers in this company recognised that the energy efficiency plan has not been as successful as expected. The observed drawback on energy efficiency has been overcome with the implementation of a corporate energy policy.[151] The corporate energy policy defines the guidelines and position of Perseus Group in relation to energy efficiency and conservation. A documentary revision of the energy policy suggests that this company envisages environmental responsibility as part of energy related activities. The energy policy of this company focuses on the achievement of the following aspects (in order of importance): 1) competitiveness; 2) efficiency; 3) technology; 4) social responsibility; 5) partnering; 6) employees engagement; 7) continuous improvement; 8) supporting; and 9) leadership.

Efficiency guidelines in this policy consist of the implementation of energy management programmes, internal energy efficiency benchmarking, and the incorporation of best-practices into standards.[152] There is also an interesting aspect which does not emerge in the narrative fragments provided by the energy managers and is a central part of the corporate energy policy. This consists of a pro-active role of the company in supporting energy efficiency policies promoted by the governmental sector where the subsidiary facilities of this company operate.[153]

The scope of the corporate energy policy is implemented worldwide through the subsidiary facilities. The energy policy in the Perseus Group has been implemented since 2008. This energy policy is regarded as part of the actions on

[148] [II.A9B.06.08.2008].
[149] [II.A9B.2.06.08.2008].
[150] [II.A9B.3.06.08.2008].
[151] [II.A9B.06.08.2008] and [II.A9B.3.06.08.2008].
[152] Perseus Group, Transforming Tomorrow, Energy Policy.
[153] This appears to support the role of governmental initiatives in supporting energy efficiecy growth as was sketched in the theory framework in chapter 4.

corporate responsibility and sustainability of the company. The main contents of the energy policy are stated as follows:

> *"It encompasses the procurement of energy-related commodities, the integration of energy considerations into process and equipment design, technology selection and procurement and individual employee behaviour."*[154]

A critical aspect in both the energy efficiency master plan and energy corporate policy is the establishing of linkages with the suppliers of energy efficiency technologies. The energy policy of the Perseus Group is conceived in the Mexican facility as beneficial because it enables looking for a group of energy efficiency suppliers with sufficient expertise based on work teams.[155] Thus work teams have the commitment to provide training in the implementation and operation of the technology they sell. This is seen as part of a service which supports the implementation of higher efficiency devices.

Three original equipment manufacturers (OEMs) were identified as already making contact with this subsidiary company in Mexico (i.e. Schneider Electric in the engineering sector; General Electric with electrical devices with an environmental orientation; and Praxair in combustion technologies – oxy-fuel burners). OEMs were described by the energy managers as large suppliers making contact with the steel sector who explain possible applications of their devices and the creativity behind it.[156] Also, part of the routines consisted of sending personnel to other plants of the company in order to identify novelty processes which can be implemented in the subsidiary company in Mexico.

A style of work based on the implementation of continuous improvement in the flat steels plant (direct reduction reactors – electric arc furnaces in figure 7.4) is being adapted to the long steels plant (blast furnaces – basic oxygen converters in figure 7.5). Skills among people are said to vary according to the work experience in

[154] Op. Cit [55].
[155] [II.A9B.3.06.08.2008].
[156] [II.A9B.06.08.2008] and [II.A9B.06.08.2008].

the plant. It was also commented that people in the long steels plant were facing more challenges in order to assimilate new changes.[157]

One of the energy managers also noted a clear distinction between vision, organisational philosophy, and the operative aspects of the integration process. Firstly, the long steels plant has specific operations in the sense that the production of wired rod and rebar is achieved by means of blast furnace and basic oxygen converters and this cannot be changed.[158] The integration of both plants into a single company is described as a synergy. In particular, some utilities in the plants are intended to provide supportive services to both steel plants. Before the integration process, the long steels plant relied on a single oxygen plant whereas the flat steels plant relied on three oxygen plants. As a result of the integration, four oxygen plants are now used according to the needs of both the long and the flat steels plant.[159] A homologation process (i.e. replication of practices, see theory sketched in Chapter 4) is also taking place with the implementation of a reliability maintenance system (RMS) in both plants.[160]

Secondly, the reported organisational change is taking place in relation to corporate vision and philosophy. This is regarded as a means to define new methodologies oriented to assure the quality of steel production. The corporate philosophy of the Perseus Group explicitly recognises exceptional responsibilities as a result of its position in industry. This company specifies three main values as part of a corporate philosophy: sustainability, quality, and leadership. Regarding leadership, the company embraces a visionary thinking in search of opportunities in daily operations.[161] A final critical aspect in this re-organisational process is identified in the cultural domain of the company. This is reflected in the following narrative fragment:

> *"Is there something else you wish to comment, that I have not considered in this energy efficiency topic, according to your views?*[162]

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[157] [II.A9B.06.08.2008].
[158] [II.A9B.3.06.08.2008].
[159] [II.A9B.3.06.08.2008].
[160] [II.A9B.06.08.2008].
[161] Perseus Group, Corporate Philosophy, Transforming Tomorrow, our Philosophy, our Values.
[162] [GC.A9B.06.08.2008].

> *"This is a matter of culture, besides that this is a business, we have to produce at a low cost. If you do not make people aware and create a culture of energy savings, this does not work. The policy [as in the corporate energy policy] talks about carrying on with energy savings at home, in ones' daily activities.*[163] *"*

7.9 Summary of the Chapter

Perseus Mexico went through an integration of steelmaking technologies, changed the organisational structure, and increased the scale in steel production after the acquisition process. Perseus Mexico specialises in the production of high quality slabs for plate applications in export markets as well as long steels. Shipments in steel products from Perseus Mexico increased 16% over the period 1992-2004 as a result of a strategy based on acquisition, product specialisation, consolidation of operations, and synergies.

Insufficient capital funding and lack to access to capital financing represented a critical barrier in the completion of the steel facility and capacity expansion with the corresponding gains in overall efficiency. It was the government and the board of directors at the Perseus Group through a public bid of the company what ultimately led to the completion and improvement of this integrated steel facility.

Among the efforts to lower energy consumption is the reduction of flaring blast furnace gases, off-gasses recovery, and improvements of the HYL-III and Midrex reactors. On the other hand, some opportunities to further lowering the energy consumption are identified within the Group and these correspond to reduction of specific energy consumption (SEC) in the operation of electric arc furnaces, recovery and use of coke oven and blast furnaces gases, temporary shut down of utilities for maintenance, and improvement of water resource management and disposal.

Strategies based on capacity expansion and the expectation of growth in steel production appeared as a major driver in the improvement of the HYL-III reactor as

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[163] [II.A9B3.06.08.2008].

well as the setting up of a MIDREX reactor with substantial gains in energy efficiency. As a result, natural gas uses have been lowered in the operation of both reactors.

Opportunities to lower energy consumption are identified by plant engineers at the bottom-line of the corporate responsibility structure of the Perseus Group. The CRT has a critical role in the organisation of energy related decisions. On the one hand, the CRT offers support in the building of capacity and sharing of best practices (i.e. this relates to the concept of firm-based capabilities as exposed in chapter 4). On the other hand, plant engineers organised around local corporate responsibility committees transmit information on energy related opportunities and negotiates with the CRT the allocation of a budget over a cycle. The CRT is responsible for measuring performance and reporting to the GMB and BD at the top of the corporate responsibility structure.

The Perseus Group is a key player in international steel markets and part of the competition strategies point to an improvement of the cost structure thus competition representing a key driver to lower the energy consumption (i.e. raw materials, electricity, and natural gas account for 90% of the energy cost improvements in 2007).

Current measures to lower energy consumption are organised through the energy efficiency master plan and the corporate energy policy of the Perseus Group. Among the capabilities of handling energy related issues in the company are the definition of better work methodologies, continuous improvement, energy benchmarking, and the measurement of overall performance. These organisational attributes appear as critical issues in the overcoming of barriers to energy efficiency in view of the opportunities to reduce carbon emissions in a group of steelmaking processes.

Chapter 8

Fugitive Emissions in Energy Industries in Mexico

Introduction

This chapter investigates the carbon and methane fugitive emissions in energy industries in Mexico. The treatment of fugitive emissions in the calculation of an overall carbon emission factor in electricity generation is a key methodological contribution in the research of this thesis. Fugitive emissions take place through venting, flaring, and energy loses at different stages in the oil and gas industries, and coal extraction. An improved life cycle assessment (LCA) presented in this chapter incorporates the fugitive emissions of the fuels used in electricity generation as this is taken into account in the calculation of an emission factor of the electricity grid. The methodology of this chapter corresponds to the first component of the carbon LCA as it was defined in chapter 1 (section 1.4.1, figure 1.4).

A major difference in the methodology developed in this thesis compared to traditional approaches is in the way the distinction between the greenhouse gases are handled in the case of electricity use within the iron and steel and industry. The traditional approach is to use a single carbon emission factor for electricity generation; however, this varies from year to year depending on the fuel and also on the relative fugitive emissions for each fuel source during each year. Consequently in this analysis a detailed assessment of all the fugitive emission has been undertaken.

The chapter presents a background of the fuel mix for electricity generation in Mexico and the data specification in sections 8.1 and 8.2, respectively. Section 8.3 presents detailed appraisals of the emissions of the three fossil fuels of gas (section 8.3.1), oil (section 8.3.2), and coal (section 8.3.3). Section 8.4 presents the methodology using a LCA and the results on the methane and carbon fugitive emissions in gas, oil, and coal fired plants. Section 8.5 contains a summary of the findings.

8.1 Background

Running an electricity generation system generally relies on a combination of different energy sources which can be classified into: 1) fossil fuels; 2) renewable(s) (i.e. wind, solar radiation, biomass, etc), and 3) nuclear energy. The emission of carbon dioxide for each unit of electricity generated (kWh) will depend on the availability of the different fuels in each country. The amount of CO_2 emissions due to electricity generation depends on the proportion of fossil fuel, renewable(s) and nuclear in power generation plants. Any attempt in the manufacturing sector to control greenhouse gases will significantly be affected by policies in the electricity sector oriented to diversify into renewable energy sources.

Dry gas is the most important energy source for electricity generation in Mexico as of 2007 (figure 8.1) and accounts for 41% in power generation while fuel oil accounts for 22% and coal represents 15%. The contribution of diesel for electricity generation is marginal (i.e. less than 1%). Total fossil fuels for electricity generation represent 78.3% whereas renewable energy accounts for 16.2% of which hydro-electricity is the most important representing 12.7% while nuclear electricity accounts for 5.4%.

The amount of CO_2 emitted due to electricity generation varies significantly across countries. For instance, per capita electricity consumption in Norway is 24,295 kWh with 0.19 kg CO_2 per unit of wealth (i.e. GDP expressed in 2000 constant US dollars) whereas per capita electricity consumption in China is 2,040 kWh with 2.68 kg CO_2 per unit of wealth in 2006 (IEA, 2008).[164]

[164] International Energy Agency, (2008), 2006 Selected Indicators for Norway and China.

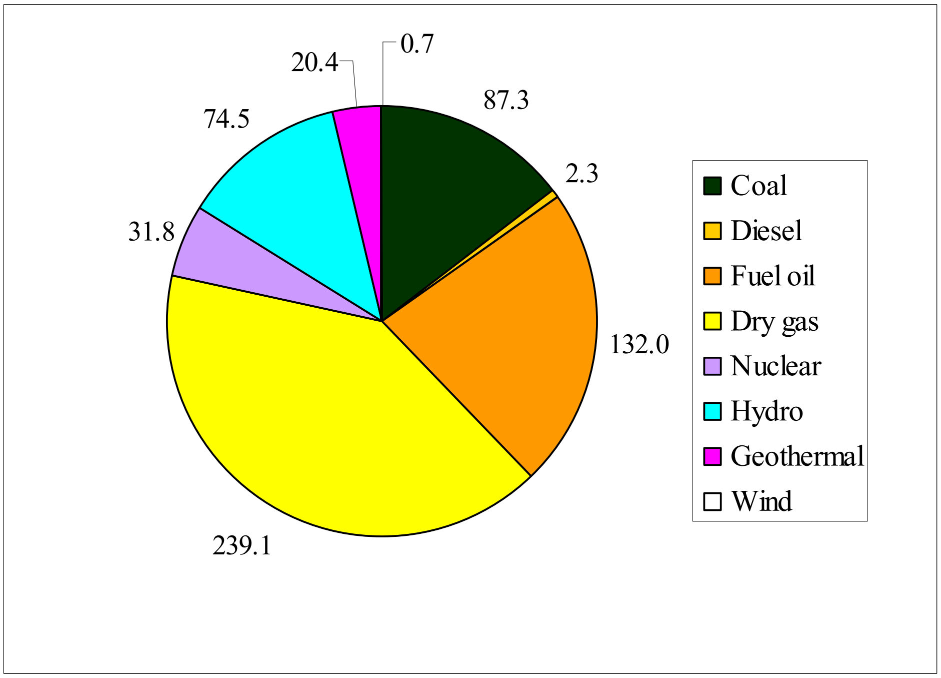


Figure 8.1 – Energy Sources for Electricity Generation, Mexico, 2007 (TWh)

Source: SENER, Balance Nacional de Energía, 2007, México.

8.2 Data Specification

The model elaborated in this chapter requires information on the following:

a) The percentage contribution of fossil fuels and renewable(s) in electricity generation.

b) The particular circumstances regarding the availability of energy sources in Mexico (i.e. if native supply of fossil fuels or imported) when referring to specific net or gross calorific values.

c) The carbon content incorporated in fossil fuels.

d) The densities and calorific values of relevant fossil fuels in the conversion of thermal energy into electricity.

e) The type of electricity generation used in the different plants and the thermal efficiency of each generation technology.

f) The amount of electricity generated with respect to a particular energy mix in a given period.

Approximate emission factors for electricity generation for different countries may be estimated from International Energy Agency (IEA) statistics (IEA 2009). Such data for China and India suggest that emission factors as high as 1000 g/kWh which offer a potential for reduction whereas in Norway it is as low as 2 gm/kWh where 99% of generation is from hydro-electricity and there are next to no opportunities for further reduction in the carbon emission factor. The evaluation of the specific emission factors for electricity is important as some processes in steel production are heavily dependent on electricity.

Data use in the LCA presented in this chapter has been obtained from energy balance tables. The Ministry of Energy in Mexico periodically publishes energy balance tables which contain the most comprehensive primary and secondary energy data on a year and monthly basis. Other critical data used in this research have been obtained from country energy balance tables provided by the International Energy Agency (IEA). This secondary data source has been used for comparative and validation purposes in the current analysis.

Calculations of a representative CO_2 emission factor for electricity presented in this chapter were derived for 2005. This year was selected because the most updated available data on the amount of fossil fuels consumed by each individual power plant also corresponds to that year.

8.3 Energy Flows in the Gas, Oil, and Coal Industries in Mexico

8.3.1 Gas Production, Processing, Transmission, and Distribution

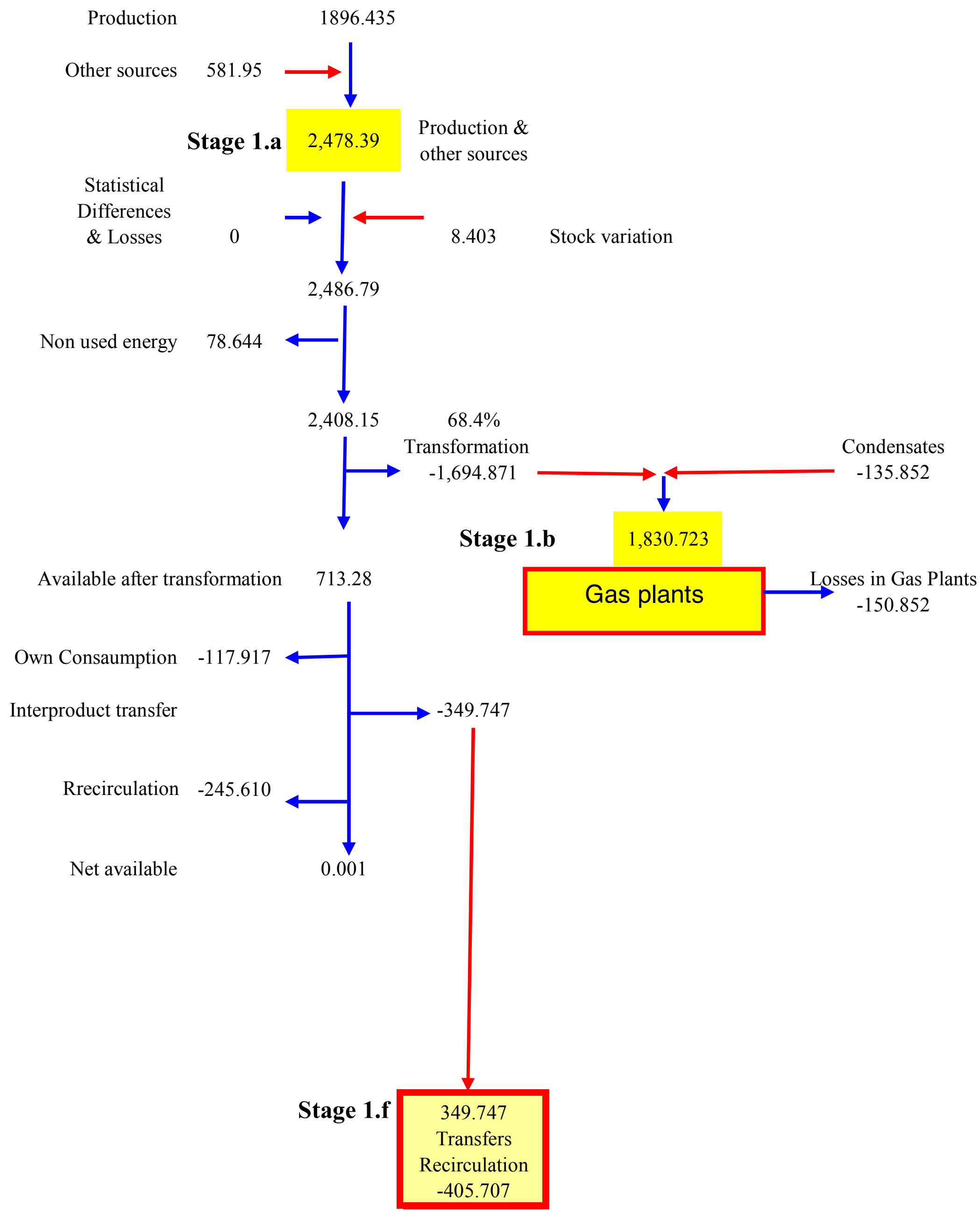
Natural gas gross domestic supply amounted to 1896.43 PJ in 2005 (figure. 8.2a). This natural gas production comprises sour and sweet gas associated with petroleum extraction in oil wells. Other sources of natural gas amounting to 581.95 PJ arise from residual gas obtained from gas plants and formation gas. These sources concern gas used for pneumatic pumping and injection in oil wells (i.e. gas lift, nitrogen, carbon dioxide, dry gas, etc.) and formation gas attached to the bed in oil fields.

Overall natural gas production was 2,478.39 PJ in 2005 (Stage 1.a in gas map Fig. 8.2a). Data in energy balance tables also take into account factors on statistical differences & loses, stock variations, and non-used energy which affect the availability of natural gas. The net total amount of gas available is thus 2,408.15PJ

There are no imports of natural gas registered as primary energy although there is a significant amount of imported dry gas which is registered as secondary energy (figure 8.2b). Of the 2408.15 PJ of available gas, 1,694.9 PJ or 68.4% of overall domestic natural gas production are inputs into the transformation processes to produce dry gas and other related gas products from gas and fractioning plants.

Raw gas feed for transformation consists of available natural gas allocated to gas and fractioning plants (stage 1.b, figure 8.2a) and includes both the 1,694.9 PJ of gas indicated above and also sour condensates which consist of a liquid current from oil wells. Details of the transformations which take place in stage 1.b are shown in figure 8.2b. In the gas plants there are inevitable losses which amount to 150.852 PJ or 8.24% of the gas inputs. Dry gas production within the gas plants is obtained by transformation of the sour gas and condensates, and in some instances tertiary sweet gas obtained in oil fields going into gas and fractioning plants and amounts to 1,679.82 PJ (Stage 1.c, figure 8.2b). The final products from the gas plants include in addition to dry gas, liquefied petroleum gas (LPG), gasolines & napthas, kerosene, fuel oil, and non-energy use products (SENER, 2005).

Dry gas is the most important product obtained from gas plants and amounts 1,137.7 PJ. The thermal energy embedded in the final dry gas accounts for 67.7% of energy incorporated in overall raw gas feed to the gas plants while other important gas related products are LPG (17.7%) and gasolines & napthas (9.3%) – (figure 8.3).



Source: based on Ministry of Energy, Balance Nacional de Energia, Mexico, 2005.

Figure 8.2a – Natural Gas Map, Mexico, 2005 (PJ)

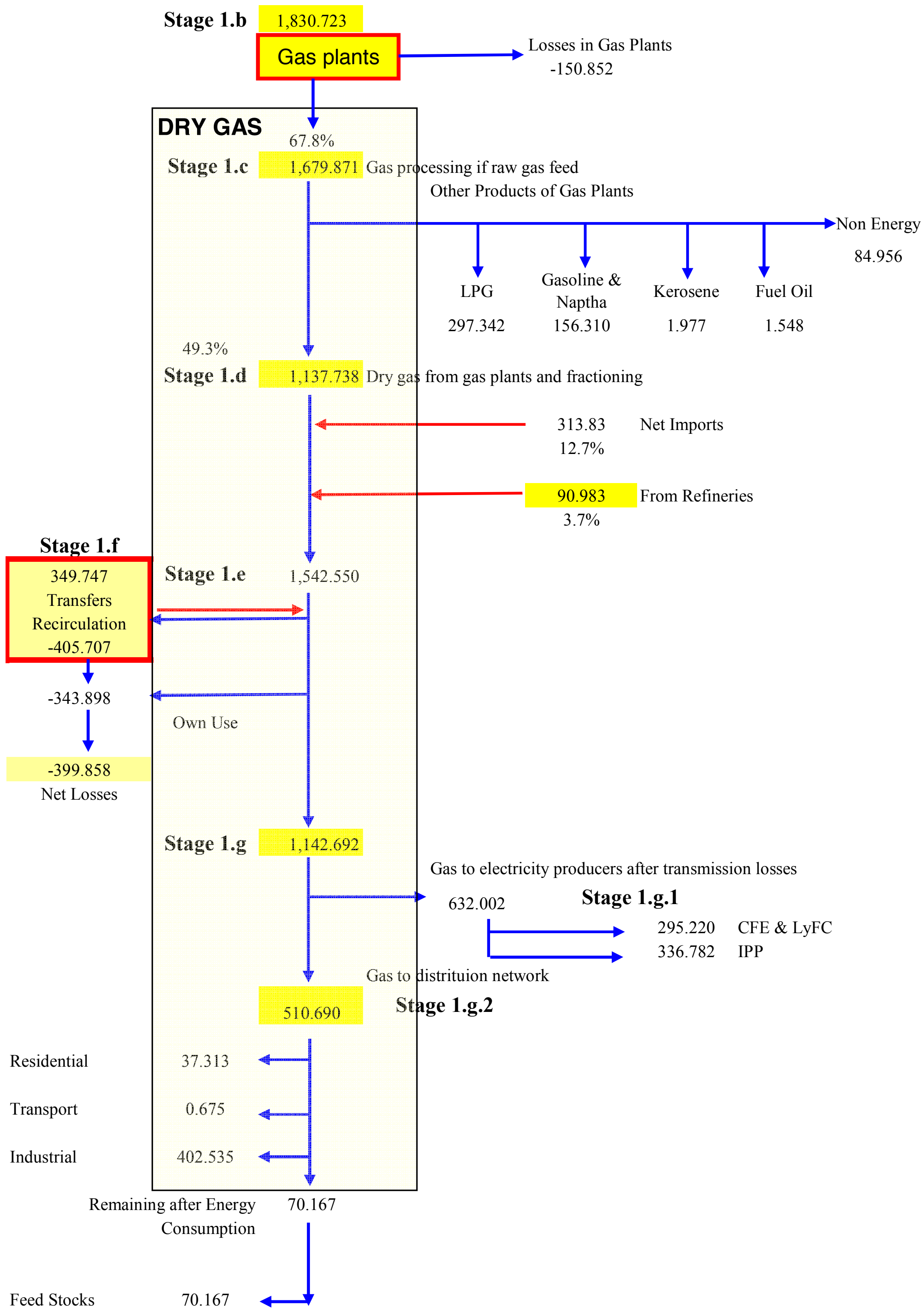


Figure 8.2b – Natural Gas Map, Mexico, 2005 (PJ) – Continuation

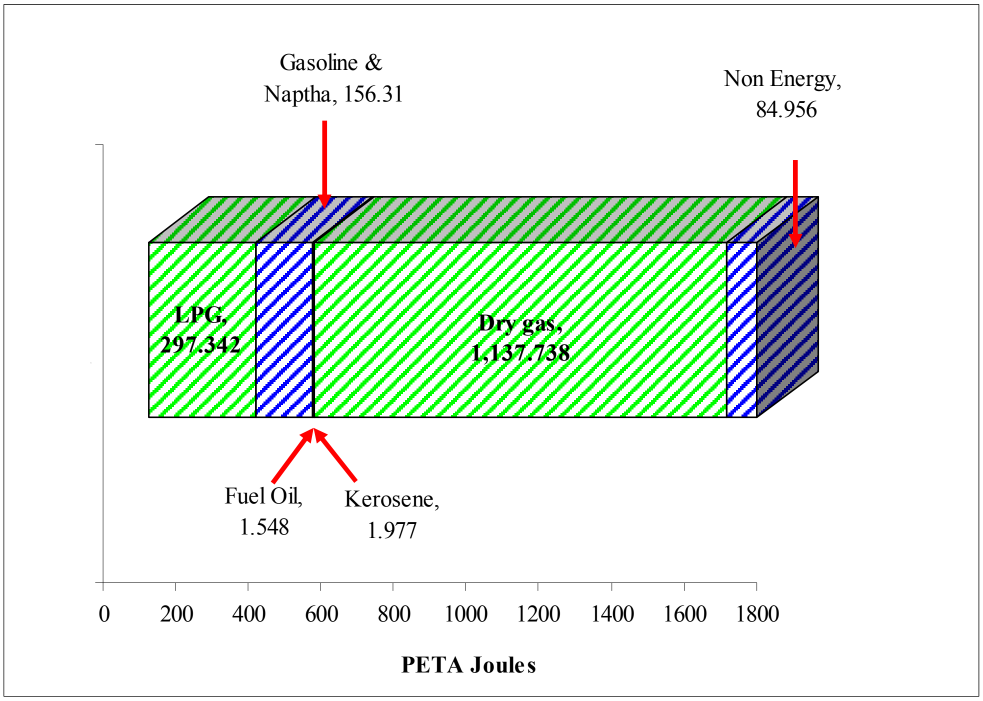


Figure 8.3 – Relative Importance of Dry Gas and Gas Related Products, Mexico, 2005 (PJ)

Gas plants produce 1,137.7 PJ of dry gas which account for 46% of overall domestic natural gas production (stage 1.d, gas map, figure 8.2b). In addition, dry gas net imports (313.8 PJ) and gas from refineries going to final consumption (90.9 PJ) account for 12.7 % and 3.7% of overall domestic natural gas production, respectively. Net imports are obtained after considering the amount of dry gas which is exported. In the case of Mexico, natural gas imports come from the United States. Natural gas imports/exports take place through distribution networks interconnecting the energy supply infrastructure across the border between Mexico and the United States (in particular, in the region of Nuevo Leon – Texas). However, the most significant natural gas trade within the NAFTA area occurs between the United States and Canada. The interconnection gas system between the United States and Mexico has increased and in this respect, natural gas exports from the United States to Mexico date back to 1997 through two main interconnection points: Texas-Monterrey duct and El Paso Energy (GTEAN, 2006). Mexico appears to have a growing dependence on foreign energy sources because natural gas imports (i.e.

liquefied natural gas) are expected to reach 41% of total overall natural gas demand by 2013 (Op. Cit).

Total available dry gas in Mexico consists of dry gas production from processing plants, dry gas imports and gas obtained from refinery plants (stage 1.e, figure 8.2b. Inter-product transference (stage 1.f, gas map, figure 8.2b) consists of a re-allocation (movements) among *"energy headings"* in balance tables due to re-classification of energy flows; for instance, natural gas directly obtained from oil fields (i.e. associated gas) is re-classified as dry gas after a transformation process.

Pneumatic pumping consists of an artificial system for oil production and is used to lift fluid in an oil well by means of gas injection into the production pipes. Natural gas re-circulation (stage 1.f, figure 8.2b) consists mostly of the recovered formation gas used initially for the pneumatic pumping in crude oil fields (Op. Cit).

The availability of dry gas to end-use economic sectors is also affected by loses through transportation, transmission, distribution, and storage. Energy loses through transportation, distribution, and storage of dry gas amounted to 399.8 PJ (or 25.9%) in 2005. Thus the net total available dry gas delivered to other economic sectors after transmission and distribution loses accounts for 1,142.7 PJ (stage 1.g, gas map, in figure 8.2b). Energy loses whether occurring in oil and gas plants or through transmission and distribution affect the overall efficiency of an energy system. Also, energy loses take place through the electricity transmission and distribution network affecting total overall efficiency (Tovey, 2008).

In the model developed in this thesis, it is assumed that power plants are connected to the transmission network (stage 1.g.1, figure 8.2b) whereas the rest of economic sectors (i.e. non-power plants) are connected to the distribution network (stage 1.g.2, figure 8.2b).

Power facilities demand the largest amount of dry gas for electricity generation (55.3%) while the industrial sector is the second largest consumer, (figure 8.2b; table 8.1). For instance, steel making is highly intensive in the consumption of electricity. Gas consumption in residential and commercial sectors is relatively insignificant in Mexico (table 8.1).

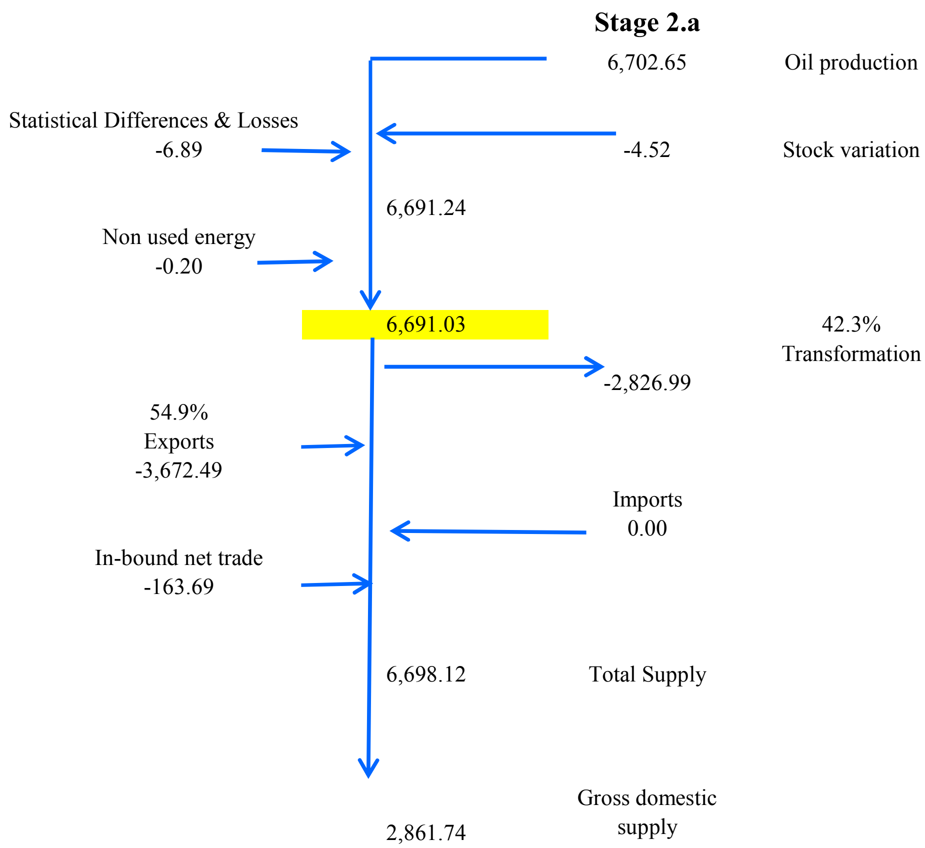
	Total in PJ	Distribution (%)
TOTAL AVAILABLE DRY GAS	**1,142.7**	
Gas to electricity producers after transmission losees	632.0	55.3%
Gas to other economic sectors after distribution loses	510.7	44.7%
Residential	37.3	3.3%
Tranportation	0.7	0.1%
Industrial	402.5	35.2%
Feed stocks	70.2	6.1%

Table 8.1 – Proportion of Dry Gas between the Transmission and Distribution Network (PJ and %)

8.3.2 Oil Extraction, Production, Transportation, and Processing

Oil production, transportation, and processing in refinery plants represent critical sources of fugitive emissions in energy industries. Oil production in Mexico accounted for 6,702.6 PJ in 2005, (stage 2.a, oil map, figure 8.4a) with oil exports being highly significant at 55% of total domestic production. A further 42.3% (i.e. the majority of the domestic consumption) is transformed in oil refineries. This fact is important in the overall quantification of energy related emissions.

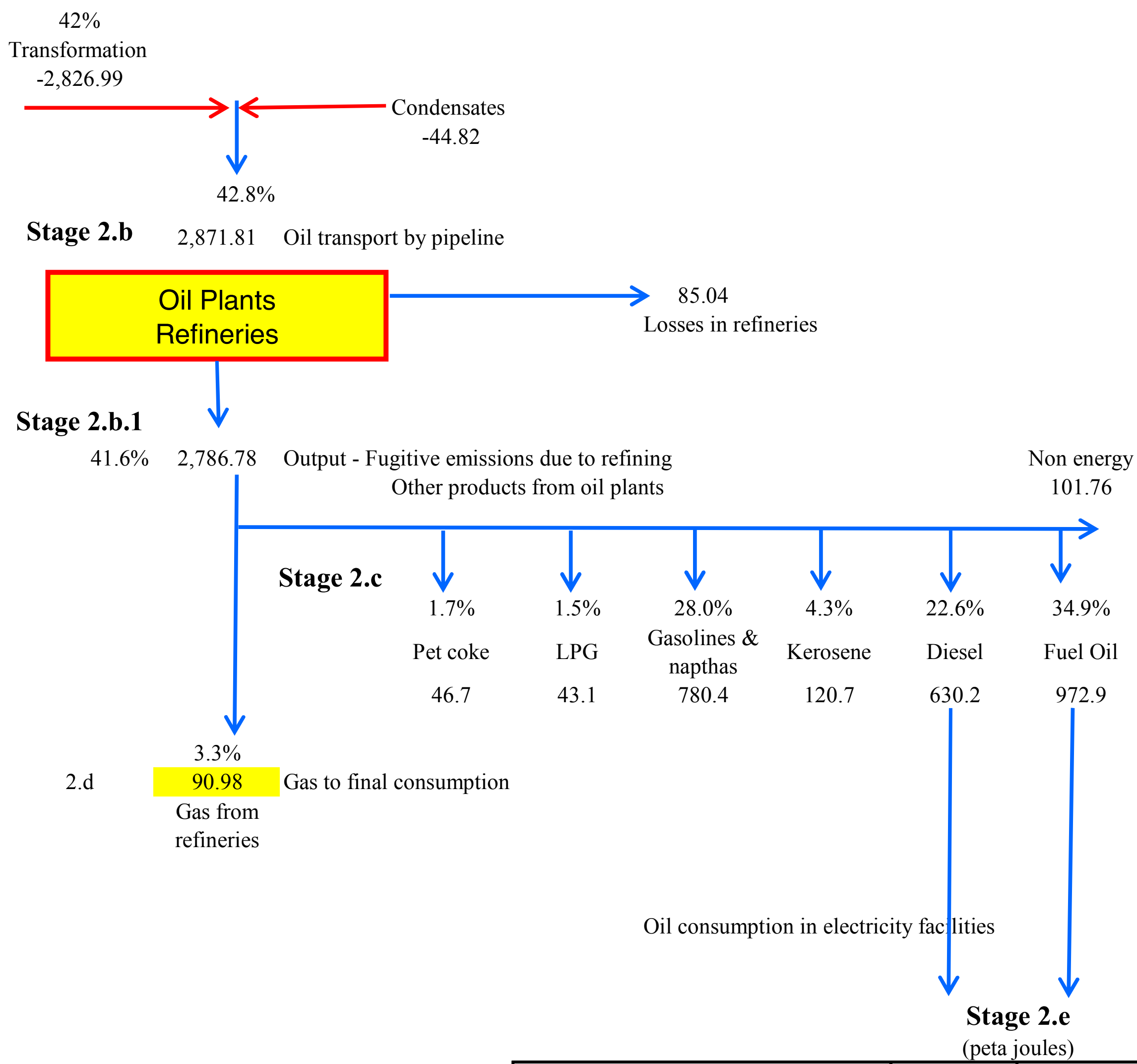
Fugitive emissions due to oil transportation through oil pipelines correspond only to raw oil and condensates feeds in refinery plants and not oil exports. Raw oil feeds and condensates diluted in the stream of raw oil going to refinery plants account for 2,871.8 PJ which represents 43% of overall oil domestic production in Mexico (stage 2.b, oil map, figure 8.4b).



Source: based on Ministry of Energy, Balance Nacional de Energia, Mexico, 2005.

Figure 8.4a – Crude Oil Map, Mexico, 2005 (PJ)

Oil processing in refineries is also a source of methane emissions in the energy sector. Raw oil feed is transformed into a group of oil products from refinery processes: pet coke, LPG, gasolines & napthas, kerosene, diesel, fuel oil, and non-energy uses (stage 2.c, oil map, figure 8.4b). There are also energy loses in oil plants (85 PJ) which are relatively smaller in comparison to total thermal energy incorporated in oil related products. In addition, a fraction of gas which is obtained from refineries is allocated to final consumption (stage 2.d, figure 8.4b). This amount of gas increases the availability of dry gas for end-use consumption in the electricity sector and other economic activities.



Fuel Consumpiton	Diesel	Fuel Oil
Power Stations CFE y LFC	13.26	624.55
Power Stations IPP	0.48	0.00
TOTAL	13.74	624.55

	(GWh)	
	3,816.9	173,486.9
	(%)	
	2.2%	64.2%

Figure 8.4b – Crude Oil Map, Mexico, 2005 (PJ) – Continuation

Fuel oil is the most significant oil related product obtained from refineries. Thermal energy embedded in fuel oil accounts for 34.9% of overall raw oil feed, followed by gasolines & napthas (28%); diesel (22.6%), kerosene (4.3%), pet coke (1.7%) and LPG (1.5%), (stage 2.b.1, oil map, figure 8.4b; and figure 8.5). Thermal energy incorporated in gas obtained from oil refineries represents 3.3% of overall raw oil feed (stage 2.d; and figure 8.4b). Fugitive emissions also occur in the production of fuel oil and diesel in oil refineries which represent energy inputs for electricity generation in conventional thermal plants and internal combustion electricity generation technology in Mexico.

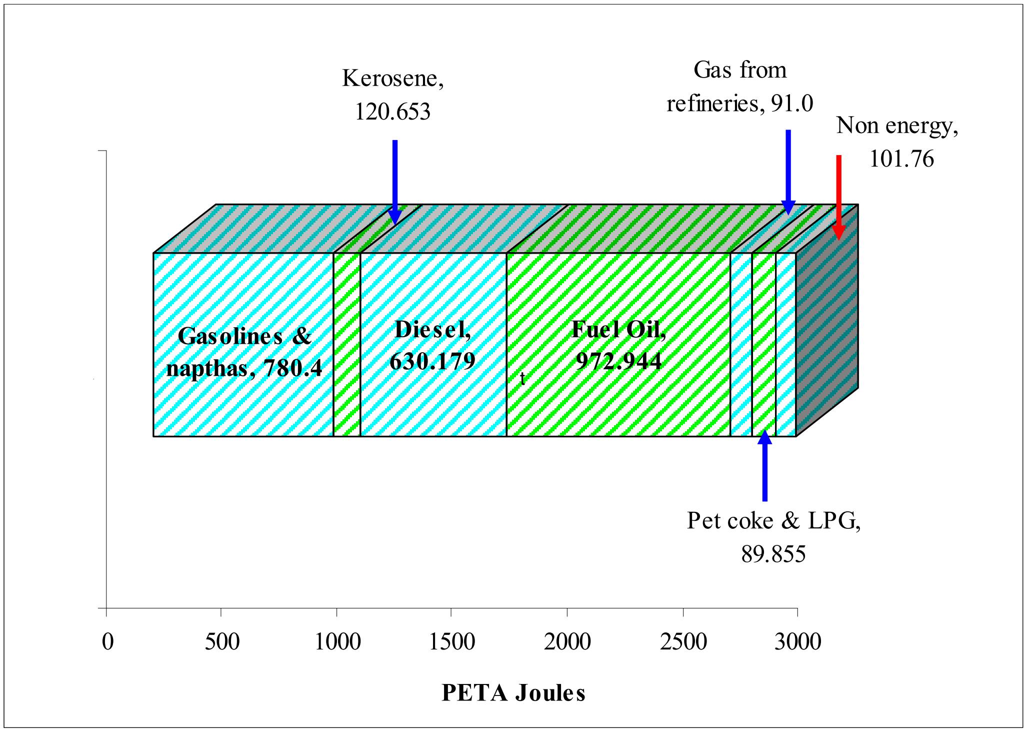


Figure 8.5 – Relative Importance of Oil Products, Mexico, 2005 (PJ)

Source: Secretaria de Energía (SENER), Balance Nacional de Energía, 2005, México.

Energy loses through oil transportation, distribution, and storage account for nearly 1 % of overall raw oil feed and diluted condensates in refineries. This category of loses in the case of oil products is registered as part of self consumption in energy balance tables for Mexico (SENER, 2005). Although energy loses are relatively smaller in comparison to raw oil feed, this is a factor affecting the overall efficiency through the energy system.

Table 8.2 shows the proportion of diesel and fuel oil as thermal energy (PJ) consumed in power facilities. Diesel consumed in power plants accounts for 2.2% of the total overall diesel obtained in oil refineries whereas fuel oil represents 64.2% of total fuel oil available. Fuel oil is a critical energy input in electricity generation in conventional thermal power plants accounting for 79.2 % of total electricity generation in 2005 whereas the contribution of diesel is relatively low (at 1.7%) but still important for internal combustion electricity generation (stage 2.e, oil map, figure 8.4b).

Total available diesel & fuel oil	Diesel (PJ)	Fuel Oil (PJ)
Electricity Power Stations CFE y LFC	13.3	624.6
Electricity Power Stations IPP	0.5	0.0
TOTAL electricity sector	**13.7**	**624.6**
Other Uses in Economic Sectors	616.4	348.4

Table 8.2 – Proportion of Diesel and Fuel Oil for Electricity Generation, Mexico, 2005 (PJ)

8.3.3 Coal Mining, Post-mining and Transformation

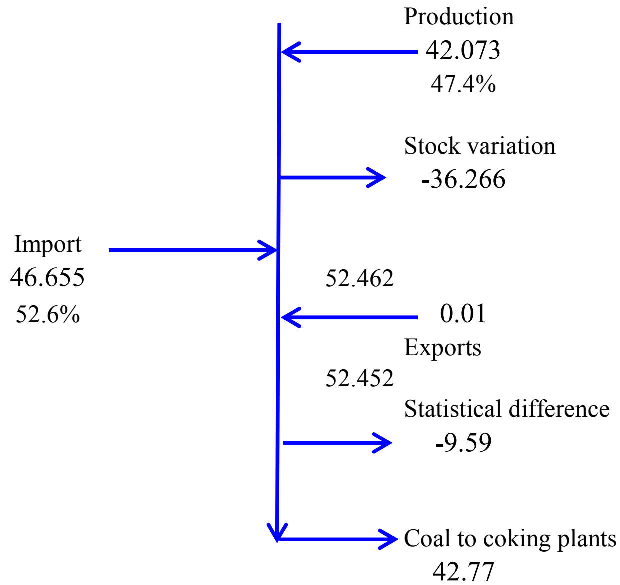
Coal production in Mexico is associated to two main productive activities:

a) Metallurgical (or coking) coal or bituminous coal which is employed in coking plants of which output is coke. Coke is a major raw material in blast furnaces in the iron/steel industry.

b) Thermal coal or sub-bituminous coal which is employed as energy source in conventional thermal electricity generation plants.

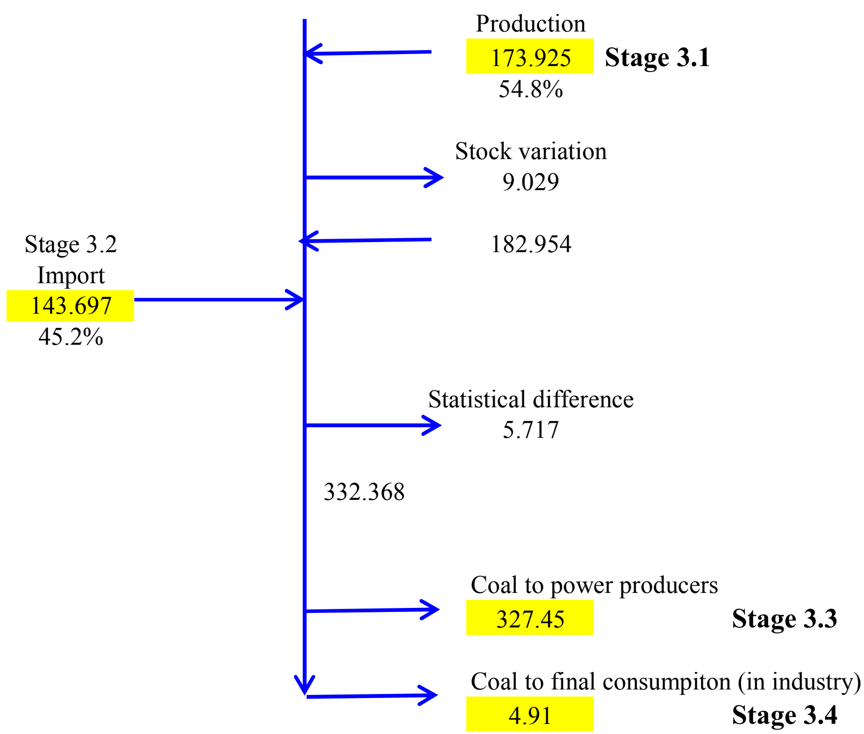
Metallurgical coal imports which are very significant in Mexico exceed domestic production. However, negative stock variations compensate the amount of imported metallurgical coal as of 2005. Domestic production of bituminous coal represents 42 PJ whereas imports represent 46.6 PJ in 2005 (figure 8.6). Domestic production of sub-bituminous coal accounts for 173.9 PJ whereas imports accounts for 143.7 PJ (figure 8.7). Coal exports tend to zero. The ratio of coal used in coking plants to coal used in electricity generation is 13.1.

Coal formation consists of a process which involves generation of methane (CH_4) and related by-products in nature. Methane embedded in coal can be unleashed due to, for instance, coal mining which is an anthropogenic activity. According to IPPC (1996), the amount of methane incorporated in coal depends on a group of factors relating to depth of a seam, pressure, and humidity. This in turn will affect calculation of methane emissions depending on the mining activity whether this is related to surface or underground mining.



Source: based on Ministry of Energy, Balance Nacional de Energia, Mexico, 2005.

Figure 8.6 – Metallurgical Coal (Bituminous Coal), Mexico, 2005 (PJ)



Source: based on Ministry of Energy, Balance Nacional de Energia, Mexico, 2005.

Figure 8.7 – Thermal Coal (Sub-bituminous Coal), Mexico, 2005 (PJ)

Coal production in Mexico comes predominantly from underground mining. However, a relative increase in coal production from surface mining in recent years can be observed. For instance, 8,693 kilo metric tonnes of coal are produced from underground mining whereas 2,612 kilo metric tonnes are obtained from surface mining which account for 77% and 23% of overall domestic coal production, respectively, as of 2003 (Figure 8.8).

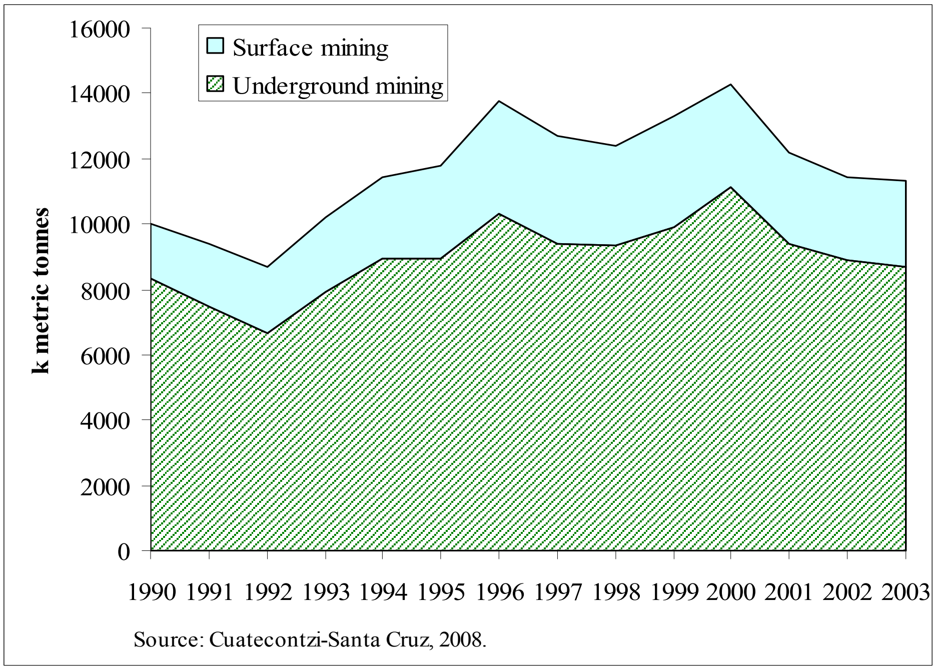


Figure 8.8 – Coal Production in Mexico, 1990-2003 (thousand metric tonnes)

Fugitive emissions from coal activities correspond to methane and carbon dioxide which arise through underground mining; surface mining; abandoned mines; and methane recovery and use (IPCC, 2006). Early approaches on greenhouse emissions related to coal suggest that processing and transportation of coal is also a source of methane emissions. Coal smashing into small particles in the stage of coal agglomeration in coking plants related to iron and steel facilities allows increasing the surface of coal thus this representing a source of methane releases into the atmosphere (IPCC, 1996). Methane emissions due to post-mining activities include treatment, transportation, and use of coal (Op. Cit).

8.4 Calculation of Fugitive Emissions in Gas, Oil, and Coal Fired Plants

8.4.1 Calculation of GHG Emission Factors per kWh in Gas Fired Electricity Stations (CCGT)

Gas fired power plants consist of conventional thermal electricity, combined cycle gas turbines (CCGT), and open cycle gas turbines (i.e. turbo gas electricity). Because the majority of total available dry gas which is consumed in the electricity sector corresponds to CCGT (i.e. 74% of 263,988.9 TJ as thermal energy embedded in dry gas), CCGT technology is used as a reference when calculating GHG emissions in electricity generation. The following stages are considered when calculating greenhouse gases emission factors for natural gas:

1) Natural gas production (stage 1.a, gas map, figure 8.2a)
2) Processing (stage 1.d, gas map, figure 8.2b)
3) Marketable gas to all economic sectors (stage 1.g, figure 8.2b) of which:
    a. Transmission to power plants (stage 1.g.1, figure 8.2b)
    b. Distribution to other economic activities and not power plants (stage 1.g.2, figure 8.2b)

Emission factors are obtained for the following greenhouse gases due to fugitive emissions, flaring industry practices, and raw CO_2 venting industry routines: methane (CH_4), and carbon dioxide (CO_2). Emission factors for fugitive emissions are reported on the basis of two major geographical/economic categories (IPCC, 2006):

1) Oil and gas operations in developed countries
2) Oil and gas operations in developing countries and countries with economies in transition

GHG emission calculations are obtained on the basis of tier 1 approach which consists of the assignation of specific emission factors associated to the stages specified above. The selected emission factors in the calculations of this model correspond to oil and gas operations in developing countries (point b above).The general equation for GHG emissions calculations using tier 1 approach is as follows (IPCC, 2006):

$$E_{gas,inudstrysegment} = A_{industry.segment} * EF_{gas,industrysegment} \quad \text{…. (8.1)}$$

Total fugitive emissions in gas industry:

$$E_{gas} = \sum_{industry.segments} E_{gas,industry.segment} \quad \text{… (8.2)}$$

Where,

- $E_{gas,industry.segment}$:annual emissions in gas industry,
- $EF_{gas,industry.segment}$:emission factor,
- $A_{industry.segment}$: activity value in gas industry.

Primary data of emission factors for each industry segment of gas activity are reported in Giga grams (Gg) of GHG emitted per million cubic meter of natural/dry gas (i.e. this unit is also equivalent to kg of GHG emitted per cubic meter of natural/dry gas). These emission factors are converted into thermal energy units (PJ) in order to apply equation (8.1) to activity data corresponding to fossil fuels as reported in energy balance tables (PJ). The following equation is employed for unit conversion of emission factors from *kg of GHG emitted per cubic meter of natural gas* (i.e. a unit of volume) into *kg of GHG emitted per PJ of natural gas* (i.e. an energy thermal unit):

$$EF_{gas.industry}^{GHGi} = \left(\frac{kg_{gas.industry}}{PJ_{gas.consumed}}\right) = \left(\frac{kg_{gas.industry}}{cum_{gas.consumed}}\right) * \left(\frac{1}{\rho_{GHGi}}\right) * \left(\frac{1}{CV_{GHGi}}\right) * 10\text{^}(9) \quad \ldots$$

(8.3)

Where,

- $EF_{gas.industry}^{GHGi}$:Emission factor of greenhouse gas i in natural gas productive activities.
- ρ_{GHGi} :density of greenhouse gas *i,(in kg per cum)*
- CV_{GHGi} :calorific value of greenhouse gas *i,(in MJ per kg)*
- $i = 2$, $GHG_1 = CH_4$ equivalent and $GHG_2 = CO_2$ equivalent.

The largest amount of methane emissions corresponds to fugitive and flaring practices and these are originated through the stage of natural gas production (94.1%). Methane emissions associated to distribution of dry gas to economic sectors and not power facilities account for nearly 3% of total methane emissions. Transmission of dry gas through the network for electricity generation facilities accounts for 2% of overall methane emissions in the gas industry (table 8.3).

Table 8.3 contains a *subtotal of methane e*missions which consist of production, processing, storage, transmission and not distribution of natural gas to end-use economic activities. This subtotal accounts for methane emissions of dry gas used as a fuel in electricity generation. The model presented in this research differentiates between emissions due to transmission of dry gas to gas fired power stations $(E_{gas,TRANSMISSION})$ and emissions due to distribution of dry gas to other economic activities $(E_{gas,DISTRIBUTION})$.

Methane (Gg)

	Fugitive	Flaring	Raw Venting	TOTAL	(%)
Production	913.7	0.1		913.8	94.1%
Processing	8.6	0.1		8.7	0.9%
Transmission	12.1	7.5		19.6	2.0%
Storage				0.8	0.1%
			Subtotal	**942.8**	
Distribution				27.8	2.9%
			TOTAL	**970.6**	

Table 8.3 – Methane (CH_4e) Emissions in the Gas Industry in Mexico, 2005 (Gg)

Carbon dioxide emissions from fugitive emissions, flaring, and raw venting practices are reported for gas production and processing (table 8.4). Processing of natural gas represents the largest amount of CO_2 emissions in the gas industry (95.6%), of which CO_2 raw venting practices accounts for the largest proportion of these emissions through stage of processing. In addition, CO_2 emissions at the stage of natural gas production represent of around 4.4% of total carbon dioxide emissions in the gas industry. Carbon fugitive emissions through transmission and storage of oil are relatively insignificant (table 8.4) in comparison to emissions originated during oil production and processing.

Carbon dioxide (Gg)

	Fugitive	Flaring	Raw Venting	TOTAL	(%)
Production	7.3	104.9		112.2	4.4%
Processing	0.7	122.2	2,322.6	2,445.5	95.6%
Transmission	2.75E-02		9.94E-02	0.1269	0.0050%
Storage				0.0035	0.0001%
			Subtotal	**2,557.8**	
Distribution				1.5	0.1%
			TOTAL	**2,559.3**	

Table 8.4 – Carbon Dioxide (CO_2e) Emissions in the Gas Industry in Mexico, 2005 (Gg)

The amount of total methane emissions in the gas industry is converted into carbon dioxide equivalent mass by multiplying the total amount of methane emissions times a methane factor of global warming potential $(x21)$. The ratio (r) of CO_2 emissions to the CO_2 equivalent mass of methane emissions in the gas industry is 12.6 which suggest a high impact of methane emissions on global warming as compared to CO_2 emissions (equation 8.4).

$$r = \frac{CO_2 emissions_{gas.industry}}{CH_4 emissions_{gas.industry} * 21} = 12.6 \qquad \text{… (8.4)}$$

The amount dry gas which is delivered to power plants after taking transmission losses into account (stage 1.g.1 in gas map, figure 8.2b) is expressed in kWh by applying the following unit conversion:

$$D_{dry.gas}(kWh) = \frac{dry.gas(PJ) * 10\hat{}(9)}{3.6} \qquad \text{… (8.5)}$$

Where,

- $D_{dry.gas}$: Amount of dry gas delivered to power plants through the transmission network (T).

The total electricity produced from dry gas inputs into all power stations is calculated as follows:

$$e_{dry.gas} = D_{dry.gas} * p_{CCGT} * \eta_{CCGT} + D_{dry.gas} * p_{Turbo} * \eta_{Turbo} + D_{dry.gas} * p_{thermal} * \eta_{thermal} \qquad \text{… (8.6)}$$

Where,

- η_{xx} : is the efficiency of electricity generation by each of the relevant technologies as calculated according to the methodology developed in Chapter 9, sections 9.3.3-9.3.5 (results presented in table 9.3).
- ***P_{xx}:*** is the proportion of total dry gas which is used for electricity generation by that technology

Emission factors for each greenhouse gas (GHG_i) per kWh of electricity generated in gas fired plants is calculated as follows:

$$GHG_i.EF._{GAS,TRANSMISSION} = \frac{(Emissions_{GAS,TRANSMISSION})*10\hat{}(9)}{e_{dry.gas}} \quad \ldots (8.7)$$

Emission factors for each greenhouse gas (GHG_i) per kWh of electricity generated considering both transmission and distribution (T & D) is calculated as follows:

$$GHG_i.EF._{GAS} = \frac{(Emissions_{GAS,TRANSMISSION} + Emissions_{GAS,DISTRIBUTION})*10\hat{}(9)}{e_{dry.gas}} \ldots (8.8)$$

Table 8.5 presents results on emissions factors for CH_4 and CO_2 equivalent per kWh of electricity generated in gas fired power plants. These emission factors correspond to the delivery of dry gas to gas fired stations through the transmission network (T) and delivery of dry gas to both gas fired plants and the rest of economic activities using both the transmission and distribution networks (T & D). However, the case of emission factor considering both (T & D) responds to comparative purposes only because in practice other economic activities do not generate electricity (i.e. the denominator in equation 8.8) but other goods and services in the economy.

GHG	**T (g/kWh)**	**T & D (g/kWh)**
CH_4e	12.5	12.8
CO_2e	33.3	33.3

Table 8.5 – Greenhouse Gas Emission Factors in all Gas Fired Plants Using Equation 8.6, Mexico, 2005 (g/kWh)

Table 8.5 was developed only at a late stage in the research when the most comprehensive data sets became available. Previously data was only specifically available for the CCGT plant and using this information, the data in Table 8.6 was originally obtained. It is this last table from which data was used in subsequent analyses in Chapters 9 and 10. The differences in the values in Table 8.5 and 8.6 are small and when incorporating all other emissions the overall error in emissions is a small percentage ~ 4 %.

GHG	T (g/kWh)	T & D (g/kWh)
CH_4e	11.6	12.0
CO_2e	31.5	31.5

Table 8.6 – Greenhouse Gas Emission Factors in Gas Fired Plants in Mexico, 2005, using data solely from CCGT plant (g/kWh)

8.4.2 Calculation of Emission Factors per kWh in Conventional Thermal and Internal Combustion Electricity Generation

Conventional thermal plants in Mexico rely to a large extent on fuel oil combustion for electricity generation (99% of overall total fuel oil consumed in electricity plants) whereas internal combustion electricity generation consumes 6% of total overall diesel allocated to electricity generation plants. Diesel is also consumed to a large extent in open gas cycle turbines or turbo gas plants (47%) and CCGT (31%). However, because the most critical and important fuel in turbo gas and CCGT plants is dry gas, this category of generation technologies is included in the previous section.

Fuel oil and diesel are two major critical outputs from oil processing in refinery plants. The following stages are considered when calculating greenhouse gases emission factors in oil industries:

1) Oil production (stage 2.a, oil map, figure 8.4a)
2) Oil transport through pipelines (i.e. only the amount of oil accounting for domestic transformation in oil plants, stage 2.b, oil map, figure 8.4b)

3) Oil refining (2.b.1, oil map, figure 8.4b)

GHG emission calculations are obtained on the basis of tier 1 approach which consists of the assignation of specific emission factors associated to the stages specified above (IPCC, 2006):

$$E_{oil,inudstrysegment} = A_{oil.segment} * EF_{oil,industrysegment} \quad \text{…. (8.9)}$$

Total fugitive emissions in oil industry:

$$E_{oil} = \sum_{industry.segments} E_{oil,industry.segment} \quad \text{… (8.10)}$$

Where,

- $E_{oil,industry.segment}$: annual emissions in oil industry,
- $EF_{oil,industry.segment}$: emission factor,
- $A_{industry.segment}$: activity value in oil industry.

IPCC (2006) guidelines report default emission factors of each industry segment of oil activity in Gg of GHG per thousand cubic meter of oil production. These emission factors are converted into thermal energy units (PJ) in order to apply equation (8.9) to activity data corresponding to fossil fuels reported in energy balance tables. The following equation is employed for unit conversion of emission factors from *Gg of GHG per thousand cubic meter of oil* (i.e. a unit of volume) into *kg of GHG per PJ of natural gas* (i.e. an energy thermal unit):

$$EF_{oil.industry} = \left(\frac{kg_{GHGi}}{PJ_{oil.consumed}}\right) = \left(\frac{Gg_{GHGi}}{10\hat{}(3) cum.oil}\right) * \left(\frac{1}{CV_{GHGi}}\right) * 10\hat{}(9) \quad \text{… (8.11)}$$

Where,

- $EF_{oil.industry}$: Emission factor of greenhouse gas i in oil productive activities.
- CV_{GHGi} : calorific value of greenhouse gas *i, (in MJ per cum)*
- i = 2, $GHG_1 = CH_4$ equivalent and $GHG_2 = CO_2$ equivalent.

According to the emission factors presented by IPCC (2006), GHG emission factors differ whether they relate to conventional oil production; heavy oil/cold bitumen production; thermal oil production; synthetic crude (from oil-sands); and synthetic crude (from oil shale). This information allows calculating specific values of GHG according to three main types of oil production in Mexico (see figure 8.9):

1) Heavy crude oil (72% of total oil production in 2005)
2) Light crude (24% of total oil production in 2005)
3) Super-light crude (4% in total oil production in 2005)

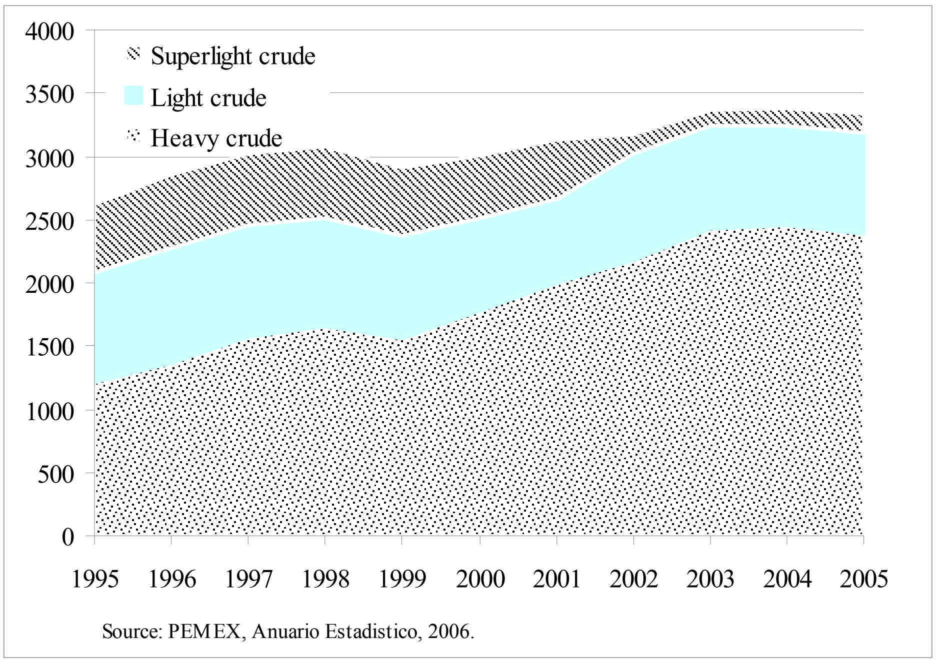


Figure 8.9 – Share of Crude Oil in Production by Type, Mexico, 1995-2005 (Thousand of daily barrels)

Production of heavy crude oil in Mexico is denominated Maya; production of light crude is regarded as Istmo; and production of super light crude is referred as Olmeca. Production of Olmeca from oil fields has considerably decreased whereas production of Maya has increased in recent years. These differences are important not only because of the different GHG emission factors reported for different types of crude production but also because of different densities and calorific values associated to each type of crude extracted in Mexico. For instance, a CV for Maya oil (i.e. 34,216.5 MJ per cum) is higher than that for Olmeca (i.e. 25,920.3 MJ per cum).

Methane emission factors for heavy oil/cold bitumen production are generally higher that those for conventional crude production.

In the model of this chapter, a calorific value (CV) for light crude oil is used for energy unit conversion of an emission factor reported for conventional crude production whereas a CV for heavy crude oil is used for energy unit conversion of an emission factor reported for heavy oil/cold bitumen production. The criteria for selecting CV for conventional crude and heavy oil production is based on the fact of a relatively small proportion of super light crude in total oil production.

Table 8.7 and table 8.8 present results of overall methane and carbon dioxide emissions in the oil industry, respectively, in 2005. Maya crude oil dominates oil production in Mexico rising from 47% to 72% between 1995 and 2005 (PEMEX, 2006). Using the structure of the oil industry (stages 2.a to 2.e in oil map, figure 8.4a and 8.4b) in Mexico as of 2005 and the specific emission factors in equations (8.9) – (8.11) it can be shown that the majority of methane emissions in the petroleum industry corresponds to the stage of production of heavy oil (i.e. Maya crude which accounts for 99.6% of total overall methane emissions in the oil industry, table 8.7).

Methane Emissions (Gg)

Production	Fugitive	Venting	Flaring	TOTAL	%
Heavy	9,671.9	2,805.5	23.1	12,500.5	99.6%
Light	0.0	42.5	1.5	44.0	0.4%
Superlight	0.0	7.6	0.3	7.9	0.1%
Total Production	**9,671.9**	**2,855.6**	**24.9**	**12,552.4**	
Transport by pipelines				0.5	0.004%
Refining				2.1	0.017%
			TOTAL	**12,554.9**	

Table 8.7 – Methane (CH_4e) Emissions in the Oil Industry in Mexico, 2005 (Gg)

The majority of methane emissions in the production heavy crude oil correspond to fugitive emissions whereas in the case of light and super light crude production, most methane emissions correspond to venting practices (figure 8.6). Differences in emissions across different types of oil production and among fugitive, venting, and flaring practices are explained in view of large differences in GHG emissions factors reported by IPCC (2006 pp. 4.55 to 4.63). This variability is related to the uncertainties of the values assigned to each emission factor. For instance, in the case of fugitive emission for offshore conventional oil production, uncertainties in emission factors reported vary between -12.5% and 800 % whereas in the case of venting and flaring practices for conventional oil production, uncertainties of reported emission factors are on a +/- 75% range (IPCC, 2006, pp. 4.55-4.63). In the model of this chapter, a value in between a lower and upper value was chosen.

Methane emissions factors associated with the transportation of oil through the pipelines are relatively insignificant (i.e. less than 1% of overall total methane emissions in the oil industry). Emission factors for methane emissions during the distribution of oil refined products (i.e. diesel and fuel oil in the case of Mexico) are not available in the IPCC guidelines (2006).

Carbon dioxide emissions in the oil industry are mostly localised during production of heavy crude (64% of total overall CO_2 emissions in the petroleum industry); light crude production (30%), and super light crude production (around 5%). Carbon dioxide emissions through oil transportation by pipelines and refining activities are relatively marginal (i.e. less than 0.01% of overall CO_2 emissions in oil activities). Flaring practices are invariably the most important source of CO_2 emissions in oil production, followed by venting practices and fugitive emissions (table 8.8).

Carbon Dioxide (Gg)

Production	Fugitive	Venting	Flaring	TOTAL	%
Heavy	669.1	883.7	3,647.1	5,199.9	64.6%
Light	0.0	5.6	2,410.3	2,415.9	30.0%
Superlight	0.0	1.0	432.9	433.9	5.4%
Total Production	**669.1**	**890.3**	**6,490.3**	**8,049.7**	
Transport by pipelines				0.043	0.001%
Refining				n.a.	0.0%
			TOTAL	**8,049.8**	

Table 8.8 – Carbon Dioxide (CO_2e) Emissions in the Oil Industry in Mexico, 2005 (Gg)

Results of methane and carbon dioxide emissions in relation to gas and oil industries presented in this research are compared to those results obtained in previous studies. In this research, it is found that 913.8 Gg of methane correspond to production of natural gas in 2005. This value is compared to 483.6 Gg of methane from both oil and gas production and 1335.6 Gg attributed to venting routines in gas activities in Mexico in 2003 (Cuatecontzi-Santa Cruz, 2005). Sources of these differences are attributed to:

1) Delimitation between fugitive, flaring, and venting activities when reporting GHG emissions through specific stages of energy industries in this research.
2) The use of updated and more refined emission factors for energy industries. IPCC methodology guidelines and associated factors changed significantly between the 1996 and 2006 version. The earlier data was used by Cuatecontzi-Santa Cruz, (2005) where as this research used the later data..
3) High uncertainties in the values assigned to emission factors in the IPCC guidelines version 2006 as well as large differences between the lower and upper value for emissions factors on fugitive emissions for methane reported in the IPCC guidelines version 1996.

The ratio (r) of CO_2 emissions to the CO_2 equivalent mass methane emissions in the oil industry is 3.05 (equation 8.12) the value of which is smaller than the (r) value in the gas industry (12.6%).

$$r = \frac{CO_2 emissions_{oil.industry}}{CH_4 emissions_{oil.industry} * 21} = 3.05 \qquad \ldots (8.12)$$

The amount of fuel oil and diesel delivered to conventional thermal and internal combustion power plants, after taking into account losses in raw oil feed transformation in refinery plants and non energy uses (stage 2.e in oil map, figure 8.4b), is expressed in kWh by applying the following unit conversion:

$$D_{fuel.oil}(kWh) = \frac{fuel.oil(in.PJ) * 10\hat{}(9)}{3.6} \qquad \ldots (8.13)$$

$$D_{diesel}(kWh) = \frac{diesel(in.PJ) * 10\hat{}(9)}{3.6} \qquad \ldots (8.14)$$

Where,

- $D_{fuel.oil}$: Amount of fuel oil delivered to conventional thermal power plants.
- D_{diesel} : Amount of diesel consumed in internal combustion power plants.

Electricity generated from fuel oil combustion in conventional thermal power plants is calculated as follows:

$$e_{fuel.oil} = D_{fuel.oil} * (\alpha) * \left(\frac{\eta_{conventional.thermal}}{100} \right) \qquad \dots (8.15)$$

Electricity generated from diesel consumption in internal combustion technology is calculated as follows:

$$e_{diesel} = D_{diesel} * (\beta) * \left(\frac{\eta_{internal.combustion}}{100} \right) \qquad \dots (8.16)$$

Total electricity generated from fuel oil and diesel inputs consists of:

$$e_{fuel.oil,diesel} = e_{fuel.oil} + e_{diesel} \qquad \dots (8.17)$$

Where,

- $\alpha + \beta = 1$: Proportion of fuel oil allocated between conventional thermal and internal combustion electricity generation.
- $\eta_{conventional.thermal}$:Thermal efficiency in a representative conventional thermal power station.
- $\eta_{internal.combustion}$:Thermal efficiency in a representative internal combustion power station.

Emission factors for each greenhouse gas (GHG_i) per kWh of electricity generated in oil fired plants is calculated as follows:

$$GHG_i.EF_{oil} = \frac{Emissions_{oil} * 10\wedge(9)}{e_{fuel.oil,diesel}} \qquad \dots (8.18)$$

Results of emissions factors for CH_4 and CO_2 equivalent per kWh of electricity generated in oil fired plants are reported in table 8.9.

GHG	(g/kWh)
CH_4e	226.1
CO_2e	144.9

Table 8.9 – Greenhouse Gas Emission Factors in Oil Fired Plants, Mexico, 2005 (g/kWh)

8.4.3 Calculation of Emission Factors per kWh in Coal Fired Power Stations and Dual Fuel Plants

In Mexico, the term carbo-electricity is related to coal fired plants. Dual fuel electricity generation relies mostly on coal combustion (i.e. above 99% of total fuel employed in a dual fuel plant). There are only two coal fired stations and one dual plant in Mexico. However, coal based electricity accounts for around 10% of total installed capacity as of 2005. The relative importance of coal based installed capacity has decreased to 9.25% of overall total capacity in 2008. The following stages are considered in the calculation of greenhouse gas emission factors in the sub-bituminous coal industry:

1) Mining and post-mining activities of which,
    a. Production (stage 3.1 in coal map, figure 8.7)
    b. Coal Imports (stage 3.2 in coal map, figure 8.7)
    c. Coal to electricity plants (stage 3.3 in coal map, figure 8.7)
    d. Coal to final consumption in industry (stage 3.4, figure 8.7)
2) Underground and surface mining of which
    a. Underground mining (77% of total coal production)
    b. Surface mining (23% of total coal production)

GHG emission calculations are obtained on the basis of tier 1 approach (IPCC, 2006):

$$E_{coal,inudstrysegment} = A_{coal.segment} * EF_{coal,industrysegment} * UCF \quad \dots (8.19)$$

Where,

- UCF : Unit conversion factor (670 g per cum, density of methane at 20 C and 1 atmosphere pressure, IPCC, 2006).

Methane emission factors are reported for coal mining and post-mining according to the deep of the seam in three major categories: low, average and high. For a mining depth shorter than 200 m a low emission factor is recommended whereas for a mining depth higher than 400 m a high emission factor is suggested (Op. Cit). Because data available in this research does not inform on the specific depths of mining activity, an average methane emission factor is chosen.

Results of methane emissions are presented in table 8.10 for both the amount of coal employed in iron & steel (i.e. coking coal) and coal employed in electricity generation (i.e. sub-bituminous coal). Methane emissions are predominantly generated in mining activities (87.8%) as compared to post-mining activities (12.2%). Methane fugitive emissions associated with sub-bituminous coal used in electricity generation $\left(Emissions_{coal,electricity}\right)$ account for 247.1 Gg (87.3%) whereas methane fugitive emissions associated with bituminous coal used in coking plants $\left(Emissions_{coal,steel}\right)$ in the iron and steel industry account for 32.3 Gg (11.4%) – (figure 8.10).

Methane Emissions (Gg)

Thermal or subbituminous coal	Coal Mining	Coal post mining	Total	%
Coal to power producers	217.0	30.1	247.1	87.3%
Coal to final consumption in industry	3.3	0.5	3.7	1.3%
Sub-total	**220.2**	**30.6**	**250.8**	
Coal to coking plants in iron and steel	28.3	3.9	32.3	11.4%
TOTAL	248.6	34.5	283.1	100.0%

Table 8.10 - Methane (CH_4e) Emissions in the Coal Industry in Mexico, 2005 (Gg)

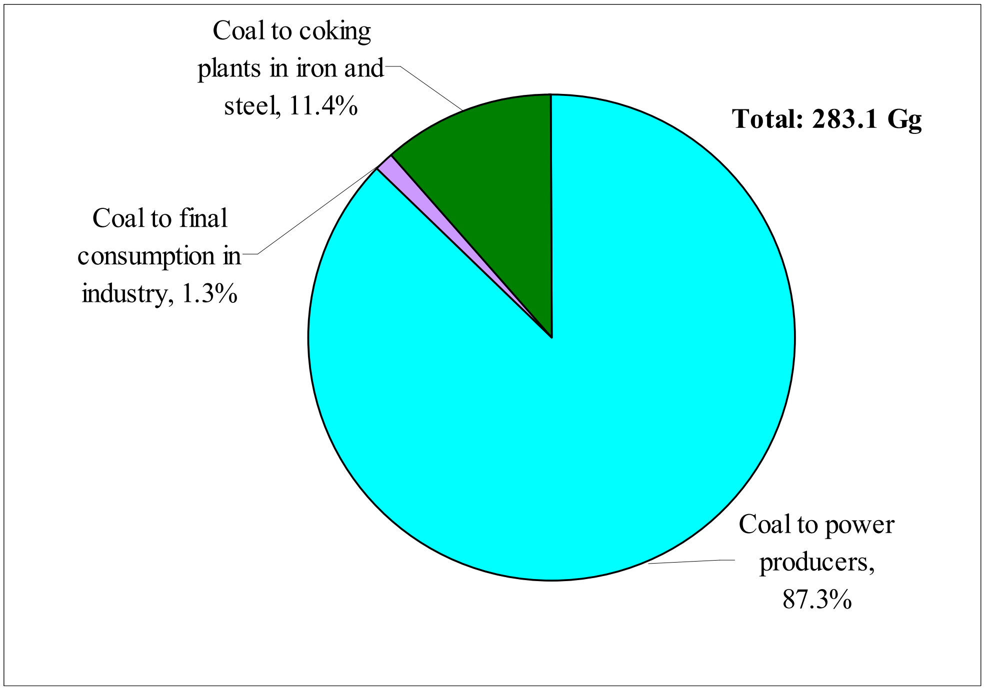


Figure 8.10 – Distribution of Methane Emissions Associated to Coal Uses, Mexico, 2005 (%)

The amount of coal employed in electricity generation accounts for 327 PJ in 2005. This amount is expressed in KWh by applying the following unit conversion:

$$D_{coal}(kWh) = \frac{coal(PJ)*10\wedge(9)}{3.6} \qquad \ldots (8.20)$$

Total electricity generated from sub-bituminous coal in coal fired stations is calculated as follows:

$$e_{coal} = D_{coal}(kWh)*\eta_{coal}/100 \qquad \ldots (8.21)$$

Where,

- η_{coal} : Thermal efficiency in a representative coal fired station in Mexico.

An emission factor of each greenhouse gas (GHG_i) per kWh of electricity in coal fired plants is calculated as follows:

$$GHG_i EF_{coal} = \frac{(Emissions_{coal,electricity})*10\wedge(9)}{e_{coal}} \qquad \ldots (8.22)$$

Methane emissions associated with sub-bituminous coal consumed in power stations (i.e. coal to power producers in table 8.9) are chosen as a value in the variable $\left(Emissions_{coal,electricity}\right)$ in equation (8.22). This amount of emissions corresponds to the proportion of coal consumed in electricity generation (87.3%). Using equation (8.22), it is found that 7.6 g of methane equivalent fugitive emissions per kWh are associated with coal fired plants (table 8.11). An emission factor may also be calculated considering fugitive emissions of both sub-bituminous coal consumed in power stations and sub-bituminous coal for final consumption in industry (i.e. a subtotal of methane emissions from coal in table 8.10). In this later case the corresponding emission factor assuming sub-bituminous coal for other industry uses are also used for electricity generation amounts to 7.7 of methane equivalent fugitive emissions per kWh.

The IPCC (2006) guidelines do not provide a reference fugitive emission factor of carbon dioxide associated to coal mining activities. In view of this data limitation, it is not possible to calculate a representative CO_2 emissions factor per kWh of the fugitive emissions of coal used in power plants with the use of the proposed methodology. This limitation is resolved in chapter 9 in section 9.3.7.

	Power plants	**Power plants & other industry uses***
GHG	g/kWh	g/kWh
CH_4e	7.589	7.703
* Not iron and steel.		

Table 8.11 – Methane (CH_4e) Emission Factors in Coal Fired Plants and Final Consumption in Industry*, Mexico, 2005 (g/kWh)

8.5 Summary of the Chapter

Gas, fuel oil, and coal are the major fuels in the mix of electricity generation in Mexico accounting for 41%, 22%, and 15%, respectively, in 2007. This puts a pressure on the growth of greenhouse gases in the electricity sector. This chapter has elaborated on a methodology to quantify the methane and carbon fugitive emissions and the corresponding emission factors during the production, refinery, and delivery of these fuels into electricity plants.

Of the total gas available, 55.3% is used in electricity generation whereas 44.7% is used in other economic sectors after taking into account transmission loses in 2005. It was found that 12.7% of overall domestic natural gas production corresponds to imports thus increasing the availability of dry gas. However, energy loses through transportation, transmission, distribution, and storage are significant and amounted to nearly 26% of net total available dry gas.

Fuel oil for electricity generation represented 64% whereas diesel accounted for 2% of overall fuel oil and diesel, respectively, obtained from refineries in 2005. Energy loses in the petroleum industry are relatively small since they account for 1% of overall raw oil feed used in refineries. Around 79% of total electricity generation in Mexico is based on the consumption of fuel oil in conventional thermal plants.

Coal is used in the iron and steel industry and in power plants for electricity generation. The majority of coal is used for electricity generation in Mexico. Bituminous coal used in coking plants in the iron and steel industry represents around 13% of the sub-bituminous coal used for electricity generation. Domestic production and imports of sub-bituminous coal used in power plants represented around 55% and 45%, respectively, in 2005.

In the gas industry, the majority of fugitive methane emissions correspond to the stage of gas production (94% circa) whereas the majority of carbon dioxide emissions are associated to the stage of gas processing (96% circa) in 2005. In the petroleum industry, the largest amount of fugitive methane and carbon dioxide emissions take place during the production of heavy crude oil (around 99% and 65%, respectively) in the same year. In the coal industry, fugitive methane emissions from coal used in power plants, the steel sector, and other industrial uses accounted for 87.3%, 11.4%, and 1.3%, respectively, in the same year.

The following table (table 8.12) summarises the fugitive emissions for gas, oil and coal as estimated in this chapter and are used in chapter 9 in the calculation of overall carbon emissions factor in the Mexican electricity sector.

	CH_4e	CO_2e
Fuel used in power stations	grams/kWh	grams/kWh
Gas	11.6	31.5
Fuel oil and diesel	226.1	144.9
Coal	7.6	

Table 8.12 – Fugitive Methane (CH_4e) and Carbon Dioxide (CO_2e) Emission Factors of the Fuels Used in Power Plants, Mexico, 2005 (g/kWh)

The carbon emission factor of the fugitive emissions of coal is not presented in this chapter for limitation reasons given above but are estimated in the next chapter.

Chapter 9

Modelling a CO_2 Emission Factor of the Mexican Electricity Grid

Introduction

This chapter presents the second component of the life cycle assessment of carbon emissions and identifies future energy scenarios in electricity generation. The results of the fugitive emission factors obtained in chapter 8 are incorporated in the calculations of this chapter. This analysis is important as some parts of the iron and steel industry are very dependent on electricity. Changes in the structure and composition of the Mexican electricity system and consequential changes in the carbon emission factor for electricity will significantly affect the future carbon emissions from the iron and steel industry

The focus of this chapter is on the calculation of emissions from stationary combustion associated to electricity and heat production as defined in (IPCC, 2006). These emissions arise from the actual conversion of the fossil fuels into electricity and the emission factors here will be primarily dependent on two factors: a) the carbon content of the fuel, and b) the efficiency of generation in the plant.

Mexico, as a non Annex I party of the Conference of the Parties (COP) of the Kyoto Protocol (article 13, p.11, UNFCCC, 1997) is not required to comply with targets of greenhouse gas emissions reductions. Interestingly, Mexico volunteered to cut carbon emissions by 50 million tonnes per year after 2012. In this proposal the power plants in the electricity sector and oil and gas industries were proposed as strategic areas to lower leakages and flaring practices as main contributors to carbon emissions (Reuters, 2009).

The Clean Development Mechanism (CDM) is one of the mechanisms under the Kyoto Protocol under which non Annex I countries can receive assistance in carbon reduction while not jeopardising an increase in the standard of living of their citizens. , Of the total of 2430 CDM projects so far approved (autumn 2010), China is at the top with regards to the number of CDM registered projects (40.6%) followed by India (22.1%) and Brazil (7.4%). Mexico is placed just after Brazil with 5.1% of registered CDM projects (UNFCCC, 2010).

It is in this context where the holistic approach inclusive of the fugitive emissions in oil and gas and the energy scenarios in electricity generation turns crucial. From a holistic approach, it is important to assess the strategies in regards to the fuel mix of electricity generation and how they have an impact on the emissions from electricity uses in the steel industry.

The chapter is organised as follows: section 9.1 introduces installed capacity in electricity generation in Mexico; section 9.2 discusses the descriptive statistics of the energy data of power plants; section 9.3 contains the methodology; section 9.4 presents carbon emissions scenarios; section 9.5 introduces a review of the energy scenarios taking into account the effect of electricity loses on carbon emissions; and section 9.6 presents a summary of the main findings.

9.1 Overview of the Installed Capacity

The total overall installed capacity in electricity generation has increased at an annual compound growth rate of 4.3% in the period 1980-2008. Overall the total installed capacity increased from 16,862 MW in 1980 to 50,803 MW in 2008. Conventional thermal electricity generation which relies on fuel oil combustion traditionally accounts for an important share in overall installed capacity in Mexico (figure 9.1). However, the relative importance of conventional thermal technology has decreased from 37.9% of overall installed capacity in 1981 to 25.3% in 2008.

In addition, Mexico relies to a large extent on the use of hydro electricity of which share in overall installed capacity has declined from 1/3 in 1981 to 22.3% in 2008. A decline in the relative importance of conventional thermal and hydro electricity in relation to overall installed capacity has been accompanied by three trends in the electricity sector in Mexico:

1) A growing importance of combined cycle gas turbines (CCGT) with respect to overall installed capacity (from 6.19% in 1981 to 10.74% in 2008).
2) An increasing share of coal fire power stations and dual plant capacity; both generation technologies account for 9.2% in 2008.
3) An increasing contribution of private sector in overall installed capacity of which importance represents 22.5% in 2008.

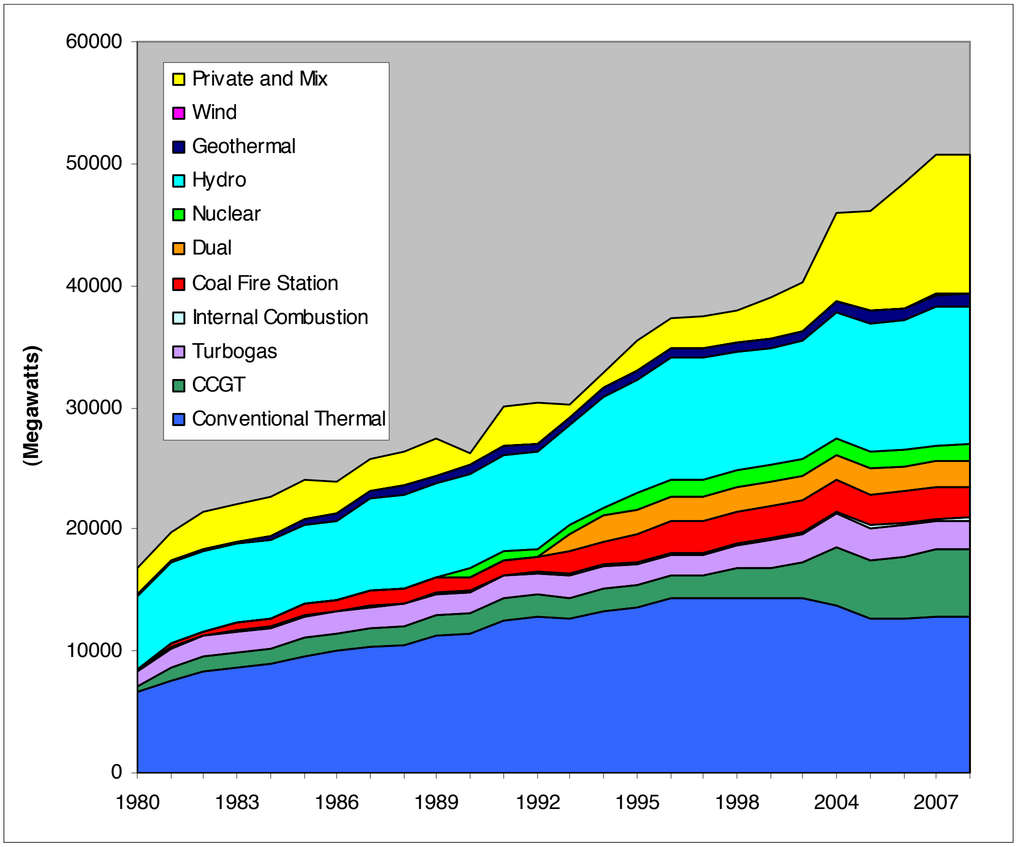


Figure 9.1 – Installed Capacity by Electricity Generation Technology, Mexico, 1980-2008 (Megawatts)

Source: INEGI, Indicadores Anuales, Subsector Eléctrico, 1980-2000; SENER, Sistema de Información Energética, Capacidad Efectiva por Fuente, 2004-2008.

9.2 Energy Data and Descriptive Statistics

Detailed calculation of CO_2 emissions from stationary combustion in electricity generation requires information on the fossil fuel consumption at the plant level. At the time of this research, the latest date at which such specific data at the plant level was available was 2005, and thus much of the detailed analysis reported here relates to this year. For the public sector electricity data, information was available at the individual plant level and there were a total of 71 power plants reported.

Data at the individual plant level is not available for the Independent Power Producers, this information is only available in aggregate terms by mode of generation. Figure 9.2 shows the distribution of fossil fuel power plants by type of generation technology and may be summarized as follows: turbo gas plants (i.e. open cycle gas turbines) account for 38%; conventional thermal plants represent 35%; CCGT (15%); coal and dual fuel plants account for 4% while the remaining 8% of fossil fuel plant are internal combustion devices. In recent years, electricity generation using CCGT technology has become increasingly important in the private sector. However, plant data used in the analysis of this chapter whether CCGT or other type of generation relates to the public sector.

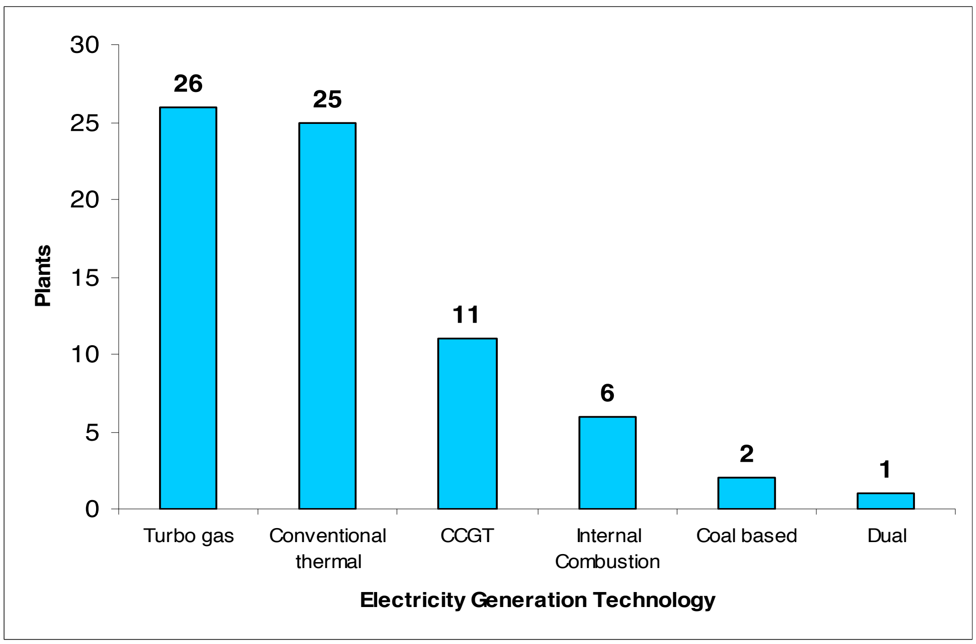


Figure 9,2 – Distribution of Power Plants by Generation Technology, Mexico, 2005

Source: SENER, Planeación Energética, Emisiones del Sector Eléctrico, 2005.

9.3 Methodology

9.3.1 Overall Efficiency in Electricity Generation

The overall efficiency in electricity generation may be calculated as follows:

$$\eta = \frac{e_t}{\xi_t} \qquad \ldots (9.1)$$

Where

$$\xi_t = \xi_{fossil.fuels,t} + \xi_{renewables.input,t} + \xi_{nuclear,t} \quad \ldots (9.2)$$

Where,

- e_t :total electricity produced by the Electricity Public Service (i.e. CFE and LyFC) and Independent Power Producers (IPP) in period *t*;
- $\xi_{fossil.fuels,t}$: is the total fossil fuel energy input from pet coke, coal, diesel, and fuel oil.
- $\xi_{renewables,t}$: is the total renewable energy input from wind, hydro, and geothermal.
- $\xi_{nuclear,t}$ is the nuclear fuel input

Overall thermal efficiency growth in electricity generation in Mexico has been sustained over the period 1965-2007 (see figure 9.3). Three factors partially account for a long term growth in the efficiency of thermal electricity production in Mexico:

1) Changes in the fuel mix of electricity generation;
2) Technological upgrading due to the incorporation of CCGT plants;
3) Cumulative production and accumulation of productive knowledge in the electricity sector.

The efficiency trend in electricity generation depicted in figure 9.3 encapsulates structural changes taking place in the electricity sector in Mexico. The efficiency in electricity generation in the public sector increased from 26% in 1965 to nearly 36% in 2007 (i.e. blue line in figure 9.3). When electricity generated by IPP is considered in the calculations obtained using equation (9.1), overall efficiency in electricity generation increased from 34% in year 2000 to nearly 40% in 2007.

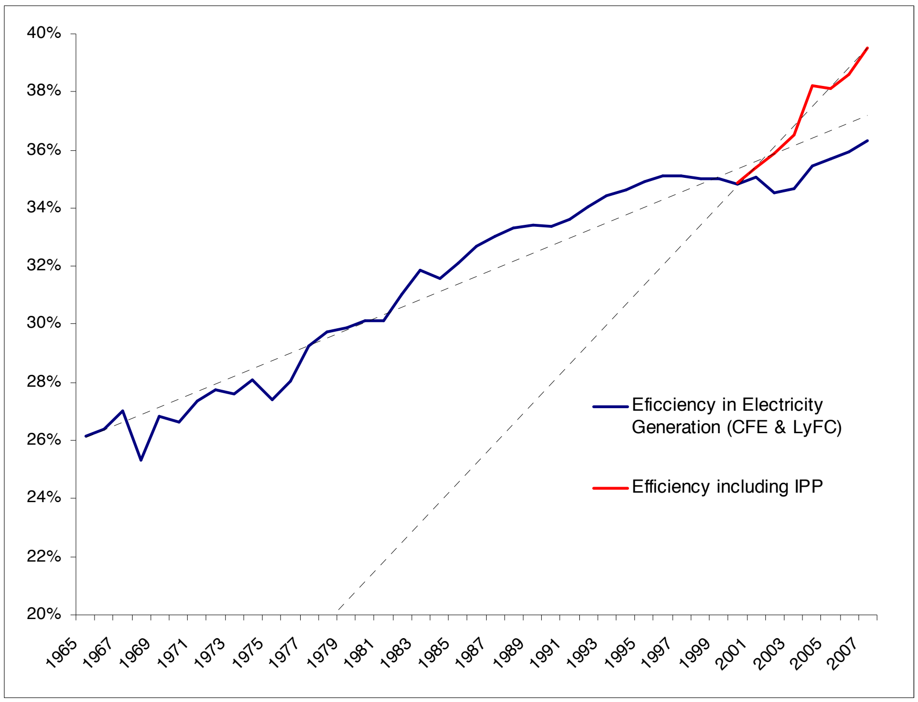


Figure 9.3 – Long Term Efficiency Trend in Electricity Generation in Mexico, 1965-2007 (%)

Source: own calculations based on SENER, Sistema de Información Energética, México.

Three observations are worthy of mentioning at this point of the analysis:

- Firstly, CCGT technology run by IPP plants has had an improvement effect on the overall efficiency in electricity generation in Mexico as of 2000. The gap between the red and blue lines in figure 9.3 represents an area accounting for increased efficiency due to participation of IPP in electricity generation.

- Secondly, at the same time, electricity generation in the public sector has also now started operation of combined cycle plants in recent years. Dos Bocas was the first combined cycle plant commissioned by CFE in 1974 whereas Hermosillo is the most recent plant to be commissioned at the end of 2005.

- The dotted black lines (i.e. linear trends) in figure 9.3 suggest an increasing rate of improvement in recent years in the efficiency of electricity generation $(\partial \eta_t / \partial t)$. Table 9.1 compares the growth rate of efficiency of electricity generation of only state-owned plants against the efficiency of both state-owned and private plants.

Structure	Period	Annual improvement rate
Long term efficiency trend (no IPP)	1965-2000 (only public sector)	0.80 %
Efficiency trend in state-owned power plants (i.e. CFE & LyFC)	2000-2007 (only public sector)	0.53 %
Efficiency trend including both state and IPP plants	2000-2007 (public sector and IPP)	1.58 %

Table 9.1 – Efficiency of Electricity Generation in Mexico (growth rate %)

9.3.2 A Particular Case: Calculation of Efficiency in IPP plants

Given the growing importance of IPP plants in electricity generation it is relevant to estimate the efficiency of these plants. CCGT relies on natural gas combustion, although according to national energy balance tables, there is also consumption of diesel in these IPP power facilities which is relatively very small as the ratio of diesel to natural gas in such plants has varied within the range of 0.1 to 1.0 % between 2001 and 2007. The gas efficiency of conversion considers the contribution of diesel to thermal energy (measured in PJ) as follows:

$$\eta = \frac{e_{IPP,t}}{\left(\xi_{dry.gas,t} + \xi_{diesel,t}\right)} \quad \ldots (9.3)$$

Where,

- $e_{IPP,t}$: amount of electricity generated by IPP and self-supply societies (equivalent to thermal energy and measured in PJ),
- $\xi_{dry.gas,t}$: dry gas input (as thermal energy, measured in PJ) used for private electricity generation,

- $\xi_{diesel,t}$: diesel input (as thermal energy) used for private electricity generation.

Thermal efficiencies of CCGT plant within IPP plants in Mexico have performed with average efficiencies of above 50% in the period 2000-2007 (figure 9.4).

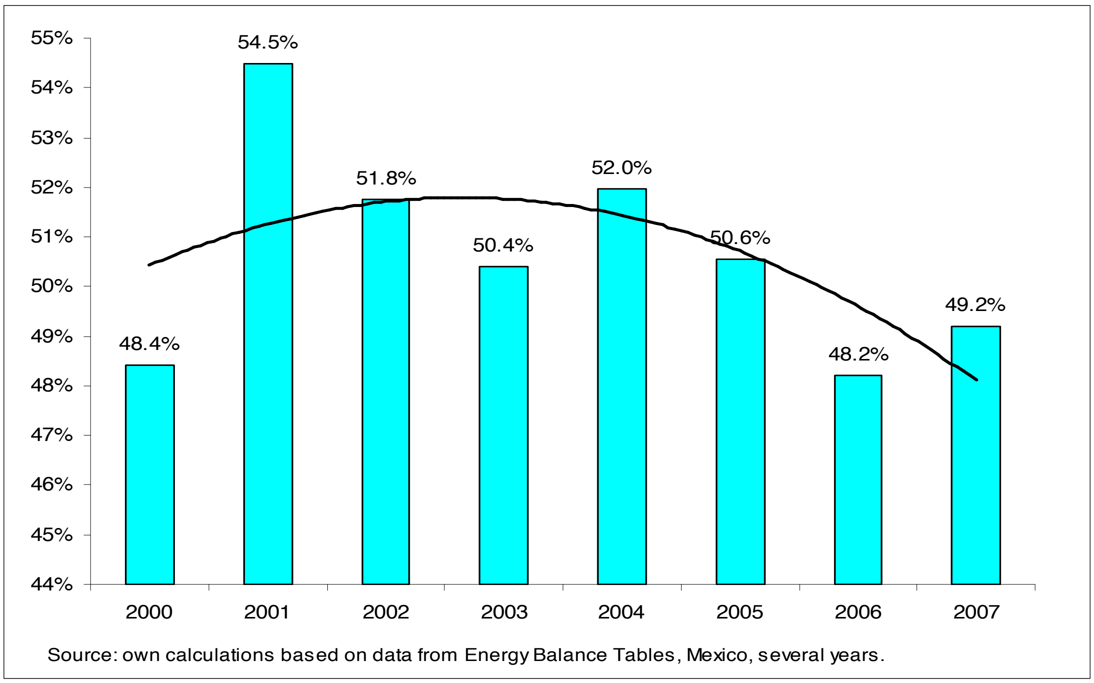


Figure 9.4 – Gas Efficiency of Conversion in Power Plants of Independent Power Producers (CCGT) in Mexico, 2000-2007 (%)

9.3.3 Calculation of Thermal Efficiencies in Electricity Generation

Data provided by the Ministry of Energy in Mexico (SENER) was used as the basis of much of the analysis reported in this chapter. Key parameters extracted from this data set include i) the type and amount of fossil fuel consumed in each power plant, ii) the declared capacity (MW), and iii) the electricity generation (GWh) in 2005. Primary data on fossil fuel consumption include:

a) Fuel oil consumption $\left(X_{fuel.oil}\right)$, unit of measurement: thousand cubic meters per year

b) Natural gas $\left(X_{gas}\right)$, unit of measurement: million cubic meters per year

c) Diesel $\left(X_{diesel}\right)$, unit of measurement: thousand cubic meters per year

d) Coal $\left(X_{coal}\right)$, unit of measurement: thousand tonnes per year

As the consumption data of all fuels were in different units conversion of the raw data in the original units of measurement to the conventional SI unit (i.e. TERA Joules, TJ) was necessary. This conversion was achieved using the following equations:

$$X_{fuel.oil}(in.TJ) = \left[\left(X_{fuel.oil} * 10^3\right) * \frac{\rho_{fuel.oil}}{10^3} * CV_{fuel.oil}\right] / 10^3 \quad \ldots (9.4)$$

$$X_{natural.gas}(in.TJ) = \left[\left(X_{gas} * 10^6\right) * \frac{\rho_{gas}}{10^3} * CV_{gas}\right] / 10^3 \quad \ldots (9.5)$$

$$X_{diesel}(in.TJ) = \left[\left(X_{diesel} * 10^3\right) * \frac{\rho_{diesel}}{10^3} * CV_{diesel}\right] / 10^3 \quad \ldots (9.6)$$

$$X_{coal}(in.TJ) = \left\lfloor\left(X_{coal} * 10^3\right) * CV_{coal}\right\rfloor / 10^3 \quad \ldots (9.7)$$

Where,

- ρ_j : Density of each fossil fuel (j), unit: kg per cubic meter (cum)
- CV_j : Calorific value of each fossil fuel (j) consumed in Mexico, unit: MJ per kg or GJ per tonne.

Energy consumption (ξ) of each fossil fuel by generation technology is calculated as follows:

In the most general form the total consumption of all fossil fuels $\left(\xi_{fossil\ fuels}\right)$ for each power station type will be given by:

$$\xi_{fossil.fuels} = \sum_{i=1}^{n} x_{i,fuel.oil} + \sum_{i=1}^{n} x_{i,gas} + \sum_{i=1}^{n} x_{i,diesel} + \sum_{i=1}^{n} x_{i,coal} + \ldots \quad (9.8)$$

Where n is the number of power stations in each fuel type.

In the case of the CCGT stations which use primarily natural gas and sometimes small quantities of fuel oil and/or synthetic gas, the relationship will be:

$$\xi_{CCGTs} = \sum_{i=1}^{n} x_{i,gas} + \sum_{i=1}^{n} x_{i,fuel\_oil} + \sum_{i=1}^{n} x_{i,syn\_gas} \quad (9.8.1)$$

Equation (9.8) for the rest of generation technologies can be generalized as follows:

$$\xi_{fossil.fuels,} = \sum_{i=1}^{n} \sum_{j=1}^{r} x_{i,j} \quad \ldots (9.9)$$

Where,

- $x_{i,j}$: Amount of fuel j consumed in plant i
- Where r represents the number of different fuels used, and in this case,

  j = 1 refers to gas

  j = 2 refers to fuel oil

  j=3 refers to synthetic gas

  Etc.

Similarly, for the steam generating plants using different fuels:

$$\xi_{COAL} = \sum_{i=1}^{n} x_{i,coal} \quad \ldots (9.10a)$$

$$\xi_{FUEL\,OIL} = \sum_{i=1}^{n} x_{i,fuel\_oil} \quad (9.10b)$$

$$\xi_{GAS} = \sum_{i=1}^{n} x_{i,gas} \quad (9.10c)$$

$$\boldsymbol{\xi_{DUAL-fuel} = \sum_{i=1}^{n} \sum_{j=1}^{r} x_{i,j}} \quad \ldots (9.11)$$

Here J will respectively relate to the component fuel types in each plant which has dual fuelling.

In Mexico, conventional thermal stations usually refer only to those steam generating stations powered by fuel oil or gas. The term "vapour" is used in the statistics when referring to these stations. This is somewhat different from normal convention which will group all steam generating stations including coal one group (conventional) and CCGT stations in another. Overall the fuel input to all steam generating stations will be:

$$\xi_{CONVENTIONAL.THERMAL\_STEAM,\_STATIONs} = \sum_{J=1}^{n} \sum_{i=1}^{n} x_{i,j} \quad \ldots (9.12)$$

In this case J can take values of:

1 – gas

2 – coal

3 – oil

etc.

For the remaining fossil fuel electricity generation stations, similar relationships as follows may be specified:

$$\xi_{INTERNAL.COMBUSTION} = \sum_{i=1}^{n} x_{i,internal\_combustion} \quad \ldots (9.13)$$

$$\xi_{TURBO.GAS} = \sum_{i=1}^{n} x_{i,turbo\_gas} \quad \dots (9.14)$$

The term turbo-gas used in Mexican statistics refers to open circuit gas turbines (OCGT).

The efficiency of electricity generation of each generation technology is calculated using equation (9.1) as follows:

$$\eta_{tech,t} = \left(\frac{e_{tech,t}}{\xi_{tech,\, t}} \right) * 100 \quad \dots (9.1.1)$$

Where,

- $e_{tech,t}$: Electricity generated by each generation technology (figure 9.2)
- $\xi_{tech,t}$: Total energy inputs consumed by each generation technology. These values are obtained according to equations (9.9) to (9.14).

For instance, the efficiency of electricity generation in CCGT plants is calculated as follows:

$$\eta_{CCGT} = \left(\frac{e_{CCGT,t}}{\xi_{CCGT,\, t}} \right) * 100 \quad \dots (9.1.2)$$

Substituting (9.9) into (9.1.2) yields:

$$\eta_{CCGT} = \left(\frac{e_{CCGT,t}}{CCGT \sum_{i=1}^{n} \sum_{j=1}^{r} x_{i,j}} \right) * 100 \quad \dots (9.1.3)$$

Where j refers to the fuel actually used.

Similar iterations are performed in the calculations of the rest of electricity generation technologies.

The total amount of fossil fuels consumed in the sample of power plants described above consists of:

$$\xi_{fosil\_fuels} = \sum_{i=1}^{n} \sum_{j=i}^{n} X_{i,j} = 1{,}109.14\,PJ \qquad \ldots (9.15)$$

A key purpose of the above relationship was also to check that the sum of the fuel consumption in the individual plants matched with the aggregate consumption as reported in the national statistics.

The overall total fossil fuel inputs and nuclear energy consumed in power generation plants is presented in table 9.2. This information is provided by national official statistics published in Mexico (INEGI, 2006). According to (Francoz-Rigalt, 1988), 94,262 kg of uranium dioxide was consumed in the Mexican nuclear power plant in 2005, and at an energy content of 15386 MW-day per short ton (INEGI, 2005), this corresponds to a total fuel input in the nuclear industry of 138.1 PJ in 2005. When this nuclear energy is added equation (9.15) becomes:

$$\xi_{all\ fuels} = \sum_{i=1}^{n} \sum_{j=i}^{n} X_{i,j} + \xi_{nuclear} = 1{,}109.14 + 138.1 = 1{,}247.24\,PJ$$

... (9.16)

The value obtained in equation (9.16) accounts for 99.5% of total overall fossil fuel and nuclear energy consumed for electricity generation and is indicative of the issue that individual plant data is not available for the Independent Power Producers. The information obtained above may also be used to estimate the thermal efficiency of the nuclear plant in Mexico, i.e.:

$$\eta_{nuclear} = \left(\frac{e_{nuclear,t}}{\xi_{nuclear,\,t}} \right) * 100 = 29.6\% \qquad \ldots (9.1.4)$$

Fuel	Conventional thermal	Internal Combustion	Turbogas	Combined Cycle	Coal based electricity	Dual	Nuclear	Total
Fuel oil	561.10	5.45	-	-	-	0.34	-	566.89
Diesel	0.48	0.79	6.35	4.29	1.43	0.28	-	13.62
Gas	58.13	0.00	10.28	195.58	0.00	0.00	-	263.99
Coal	-	-	-	-	174.61	96.88	-	271.49
Uranium	-	-	-	-	-	-	138.13	138.13
TOTAL	619.71	6.24	16.63	199.87	176.04	97.50	138.13	1,254.11

Table 9.2 – Fuel Consumption in Electricity Generation in Mexico, 2005 (PJ)

Source: INEGI, El Sector Energético en México, 2006.

Results of the thermal efficiencies in fossil fuel electricity plants are presented in figure 9.5 and may be compared to those values obtained by Llamas et al. (2005). Differences in thermal efficiencies between the results presented in this research and values from Llamas et al., (2005) will be a consequence of the different year of reporting. Their report was published in 2005 and referred to data in 2003 whereas this research refers to 2005 and energy scenarios up to 2030.

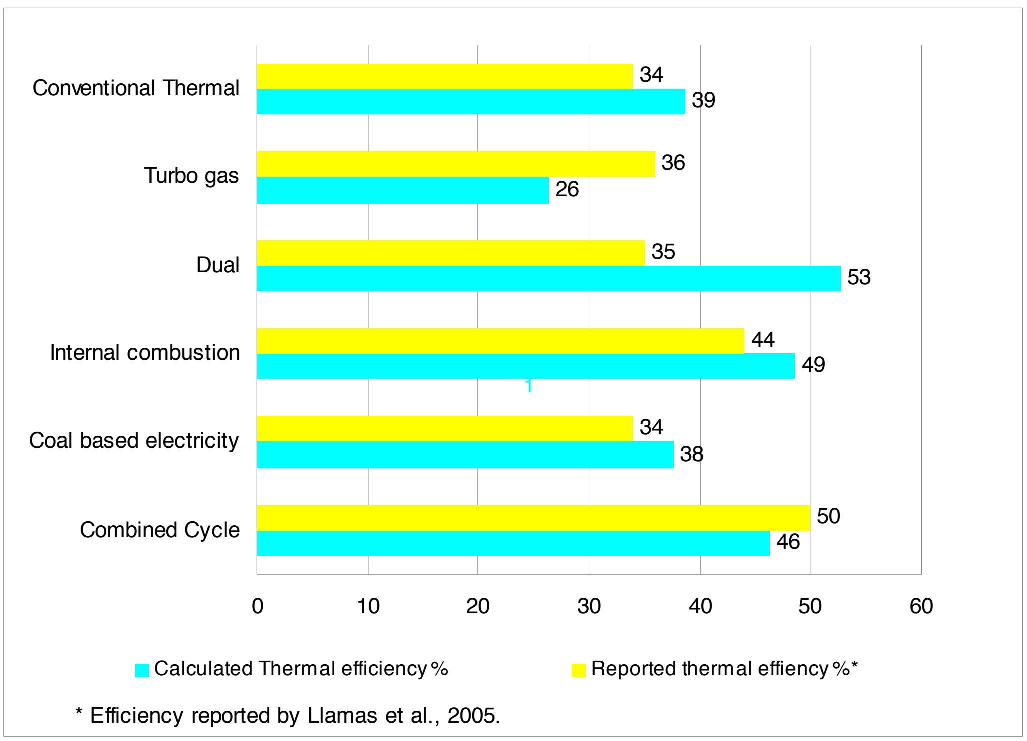


Figure 9.5 – Thermal Efficiency by Electricity Generation Technology, Mexico, 2005 (%)

The efficiency values show in figure 9.5 for dual fuel stations as computed appear to be in error as the value is significantly above (at 53%) that obtained from other steam generating plant (e.g. the conventional thermal (by fuel oil or gas) and coal (at ~38%). Since the dominant fuel in the dual fuel plant in 2005 was coal (~ 99%) it would be expected that the efficiency of this plant would be comparable with that of the power station using only coal.

In this respect, an alternative methodology was developed in order to correct the value of thermal efficiency for this type of plant as discussed in section 9.3.4. In addition the values of efficiency for internal combustion generation are also high. Indeed even the values reported by Llamas et al. (2005) are higher than the normally accepted maximum of ~40%. An alternative methodology to estimate the efficiency of such plants is given in section 9.3.5.

9.3.4 Adjustment of Thermal Efficiencies in Coal Fired and Dual-fuel Plants

The proportion of coal ($\mathbf{p_{coal}}$) burnt in a dual-fuel power plant is weighted in relation to overall energy inputs to this plant making use of equation 9.11:

$$p_{coal} = \frac{x_{i,coal}}{C_{balance\ table}} \quad \ldots (9.17)$$

where $C_{balance\ table}$ is the total coal consumption for electricity generation as derived from balance tables.

The total amount of electricity generated from coal combustion in both coal-fired plants and a dual-fuel plant (units in GWh) is now accounted into a single equation as follows:

$$e_{All\ Coal\ generation} = e_{Coal\ generation} + p_{coal} * e_{Dual\ fuel\ generation} \quad \ldots (9.18),$$

or in PJ as:

$$e_{All\ Coal\ generation} = (e_{Coal\ generation} + p_{coal} * e_{DDual\ fuel\ generation UAL}) * \left(\frac{3.6}{10^3}\right)$$

… (9.18.1)

The efficiency of electricity generation in both coal-fired and dual-fuel plants consists of:

$$\eta_{all\,coal} = \left(\frac{e_{All\,coal\,generation}}{C_{balance\,table}} \right) * 100 \quad \ldots (9.19)$$

This adjustment gives a more realistic efficiency of 35.8%. It would thus appear that there is an error in the specific fuel inputs as reported for the plant data of individual dual fueled power station. Since coal represents over 99% of the generation in this station, this revised efficiency will be used in subsequent calculations.

9.3.5 Adjustment of Thermal Efficiencies in Internal Combustion Plants

Internal combustion plants employ either diesel or fuel oil for electricity generation. Five out of the six power plants generating electricity using internal combustion engines employ only diesel whereas the remaining plant uses predominantly fuel oil and a smaller amount of diesel.

In this case, the total amount of electricity generation of internal combustion plants aggregated and this amount is divided by the total overall consumption of diesel and fuel oil which is consumed by all internal combustion plants. The total amount of fuel consumption consumed in internal combustion engines was obtained from aggregated industry statistics. The total electricity generated by the internal combustion plant which relies on fuel oil consumption is then calculated as follows:

$$e_{fuel\,oil, INT.COMBUSTION} = \sum_{i=1}^{n} e_{i, INT.COMBUSTION} \quad \ldots (9.20)$$

Similarly, the electricity generated from diesel is given by:

$$e_{diesel, INT.COMBUSTION} = \sum_{i=1}^{n} e_{i, INT.COMBUSTION} \quad \ldots (9.21)$$

The overall efficiency of generation in internal combustion plant is calculated as follows:

$$\eta_{i,INT.COMBUSTION} = \left(\frac{\left[\sum_{i=1}^{n} \sum_{j=1}^{r} e_{i,j} \right]_{internal.combustion}}{FO_{Overall.internal.combustion} + D_{Overall.internal.combustion}} \right) * 100$$

… (9.22)

Where $\boldsymbol{FO}_{\mathbf{Overall.internal.combustion}}$ is the aggregated fuel oil consumption, and $\boldsymbol{D}_{\mathbf{Overall.internal.combustion}}$ is the aggregated diesel consumption

A summary of efficiencies according to this modelling exercise is presented in table 9.3.

Technology	Efficiency
Conventional thermal plant	38.6%
CCGT plant	46.2%
Turbo gas plant (open gas cycle)	26.3%
Coal and dual plant	35.8%
Internal combustion plant	38.3%
Nuclear plant	26.9%
Fluidized bed combustion plant (coal)[165]	31.2%
Fluidized bed combustion plant (pet coke)[166]	35%

Table 9.3 – Efficiency of Generation in Mexican Electricity Plants, 2005 (%)

The efficiency of electricity using CCGT plants run by IPP cannot be computed using individual power station data and instead was estimated using aggregated data for both the electricity generation and fuel consumption using equation 9.3. This represents an alternative methodology in comparison to the methodology developed in sections 9.3.3-9.3.5. In particular, the efficiency of gas conversion in CCGT IPP plants was 50.6% in 2005. This value may be compared

[165] The declared maximum authorized electricity generation in this fluidize bed combustion plant is 3,650 GWh/year and, on average, it is expected to consume 11,709.8 GWh of sub-bituminous coal in 2010.

[166] The declared maximum authorized electricity generation in two fluidized bed combustion plants is 3824.5 GWh/year and, on average, they consume 10,927.7 GWh of pet coke.

with the gas efficiency of conversion in public CCGT plants presented in table 9.3 (i.e. 46.2%). It can be stated that the efficiency of CCGT plants run by IPP is higher that the CCGT efficiency managed by the electricity public sector in 2005. It should be noted that the value of gas efficiency of conversion in CCGT plants which is referred to in the calculations of chapter 8 corresponds to public sector CCGT plant.

9.3.6 Calculation of a CO_2 Emission Factor Concerning Stationary Combustion in Mexican Power Plants

In the production of electricity all generating plant will emit carbon dioxide depending on the carbon content of the fuel used and also the efficiency of generation of the plant using that fuel. In the case of gas as a fuel there will be several different emission factors depending on whether the technology of conversion is open circuit gas turbine (turbo-gas), conventional steam generation power by gas, or combined cycle gas turbine technology. Generally, coal fuels will have a high emission factor with lower factors for oil and gas.

For completeness in this section reference is also made to renewable energy and a newer technology using fluidized bed combustion of Pet Coke. As a general principle, the larger the share of renewable(s) in electricity generation, the lower will be the overall CO_2 emission factor.

Equation (9.8) provides the basis to estimate the total CO_2 emissions arising from electricity generation using fossil fuel technology. For convenience equation 9.8 is repeated below:

$$\xi_{fossil.fuels} = \sum_{i=1}^{n} x_{i,fuel.oil} + \sum_{i=1}^{n} x_{i,gas} + \sum_{i=1}^{n} x_{i,diesel} + \sum_{i=1}^{n} x_{i,coal} + \ldots\ldots\ldots \tag{9.23}$$

The total carbon dioxide Emission from fossil fuels $E_{fossil\,fuels}$ is then given by:

$$E_{fossil.fuels} = \sum_{i=1}^{n} x_{i,fuel.oil}.\varepsilon_{fuel\,oil} + \sum_{i=1}^{n} x_{i,gas}.\varepsilon_{gas} +$$
$$\sum_{i=1}^{n} x_{i,diesel}.\varepsilon_{diesel} + \sum_{i=1}^{n} x_{i,coal}.\varepsilon_{coal} + \ldots\ldots\ldots \qquad (9.24)$$

This can be abbreviated to:

$$E_{fossil.fuels} = \sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_{j} \qquad \ldots (9.25)$$

Where as in previous cases, j takes on a different value for each fossil fuel.

The overall emission factor ($\varepsilon_{overall}$) arising from fossil fuel stations will then be given by:

$$\varepsilon_{fossil\_fuel} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_{j}}{\sum_{i=1}^{n} e_{i,fossil\_fuels}} \qquad \ldots (9.26)$$

To assess the overall emission factor for electricity generated in Mexico, it is also necessary to include the electricity generated by the nuclear plant, and also renewable generation such as hydro etc, and also newer technologies involving fossil fuels which may be used in the future. Some of these renewable generation technologies, particularly geothermal will have emissions for each unit of electricity generated.

In this research, results involving CO_2 emissions from geothermal energy used emission factors provided by Bloomfield et al., (2003) – i.e. (0.20 lbs CO_2/kWh or 90.718 g/kWh). The Sustainable Development Commission (2006) report the overall CO_2 emissions associated with nuclear electricity generation as investigated by eight different research groups/companies.[167] These emissions cover the full fuel cycle including fuel fabrication and do vary with reactor type, and also method of fuel enrichment. The average emission from these different sources is 15.1 g/kWh. Operational CO_2 emission factors for hydro electricity and wind energy are assumed to be zero.

The above equation in its most general form will become:

$$\varepsilon_{overall} = \frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j\right]_{fossil\ fuels} + \left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j\right]_{nuclear} + \left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j\right]_{renewable}}{\left[\sum_{i=1}^{n} e_i\right]_{fossil\ fuels} + \left[\sum_{i=1}^{n} e_i\right]_{nuclear} + \left[\sum_{i=1}^{n} e_i\right]_{renewable}} \quad \ldots (9.27)$$

Note that in this example the possibility of electricity generation from different nuclear technologies exists. In most countries there is a single dominant nuclear generation technology (often the Pressurised Water Reactor). However, in some countries such as the UK, there are several technologies in existence (e.g. in the UK, Magnox reactors, Advanced Gas Cooled Reactors, and also Pressurised Water Reactors). The above equation is intended to be general to cover all technologies.

The above relationship can also cover emissions associated with renewable technologies such as electricity generated from geothermal sources and also biofuels. In addition, the fossil fuel section can also be extended to cover other developments. In the base year for which analysis was done (i.e. 2005) there were no plants using fluidized bed combustion technology in the public sector, but such capacity is planned in the future using alternative fuels such as pet coke. The equations above are sufficiently general to include any such future developments, including, if appropriate, Integrated Gasification Combined Cycle (IGCC) stations.

In the more distant future, i.e. post 2020, there may well be the development of fossil fuel plants which incorporate carbon sequestration, although the deployment of these is unlikely to be that significant overall before the end of the decade 2020 –

[167] The following authors are cited in the Sustainable Development Commission Report, (2006): Spadaro et al. (2000); Van de Vate, IAEA (1997); Tokimatsu, (2000); White, Kulcinski and Radcliffe, (1998); White and Kulcinski, (1998); Meier, (2002); Voss, (2000)

2030. The above equation can be modified to incorporate carbon sequestration by the introduction of the parameter $\mathbf{s}_i$ which reflects the proportion of carbon dioxide not captured by sequestration:

$$\varepsilon_{overall} = \frac{\left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j.s_i\right]_{fossil\ fuels} + \left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j\right]_{nuclear} + \left[\sum_{i=1}^{n}\sum_{j=1}^{r} x_{i,j}.\varepsilon_j\right]_{renewable}}{\left[\sum_{i=1}^{n} e_i\right]_{fossil\ fuels} + \left[\sum_{i=1}^{n} e_i\right]_{nuclear} + \left[\sum_{i=1}^{n} e_i\right]_{renewable}} \quad \ldots (9.28)$$

Typically it is expected that carbon sequestration will remove ~ 90% of emitted carbon in any power station leading to a value of $\mathbf{s}_i$ of 0.1. Currently, of course, $\mathbf{s}_i = 1$.

Results for the CO_2 emissions per kWh for each electricity generation technology in 2005 are presented in table 9.4. This table consists of a matrix which shows a structural relationship showing the effective emission factors for each energy source for each generation technology. In addition the proportion of electricity generated by each technology is also shown. The last column of table 9.4 shows overall total emissions by type of electricity generation technology. Of the fossil fuel generation technologies, CCGT has the lowest CO_2 emission factor at 428 g of CO_2 per kWh whereas turbo gas plants show the highest CO_2 emission factor at 879 g of CO_2 per kWh. This is despite the fact that coal combustion causes a greater emission of CO_2 than gas because of the higher carbon content of the fuel. This apparent contradiction arises solely from the poor efficiency of open circuit gas turbine stations. Nuclear energy is a non-fossil fuel technology of which emission factor is found as the lowest (15.1 g of CO_2 per kWh). It is noteworthy that the planned new alternative fuel of pet coke has an emission factor at over 1000 g/kWh which is significantly worse than any of the other current technologies.

Power Plant	Electricity Generation (GWh)	% in Electricity Generation	Fuel Oil	Natural Gas	Diesel	Coal	Nuclear	Petcoke	Geothermal	TOTAL
Combined cycle gas turbine	25,120.9	14.3%	6.05	409.52	12.13	-	-	-	-	427.70
Coal-based & dual	32,655.4	18.6%	0.78	-	3.85	771.52	-	-	-	776.15
Internal combustion	663.8	0.4%	475.09	-	81.38	-	-	-	-	556.46
Turbo gas	783.3	0.4%	-	339.04	539.94	-	-	-	-	878.98
Conventional thermal	67,006.7	38.1%	629.97	52.31	0.67	-	-	-	-	682.95
Nuclear	10,805.0	6.1%	-	-	-	-	15.13	-	-	10.01
Fludized bed combustion (pet coke)	3,824.5	2.2%	-	-	-	-	-	852.73	-	852.73
Fluidized bed (coal) till 2010	0.0	0.0%	-	-	-	1,071.78	-	-	-	1,071.78
Geothermal	7,299.0	4.2%	-	-	-	-	-	-	90.72	90.72
Wind	5.0	0.0%	-	-	-	-	-	-	-	0.00
Hydro	27,611.0	15.7%	-	-	-	-	-	-	-	0.00
OVERALL	175,774.6	100.0%	242.95	79.98	5.42	143.33	0.62	18.55	3.77	**494.62**

Table 9.4 – Carbon Dioxide (CO_2e) Emissions Factors during Electricity Generation in Mexico, 2005 (g/kWh)

9.3.7 Observed CO_2 Emission Factor for Delivered Electricity

Fugitive emission factors calculated in Chapter 8 are incorporated in the estimation of the overall CO_2 emission factor of the Mexican electricity grid. These factors are derived by adding the fugitive emissions of the relevant fuel to the emission factor derived above during the actual generation of electricity and are shown in figures 9.6 – 9.8. These overall emission figures will relate to the emission factors as delivered from the respective power stations. For final electricity consumption at the point of use, the electricity losses associated with the transmission of electricity must also be included, and these are discussed in this section.

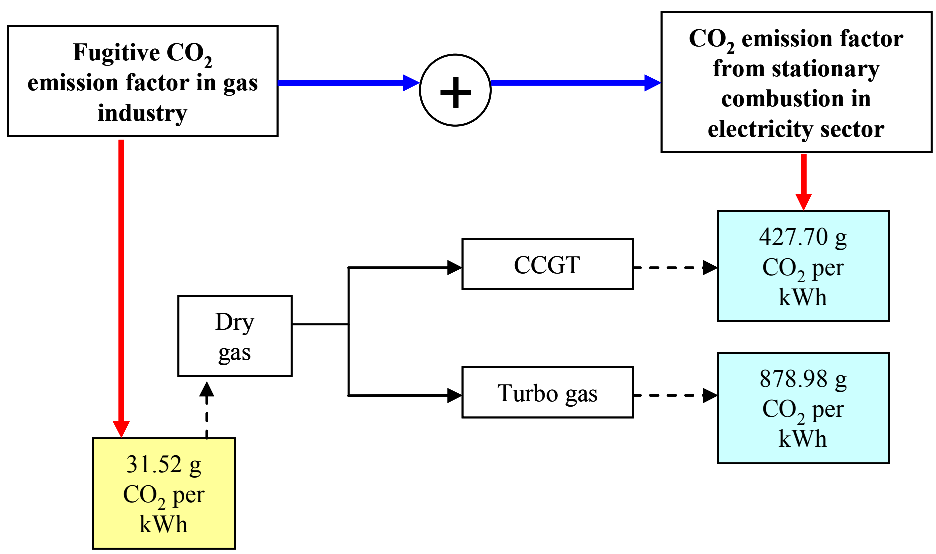


Figure 9.6 – Overall CO_2 Emission Factor for Delivery of Electricity from CCGT and Turbo-gas Plants in Mexico, 2005 (g CO_2e/kWh)

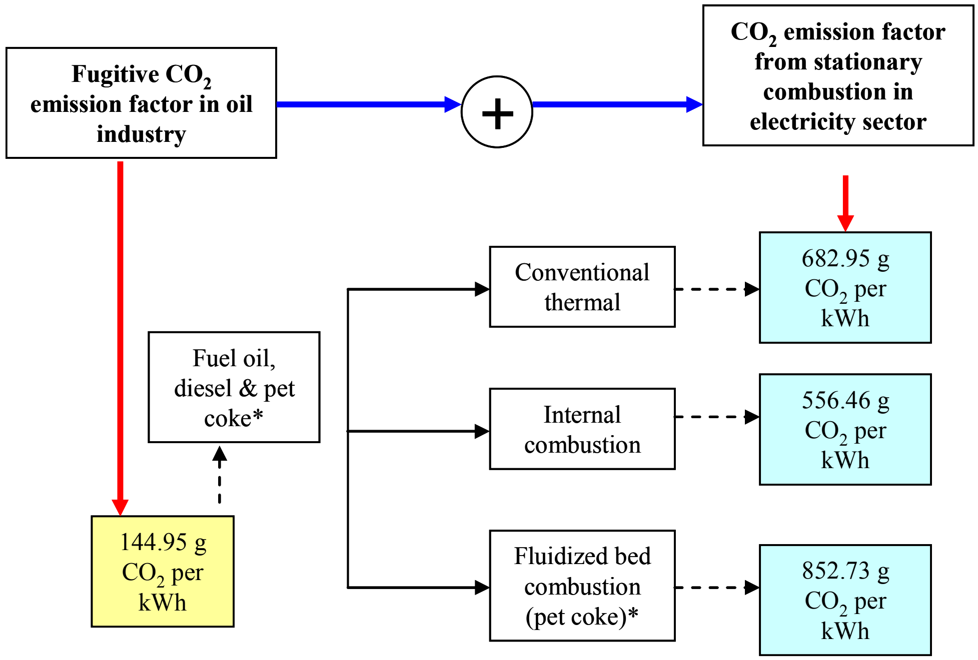


Figure 9.7 – Overall CO2 Emission Factors for Delivery of Electricity from Conventional Thermal, Internal Combustion, and Fluidized Bed Combustion Plants in Mexico, 2005 (g CO2e/kWh)

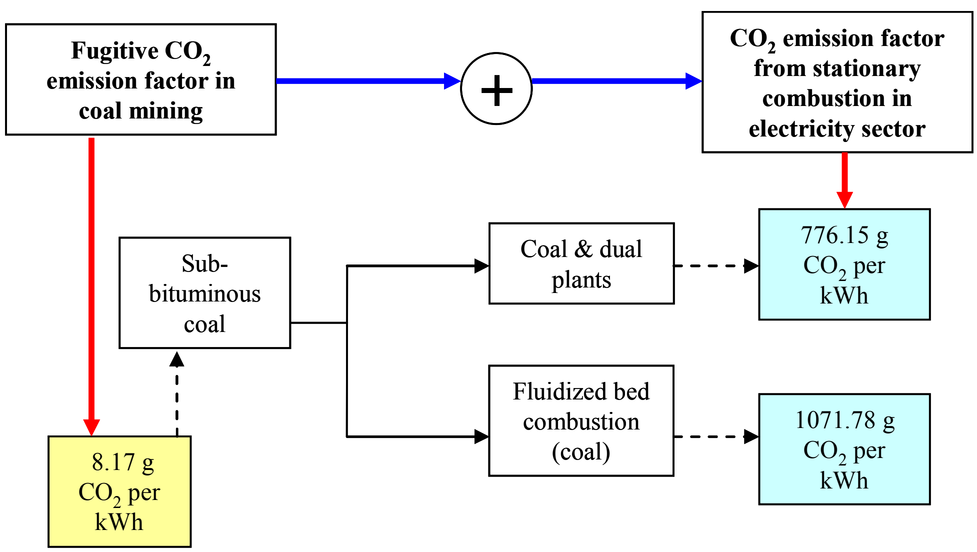


Figure 9.8 – Overall CO_2e Emission Factor for Delivery of Electricity from Coal and Dual-fuel Plants in Mexico, 2005 (g CO_2e/kWh)

Data from IPCC (2006) do not incorporate CO_2 emission factors for coal mining activities. This represents a limitation which is resolved while specifying the amount of fuel/energy consumption in coal mining activities. According the economic census in Mexico (2004), 147,580 thousand current Mexican pesos accounted for electricity expenditures in coal mining in 2003. This electricity expenditure is divided by an average price of electricity in industrial activities in Mexico in the same year (i.e. 0.23 current Mexican pesos per kWh). The corresponding electricity consumption in coal mining accounts for 652.3 GWh or 2,300 TJ in 2003. In principle, the analysis should be done for 2005 but available information corresponds to 2003.

It is assumed that the distribution of fuel and electricity consumption in coal mining is similar to that observed in coal mining activities in the United Kingdom. These are potentially major assumptions, but as will be shown, as the overall production of electricity from coal is relatively small (<10%), and the fugitive emissions are <3% of total emissions from coal generation, the overall error arising from this approach will be small. These assumptions are:

1) The proportion of fuels and electricity consumption in mining activities are assumed to be similar in Mexico and the United Kingdom,

2) The attributes of technology in coal mining are assumed to follow a similar productivity performance (i.e. x input yields y output both in Mexico and United Kingdom).

Electricity, natural gas and self consumption of coal represent 82.3%, 14.1%, and 3.6% of total energy consumption in coal mining in the United Kingdom in 2003. In this respect, it is assumed that the 2,300 TJ of electricity in Mexico accounts for 82.3% of total energy consumption in coal mining (i.e. as in the case of the United Kingdom), and hence gas and self coal consumption are worked out by extrapolating the UK figures. Using this methodology, it is estimated that 394.4 TJ of natural gas and 99.5 TJ of coal consumed in coal mining activities in Mexico in 2003. While this approach involves several assumptions it does give values which will be more realistic than ignoring such aspects altogether as implied in IPCC (2006)

To estimate the fugitive emissions associated with the delivery of coal to the power stations, it is necessary to estimate the total emissions arising for all fuel use in the coal mining industry. Electricity is used in the industry and to estimate the fugitive emissions for coal not only must the overall emission factor for electricity generation be estimated, but also the associated transmission losses.

Electricity loses (e_L) also occur during the delivery of electricity through the transmission and distribution networks for end-use either in industry or residential/commercial sectors. These losses affect the overall efficiency of the electricity sector, and will be critical when the carbon emissions associated with electricity at the point of end use (rather than at point of generation) are considered. Electricity output in Mexico has increased in a sustained manner along time (figure 9.9), and can be characterized in two main periods:

1) A historical trend in electricity output with a compound growth rate of 7.4% in the period 1965-2000.
2) A compound growth rate of 2.4% in electricity output in the period 2000-2007.

In this respect, the growth in electricity output slows down dramatically (i.e. a change in a structural condition related to economic activities) between the periods 1965-2000 and 2000-2007. In general, this has a positive effect on overall reduction in CO_2 emissions because low growth in electricity output means a relatively less activity in fossil fuel combustion. Figure 9.9 also plots transmission loses in electricity as a proportion of total electricity output for the period 1965-2007 (secondary axis, figure 9.9). Notice a minimum historical in transmission losses in 1980 (around 12% as compared total electricity output). Afterwards, there is an increase in electricity transmission loses which partly reflect two structural conditions in the Mexican electricity grid:

1) Transmission loses ($\mathbf{e_{Lt}}$) grew from 12% of total electricity output in 1980 to 15% in 1995.
2) Afterwards, the growth in transmission loses slowed but still increases from 15% of total electricity output in 1995 to 17.4% in 2007.

These values should be compared with a figure of 8.5% in the UK. One reason for the increase in losses in recent years despite the improved efficiency of generation may be associated with a relative change in the geographic distribution of centres of electricity generation compared to the centres of demand.

The higher the proportion of transmission loses with respect to total electricity generated, the higher will be the associated emission factor value for each generation technology. To account for these losses, the overall CO_2 emission factor for each generation technology must be weighted by the proportion of transmission losses in electricity delivery as follows:

$$\boldsymbol{Overall.Delivery.CO}_{2,tech,j,t} = \boldsymbol{CO}_{2,tech,j,t} * \left(\frac{1}{1 - \lambda / 100} \right) \quad \text{… (9.29)}$$

Where,

- $\lambda = \left(\frac{e_{Lt}}{e_t} \right) * 100$ - i.e. the transmission loses in electricity delivery as a proportion of total electricity output as shown by the dashed line in figure 9.9).

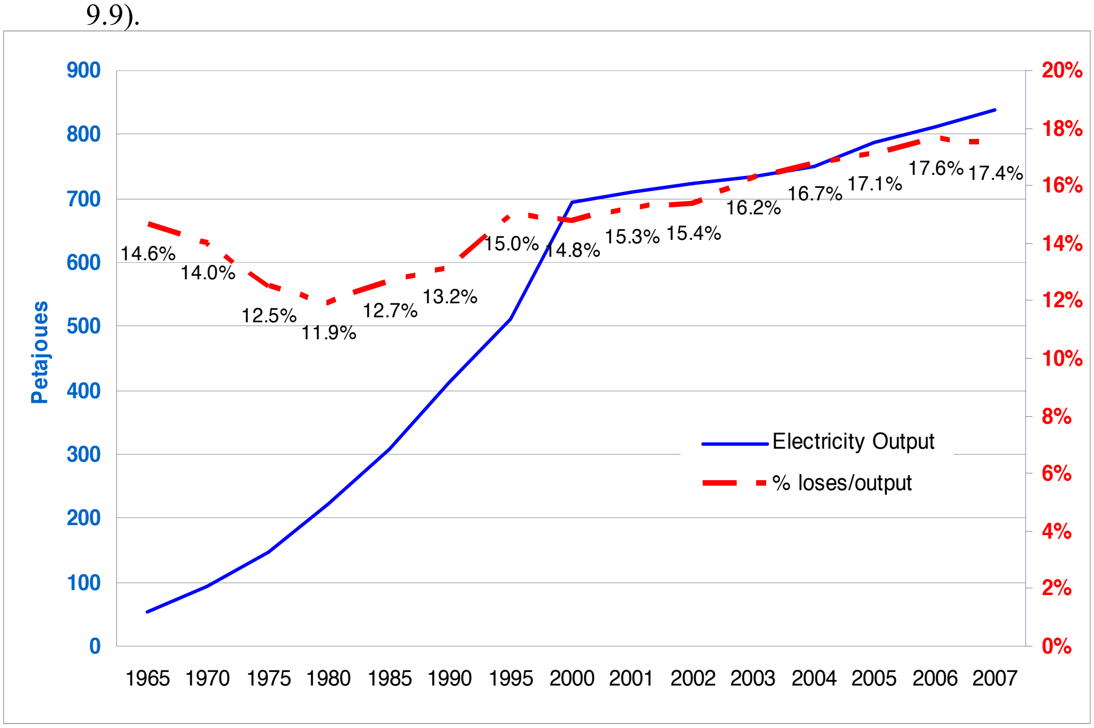


Figure 9.9 – Historical Electricity Output (PJ) versus Transmission Losses in Mexico (%)

As coal is used both in the mining industry and also in the generation of electricity which is then used for coal mining, a potential problem arises as the fugitive emissions from coal are not known. However, this can be overcome by initially assuming a value for such coal emissions and using this to estimate the actual emissions. In reality, the initial guess will not equal the computed value and the procedure is then iterated until the initial guess and computed values are identical. This iteration may be summarised in the following steps:

1. The amount of natural gas used in coal mining in Mexico is multiplied by the relevant emission factor of gas combustion in energy industries reported by IPCC (2006) – (i.e. 195.5 g CO_2 per kWh) together with the fugitive emissions in the supply of gas as estimated in chapter 8.
2. The amount of coal consumed directly multiplied by its relevant emission factor together with the fugitive emission factor. This latter factor is initially unknown and initially a value of 10 g/kWh was assumed. Ultimately after iteration a corrected value can be obtained.
3. The amount of electricity consumed multiplied by the overall emission factor for electricity which in this case will include the transmission losses. Once again, the fugitive emissions from coal used in electricity generation and an initial value of 10 g/kWh was assumed

From the above information it is then possible to calculate, using several iterations, a definitive value for the fugitive emissions for coal production as 8.17 g/kWh.

The estimates of overall CO_2 emission factors for different modes of electricity generation are shown in Table 9.5. The emission factors are separated according to the fugitive CO_2 emission factors arising from fuel production, CO_2 emission factors from stationary combustion in the power stations themselves, and the corresponding emission factors arising from transmission losses for delivered electricity to the point of end use. Overall the emission factor for electricity generated (including fugitive emissions) in 2005 was 529.6 g/kWh, whereas the overall emission factor for delivered electricity (i.e. including transmission losses) was 638.7 g/kWh. It is interesting to note, in view of the assumptions made in the estimations of fugitive emissions in coal production, that if this fugitive emission factor has been ignored (i.e. set to zero), then the emission factors for electricity generation and overall delivery would have only fallen to 528.4 g/kWh and 637.26 g/kWh, respectively, a difference of just 0.23%. Thus the approximations made in the assumptions during the estimation of fugitive emissions in coal production are very reasonable.

A	B	C	D	E	F	G	H
Plant type	Capacity	Generation		Fugitive emissions	Power station emissions	Total emissions	Electricity transmission & distribution losses
	MW	GWh	%	g/kWh	g/kWh	g/kWh	g/kWh
Coal &duel fuel	4,700	32,655.4	15.0%	8.17	776.1	784.0	945.6
Conventional thermal	12,711	65,164.1	30.0%	145.0	683.0	827.9	998.5
Turbo gas	2,632	1,404.9	0.6%	31.5	879.0	910.5	1,098.2
CCGT	14,017	71,568.9	32.9%	31.5	427.7	459.2	553.9
Internal combustion	179	779.6	0.4%	145.0	556.5	701.4	846.0
Nuclear	1,365	10,804.9	5.0%	0.0	15.1	15.1	18.2
Hydro	10,544	27,615.1	12.7%	0.0	0.0	0.0	0.0
Geothermal	960	7,298.5	3.4%	90.7	0.0	90.7	109.4
Other renewable	2	5.0	0.0%	0.0	0.0	0.0	0.0
Total	47,110	217,296.6	100.0%				

Table 9.5 – Carbon Dioxide (CO_2e) Emission Factors in Electricity Generation, Mexico, 2005

Values in the last column of table 9.5 are used to estimate an overall CO_2 emission factor representative of all type of generation technologies in Mexico. The relative importance of each CO_2 emission factor depends on the share of each generation technology in overall total installed capacity and the load factor. The load factor provides an indication of the capacity utilization of a power plant during a year, and ranges from as low as 6.1% in the case of turbo gas plants to as high as 90% for the nuclear plant. Turbo gas plants have a very low efficiency and hence high associated carbon emissions; however, unlike other generating plant they are very responsive to changes in demand and can come on line in 2 – 3 minutes from standstill. Conventional stations, on the other hand can take several hours, and in some cases over 24 hours or more to come on line from cold. Turbo gas plants are used for their dynamic response at periods of peak demand only.

The load factor for wind generation in Mexico is 26.2% which indicates that nearly twice the installed capacity of wind will be required to generate the same amount of electricity as is currently generated by internal combustion (load factor 49.8%) or more than three times the installed capacity of nuclear (load factor 90.2%). The load factor of utilization of a given plant will not directly affect the carbon emissions of the plant (technology) as it is the efficiency of the plant which will determine the actual emissions.

However, there is a secondary effect in that for any given fossil fuel technology, the efficiency is affected by the load factor. The precise nature of the relationship between efficiency and load factor is often difficult to ascertain with any accuracy, but generally for a coal or dual fuel power station which typically has a load factor of nearly 80% (Figure 9.10) will have an efficiency typical of that technology (~38% in this case). As the load factor reduces, the station will be not generating for increasing periods of time, and on each start up there is an overhead of fuel consumption before output is synchronized to the grid. Consequently, the efficiency will fall slightly; the actual reduction will depend on whether the generating set is still warm and on how long it has been since the last generation took place. As the stations become older, they tend to be used less and the load factor falls further with an even more significant reduction in overall efficiency.

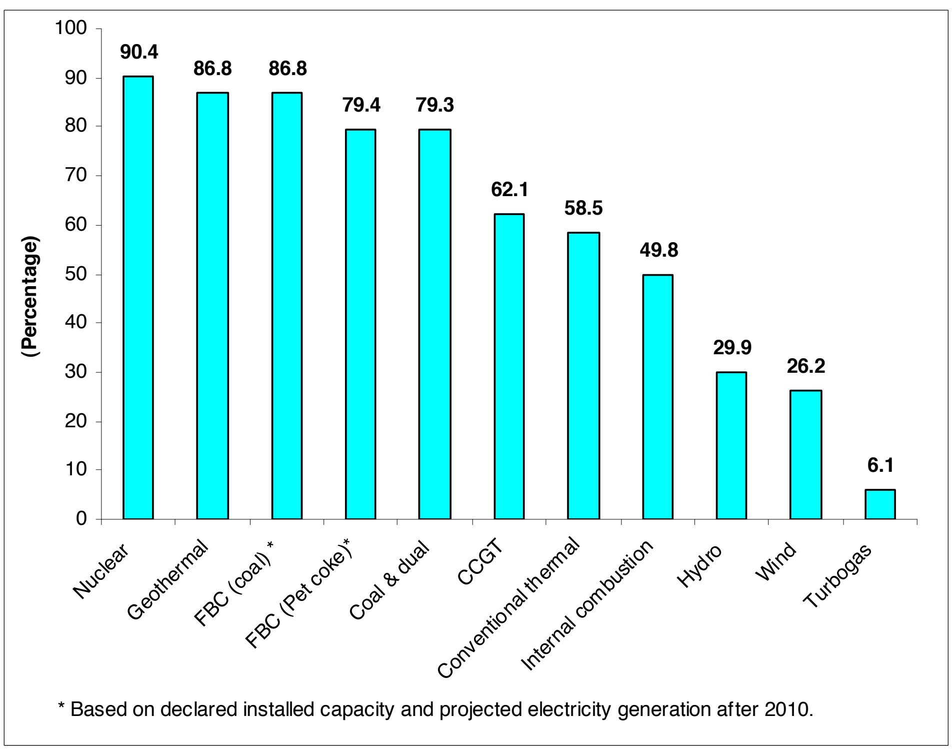


Figure 9.10 – Load Factors by Electricity Generation Plant, Mexico, 2005 (%)

An overall CO_2 emission factor accounting for the set of available electricity generation technologies in Mexico is calculated as follows:

$$\boldsymbol{Overall.CO_{2,t} = \sum_{j=1}^{r} Overall.Delivery.CO_{2,tech,j,t} * \frac{c_{tech,j}}{C}} \quad \text{… (9.30)}$$

Substituting equation (9.29) into (9.30) to incorporate the effects of transmission losses yields:

$$\boldsymbol{Overall.CO_{2,t} = \sum_{j=1}^{r} CO_{2,tech,j,t} * \left(\frac{1}{1-\lambda/100}\right) * \frac{c_{tech,j}}{C}} \quad \text{… (9.31)}$$

$$Overall.CO_{2,2005} = 638.7\,g.CO_2 / kWh$$

Where,

- $\frac{c_{tech,j}}{C}$: Proportion of in installed capacity of generation technology j in relation to overall installed capacity C.

Results for the overall CO_2 emission factor in electricity supply over the period 2005-2008 (i.e. including transmission losses) are presented in figure 9.11. Overall emission factors reduced from 638.7 g CO2 per kWh in 2005 to 559.7 g CO2 per kWh in 2008 which can be largely attributed to the increasing participation of CCGT generation by independent power producers (IPP).

The overall CO_2 emission factor for electricity supply in Mexico as developed above indicates a baseline figure of 638.7 g of CO_2 per kWh as of 2005 against which it is now possible to compare both historical and future trends (i.e. scenarios) as far as the local and external conditions in the availability and supply of fossil fuels. However, this figure may change not only from changing fuel mixes within Mexico but also if there is a change in the proportion of fuel consumed which is produced within Mexico to that which is imported for other countries.

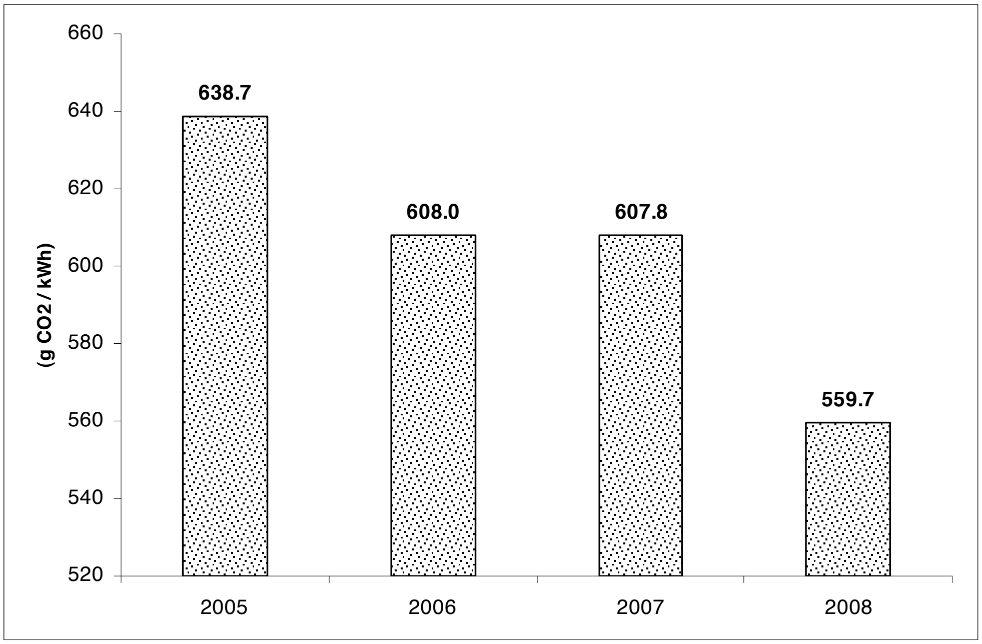


Figure 9.11 – Overall CO_2e Emission Factors in Electricity Generation, Mexico, 2005-2008 (g CO_2e/kWh)

The most critical feature in the model summarized in equation (9.31) is the relative distribution of electricity generated by each generation technology. The four alternative scenarios which are built in the following section are based on the following assumption:

$$\left[CO_2 \text{ emission per kWh}\right]_{year\,t} = \frac{\sum_{tech=1}^{p}\left[e_{tech}\right]_{year\,t}\cdot\left[\varepsilon_{tech}\right]_{2005}}{\sum_{tech=1}^{p}\left[e_{tech}\right]_{year\,t}}\cdot\left(\frac{1}{1-\lambda/100}\right)$$

… (9.32)

As noted above, the overall emissions in 2005 were 638.7 g/kWh.

The overall total installed capacity considers both the public and private sector electricity generation. It is, however, important to note that the amount of private electricity generation reported in the energy balance tables corresponds only to the category of independent power producers (IPP which are basically CCGT plants. However, private electricity generation also includes other small producers such as "self-supply societies", cogeneration, small scale electricity production, and private electricity import and exports.

The amount of electricity reported in energy balance tables does not take into account these categories because it appears that they are reported as part of electricity generated in the industrial sector. This proportion of private electricity generation is part of a regulated activity which is subject to a maximum allowable limit for electricity generation and installed capacity (Diario Oficial de la Federación, 1993).

Fluidized bed combustion technology (FBC) which uses petroleum coke for electricity generation accounts for part of private electricity under a regulated activity and is due to start operations in 2010. Although FBC is part of private electricity which is not reported in energy balance tables, it is considered a fraction of FBC installed capacity in the modelling of alternative scenarios in the latter part of this chapter, and it might become a significant generating capacity in the future.

In the modelling of emissions from electricity generation, 2005 was taken as the base year as this was the latest year for which full data were available. Instead, the emission factors for each technology as determined for 2005 were used to estimate the relevant overall emission factor in each year depending of the actual total generation by each technology in that year. The same was also true for the years 2006 to 2008 were incomplete data are currently available, but sufficient is known regarding the actual generation. For the year 2009, for which no data on total generation by technology is yet available and also for the scenario years 2009 – 2030, a different approach was taken to estimate the electricity generated. Firstly it was necessary to estimate probable total demand for electricity in the scenario year in question and secondly to estimate the distribution of generation technology used in that year.

The projected demand for 2009 and all future years up to 2030 was modelled with three different growth rates as discussed in section 9.4.1. For the years 2009 – 2017, Government Projected installed capacity was assumed as discussed in section 9.4.2 whereas in subsequent years to 2030 five difference scenarios of capacity growth were assumed as discussed in sections 9.4.3.1 – 9.4.3.5.

The total amount of electricity ($E_{year\ t}$) generated in a future scenario year will be given by:

$$E_{year\ t} = \sum_{tech=1}^{p} \left[c_{tech}\right]_{year\,t} . \left[load.factor_{tech}\right]_{year\,t} . 8760 \qquad \ldots (9.33)$$

The computed value of $E_{year\ t}$ should also equal the projected demand $D_{year\ t}$. At the present, the load factor in year t will be unknown, and initially it is assumed that the respective load factors in equation 9.33 equal the values in the same year, 2005. However, in general this will not be the case as the load factors in year t will not be the same as those in 2005, so

$$E_{year\ t} \neq D_{year\ t} \quad \ldots (9.34)$$

The load factors in equation 9.33 must be adjusted appropriately until the equality relationship in 9.43 is valid. This adjustment may be done by one of several ways:

i) All load factors are scaled by the same value. This scaling can be achieved using the following relationship:

$$load.factor_{tech,year\ t} = \frac{D_{year\ t}}{E_{year\ t}}.load.factor_{tech,2005} \ldots (9.35)$$

ii) The load factors of renewable energy sources are largely dictated by the availability of the resource, and not demand requirements as is the case with conventional generation. Similarly, the nuclear plant will normally be run at base load except during outages for refueling/maintenance. It is thus only fossil fuelled plant that are likely to have their use varied in accordance with demand, and in this case it should be only then the load factors of the fossil fuelled plant adjusted,

If load $factor_{renewable,2005}$ is the weighted mean load factor for all renewable generation in 2005, and $load.factor_{nuclear,2005}$ and load $factor_{fossil\ fuels,2005}$ are the corresponding load factors for nuclear generation and fossil fuel generation in 2005, then the adjustment for all fossil fuel load factors for year t will be given by:

$$load.factor_{fossil\_fuel\_tech, year\ t} = \frac{D_{year\ t} - \left(\begin{array}{l} \left[c_{renewable}\right]_{year\ t} . \left[load.factor_{renewable}\right]_{2005} \\ + \left[c_{nuclear}\right]_{year\ t} . \left[load.factor_{nuclear}\right]_{2005} \end{array} \right) . 8760}{\sum_{fossil\ fuel\_tech=1}^{p} \left[c_{fossil\ fuel\_tech}\right]_{year\ t} . \left[load.factor_{fossil\_fuel\_tech}\right]_{2005} . 8760} . load.factor_{fossil\_fuel, 2005}$$

… (9.36)

iii) Since CCGT technology is the one likely to be deployed in any new fossil fuel power plant, it is only the load factor of this plant type that is adjusted with load factors for all other technologies remaining the same as in 2005. In this case the load factor for CCGT generation in year t will be given by:

$$load.factor_{CCGT, year\ t} = \frac{D_{year t} - \left(E_{year t} - \left[c_{CCGT}\right]_{year t} . \left[load.factor_{CCGT}\right]_{2005}\right) . 8760}{\left(\left[c_{CCGT}\right]_{year t} . \left[load.factor_{CCGT}\right]_{2005}\right) . 8760} . load.factor_{CCGT, 2005}$$

… (9.37)

It makes sense to adopt the strategy indicated by equation 9.37, although the other two strategies would be possible.

With the appropriate adjustment for load factor in the relevant technology(ies), the total electricity generated by each technology can be estimated in any future year, and from that the total CO_2 emissions for that year can be calculated as well as the relevant CO_2 factor for overall electricity generation for that year.

9.4 Carbon Dioxide Emission Scenarios in Electricity Generation

Since the iron and steel industry consumes significant amount of electricity, the overall emissions of green house gases will depend on decisions made external to those companies, (i.e. the decisions about the choices of fuel mix for electricity generation in the future). In this section, projections on future carbon dioxide emissions are elaborated according to four alternative scenarios for electricity generation in Mexico:

1) The declared governmental policy, (i.e. SENER projections, 2008) in the period 2009-2017, with a continuation of the present energy policy trends on capacity expansion up to 2030.
2) As (1) but with a large share of coal-based electricity and pet coke in the energy mix in the period after 2017 which are the limit of current Government Projections.
3) As (2) but with a large share of renewable electricity generation in place of the coal/pet-coke generation.
4) An increasing share of nuclear and renewable electricity generation in the period post 2017.

With a growth in electricity demand expected over the next twenty years, new generation capacity will need to be brought on line, not only to cope with the increase in demand, but also to replace older stations as they come to the end of the working lives. Any replacement of generating capacity will normally have a beneficial effect on carbon reduction. Either the replacement capacity will be more advanced than that which it replaces and hence more efficient, or it will be of a more efficient technology – e.g. the replacement of conventional thermal generation by CCGT stations.

9.4.1 Projected growth in Electricity Demand

Growth in electricity demand, and hence generation will depend on the demand generated by economic sector activities with increased demand following economic growth. In this research, three scenarios are explored in relation to selected default growth rates in electricity output over the period 2009-2030:

1) A low growth based on a compound growth rate of 0.5%
2) A medium growth based on a compound growth rate of 2.0%
3) A high growth based on a compound growth rate of 3.5%

The projected growth in electricity output in the industrial sector is 3.5% in the period 2007-2017 (table 9.6). This growth rate in electricity demand in industry is taken as reference in this research for the scenario of high growth.

	Average annual growth rate	
	1997-2007	2007-2017
National consumption	3.9%	3.3%
Self-generation consumption	10.2%	2.7%
Electricity Public Service Sales	3.3%	3.4%
Residential	4.5%	3.7%
Commercial	3.1%	3.2%
Services	2.9%	1.8%
Farming/Agriculture	0.2%	1.6%
Industrial	3.2%	3.5%
Midium firms	4.7%	3.7%
Large firms	0.9%	3.1%

Source: SENER with data from CFE, Mexico, 2008.

Table 9.6 – Annual Growth Rate in Electricity Consumption, Scenarios for Mexico, 2007-2017 (%)

A low growth scenario for electricity generation appears much more realistic in Mexico. Figure 9.12 plots the amount of electricity generation which is simulated on the basis of the default growth rates in electricity for three alternative scenarios. The first part of figure 9.12 corresponds to electricity output observed during the period 1965-2007 (i.e. this period corresponds to historical electricity output depicted in figure 9.9). Electricity output under each scenario consists of:

1) Electricity output for low growth scenario: $\sum_{t=2009}^{2030} e_{low,t} = 265{,}683$ GWh

2) Electricity output for medium growth scenario: $\sum_{t=2009}^{2030} e_{medium,t} = 368{,}056$ GWh

3) Electricity output for high growth scenario: $\sum_{t=2009}^{2030} e_{high,t} = 507{,}455$ GWh

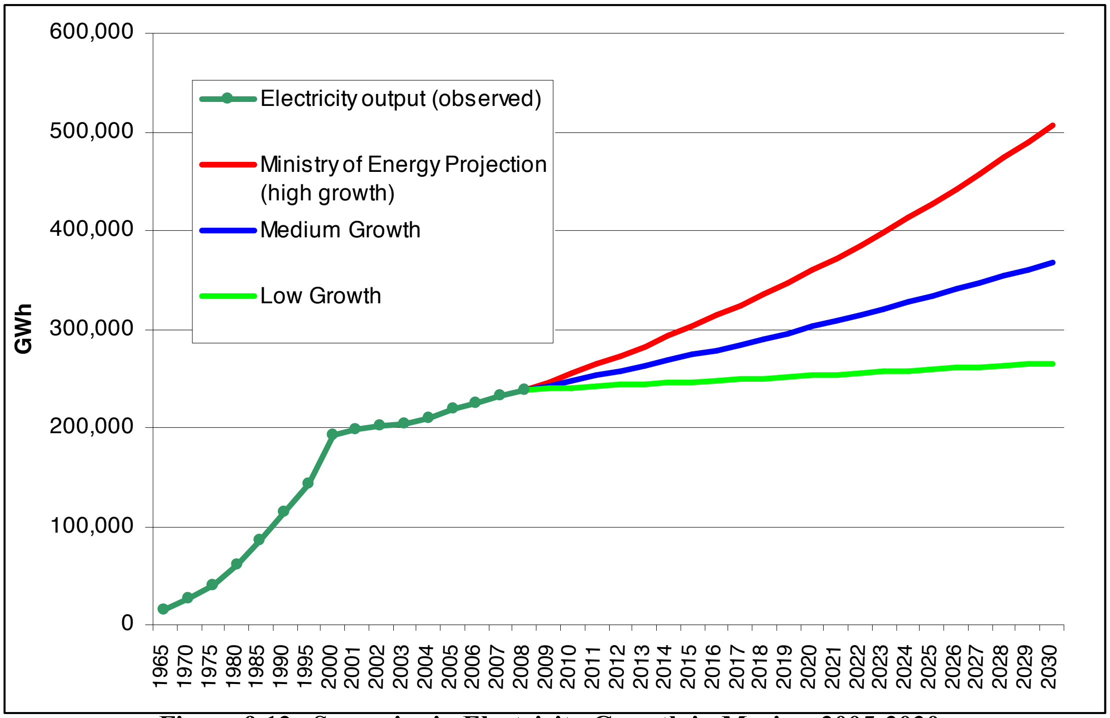
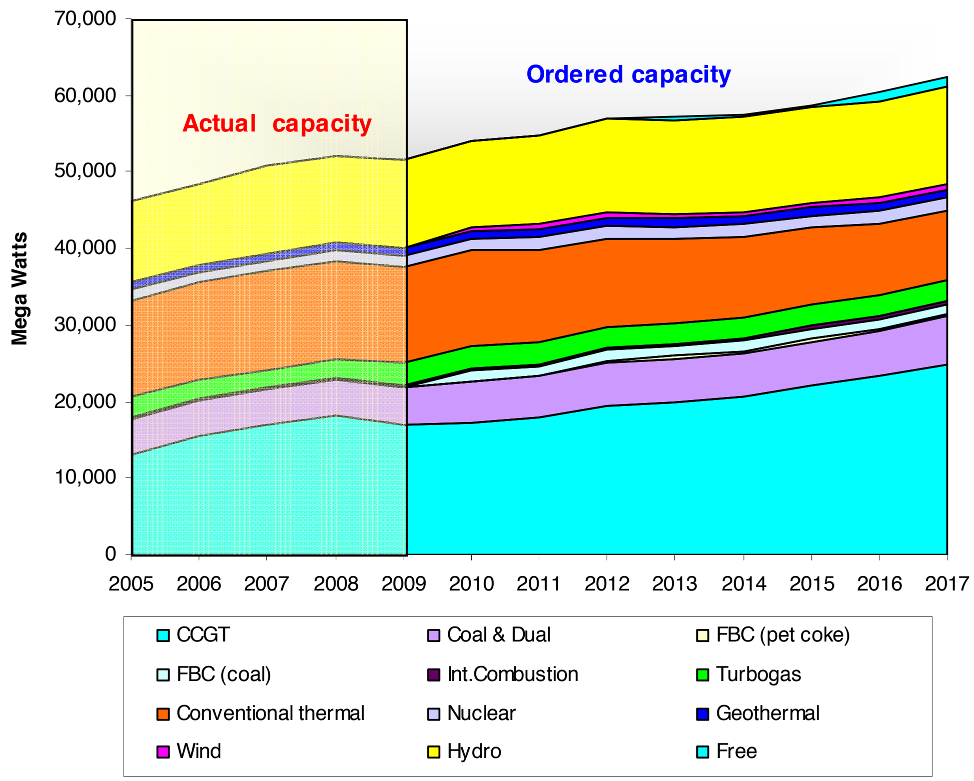


Figure 9.12 Scenarios in Electricity Growth in Mexico, 2005-2030

9.4.2 Declared Governmental Policy to 2017

Figure 9.13 presents installed capacity according to the projections made by the Ministry of Energy in Mexico for the period 2009-2017. Although these trends represent projections they should be referred as capacity already ordered according to the governmental forecasting. Requirements of additional capacity require retrofitting and expansion projects for 25 power stations. These requirements currently rely on financial schemes which are not yet fully implemented. This would account for additional 10,795 Megawatts of installed capacity accumulated over the period 2011-2017 (SENER, 2008). This additional capacity would represent 20.7% the actual total overall installed capacity in 2008.



Source: based on projections made by SENER, Prospectiva del Sector Electrico, 2008-2017; and Comision Reguladora de Energia, Permisos de Energia Electrica Adminitrados, 2008.

Figure 9.13 – Distribution of Installed Capacity by Electricity Generation Technology, Mexico, 2005-2017 (Megawatts)

The majority of the increased capacity will come from CCGT generation in the period 2009-2017. Fluidized bed combustion (FBC) of sub-bituminous coal gains a modest terrain in capacity expansion in Mexico. The Ministry of Energy does not include in their projections the incorporation of fluidized bed combustion of petroleum coke in capacity expansion. However, CRE lists in their dataset 550 Megawatts of authorized installed capacity relating to the operation of two pet coke FBC power stations since 2004. Pet coke FBC installed capacity is only included in the scenarios modelled on declared governmental policy after 2009 in order to assess the effect of pet coke FBC on overall CO_2 emissions projections.

9.4.3 Future Electricity Scenarios

The impacts of five separate scenarios relating to different future electricity mixes are explored in the following sections. All scenarios assume government policy up to

2017 holds and variations only take place thereafter in the period 2017-2030. These scenarios may be summarised as:

- Scenario 1 (Section 9.4.3.1): all existing capacity and generation is maintained in the post 2017 period with the exception of CCGT generation which is varied to accommodate the changes in growth. In this scenario, the average load factors for the period 2005 – 2008 were assumed, but in some cases, particularly in the low growth scenario, the projected future capacity, particularly with CCGT may be such that if the load factors are maintained, then the electricity generated would exceed the projected demand. In this case, the load factor of just the CCGT capacity was adjusted downwards appropriately. In the later stages of the scenario, the generated electricity may fall short of the predicted demand, and in this case, the load factor was increased. However, if this load factor exceeded 75%, often taken as a maximum capacity for this type of generation, then additional capacity was installed.

- Scenario 2 (Section 9.4.3.2): this followed a similar trend to that in Scenario 1, except that the percentage use of all generation was held constant at the 2017 mix. Once again a similar procedure to those in Scenario 1 was implemented if the total projected generation exceeded or fell short of the projected demand.

- Scenario 3 (Section 9.4.3.3): once again this followed a similar trend to Scenarios 1 and 2 except that any adjustment was done solely in the coal/dual fuel plant.

- Scenario 4: (Section 9.4.3.4): In this scenario, the nuclear generation was held constant – which in reality would imply the replacement of the existing plant at the end of its life. In addition, generation by coal/dual fuel, conventional stations (i.e. oil) and open circuit gas turbines were assumed to decline from their current level in 2017 to just 1% of total installed capacity by 2030. As with Scenario 1, CCGT generation was used as a flexible generator, while all the renewable sources saw the following increases: to 2% of installed capacity in the case of geothermal, 15% in the case of wind, 9% in the case of solar and an increase from 20% - 27% in the case of hydro. For wind this represents a particularly challenge and this is discussed further in section 9.4.3.4.

- Scenario 5: (Section 9.4.3.5): This scenario was similar to Scenario 4 except that there was also a significant increase in nuclear generation and as such represents the lowest carbon scenario.

9.4.3.1 Scenario 1 - Gas CCGT Scenario

In this scenario, it is assumed that the trend of closing the conventional generation plants and also the open circuit gas turbines (i.e. turbo gas) in recent years will continue at the same rate and by 2030, the capacity of both will be approximately 40% of the present level – i.e. around 5,000 MW in the case of conventional generation compared to ~12,500 MW in 2005.

In the low growth scenario the projected CCGT generation capacity according to Government policies of 24,708 MW in 2017 will be sufficient to cover generation needs until 2030. In some cases there will be a need to replace older capacity with new generation but there is not need for an increase in overall capacity.

In the medium growth scenario, the CCGT capacity in 2017 will continue to be adequate until around 2022, but there after will steadily increase to around 35,000 MW by 2030. In the high growth scenario, a significant increase in generation capacity post 2017 will be required and will reach over 56,000 MW in 2030.

Figure 9.14 shows the trend in the carbon emissions in this scenario over the period both for the basic generation and also for the "as delivered" electricity which is required in the modelling in Chapter 10. It is interesting to note that the three growth scenarios are very similar, and this is a partly consequence of the relatively high current ordering of CCGT plant at the present time.

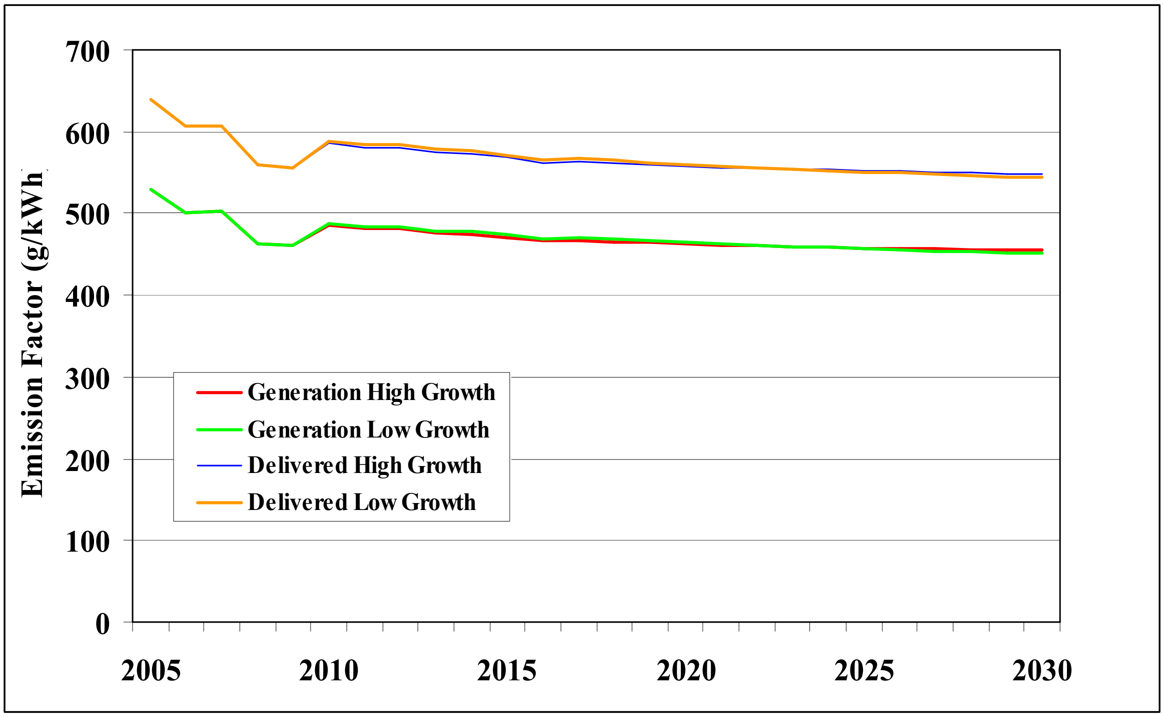


Figure 9.14 - Scenario 1, Carbon Emissions in the CCGT Scenario, Mexico, 2005-2030

The reason why the three trend lines differ by less that 4g CO_2 per kWh in 2030 despite the significant difference in growth rates is because at the higher growth rate, the percentage generation of the relatively lower emission CCGT stations is much higher and nearly compensate for the emissions which would arise from the difference in the growth rates.

9.4.3.2 Scenario 2 – Maintaining the Proportional Fuel Mix

This scenario explores the changes in carbon dioxide emissions where a policy to maintain the fuel mix which is reached in 2017 throughout the remainder of the scenario period. In the scenario, it is assumed that there is no change in the generation capacity and consequently the electricity generated in the low carbon energy sources (i.e. nuclear and renewable).

There is appropriate adjustment of load factors or capacity however in this scenario all adjustment is spread across all fossil fuel generation. When there is low growth the installed capacity of CCGT generation rises to 24,708 MW under the current Government Policy and remains static thereafter.

For medium growth the CCGT capacity raises to just over 32,000 MW by 2030 compared to 35,000 MW in the previous scenario while for high growth the CCGT capacity in 2030 is just less than 49,000 MW (compared to over 56,000 MW).

Figure 9.15 shows the carbon emissions for this scenario. The differences in the three growth scenarios is more marked as under this scenario, the proportion of low carbon generation will fall particularly in the medium and high growth scenarios.

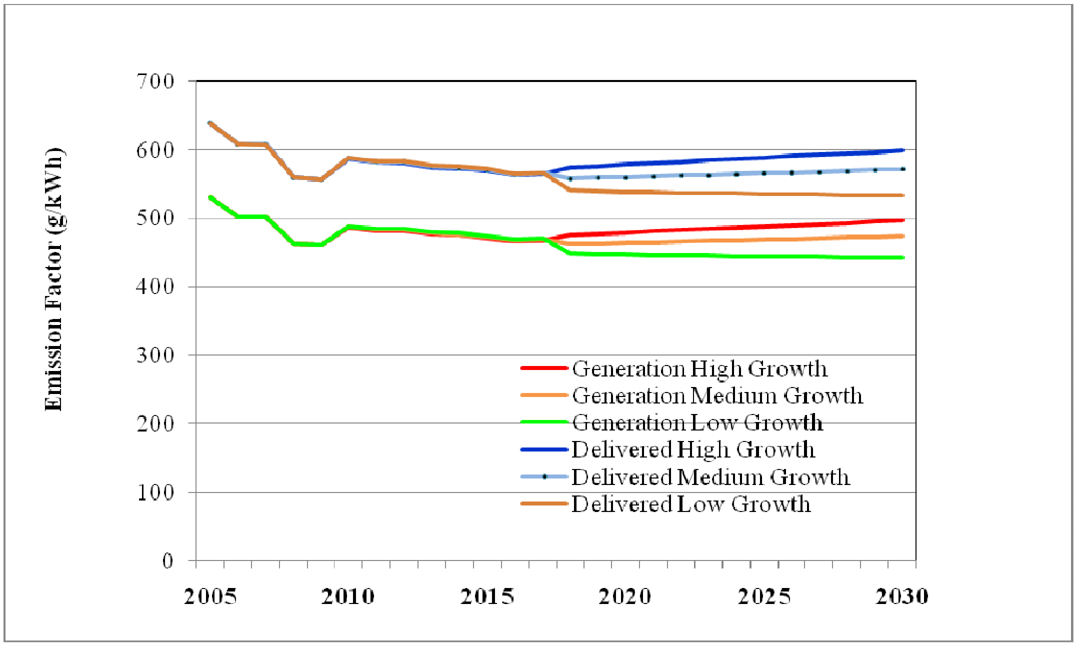


Figure 9.15 – Scenario 2, Carbon Emissions Maintaining the Governmental Energy Policy after 2017, Mexico

9.4.3.3 Scenario 3 – Increasing Dominance of Coal for Electricity Generation

The third scenario explores how the overall carbon dioxide emission factor would change under a policy of increasing participation of coal and pet coke FBC installed capacity after 2017. In this case, it is assumed that there would be an increase in coal and dual installed capacity from around 10% in 2017 to nearly 25% in 2030; installed capacity of FBC of pet coke increases from 0.5% in 2017 to 1% in 2030 whereas FBC of coal grows from around 2% to 5% in the same period. In this scenario, the share and distribution of renewable(s) installed capacity remains constant as of 2017. This approach effectively considers the effective reduction of installed capacity of gas fired plants (i.e. CCGT and open gas cycle turbines) while coal and pet coke FCB plants expand. This scenario corresponds to the most carbon dioxide intensive given high carbon content and the associated emission factor for coal and pet coke and should be compared with the emission factors in table 9.5. In practice, the realization of this scenario will depend on the availability of coal and the cost/effectiveness of coal generation technology in relation to other generation technologies; in particular, gas fired plants. For instance, the price of coal is a function of future coal reserves and costs of production (Lefevre et al., 1999), and appears to have a lower price in relation to natural gas in the Asia Pacific Economic Cooperation (APEC). On the other hand, if the price of carbon were to rise significantly, this would shift the emphasis back in favour of the lower carbon technologies and gas.

The proportion of coal imports as compared to domestic coal production in Mexico has increased dramatically from 6.3% in 1965 to 57.5% in 2007. If this trend continues, it is very likely that increasing the capacity of coal fired plants would rely on increasing coal imports.

Coal has a high emission factor for CO_2 and though the fugitive emissions are low the total emissions from this electricity generation using this fuel will be the highest (apart from pet coke). The only way in which coal can compete on a carbon emission basis with other fuels would be with the advent of carbon sequestration and storage (CCS). However, although there are a few very small plants now operating, it will not be much before 2020 that sufficient experience will have been gained, from the demonstration CCS plants now planned to be commissioned around 2015 in several countries, to allow large scale commercial exploitation of the technology. With construction times of up to 5 years, it will only be towards the very end of the scenario period that such technology will have much impact in Mexico, and has been neglected in this present scenario.

Figure 9.16 shows the carbon emissions arising from this scenario. In the low growth scenario, there is adequate capacity for all types of generation still remaining in the period after 2017. As a result the low growth scenario is very similar to those from the previous scenarios except that there is a shift in terms of load factor away from CCGT to coal.

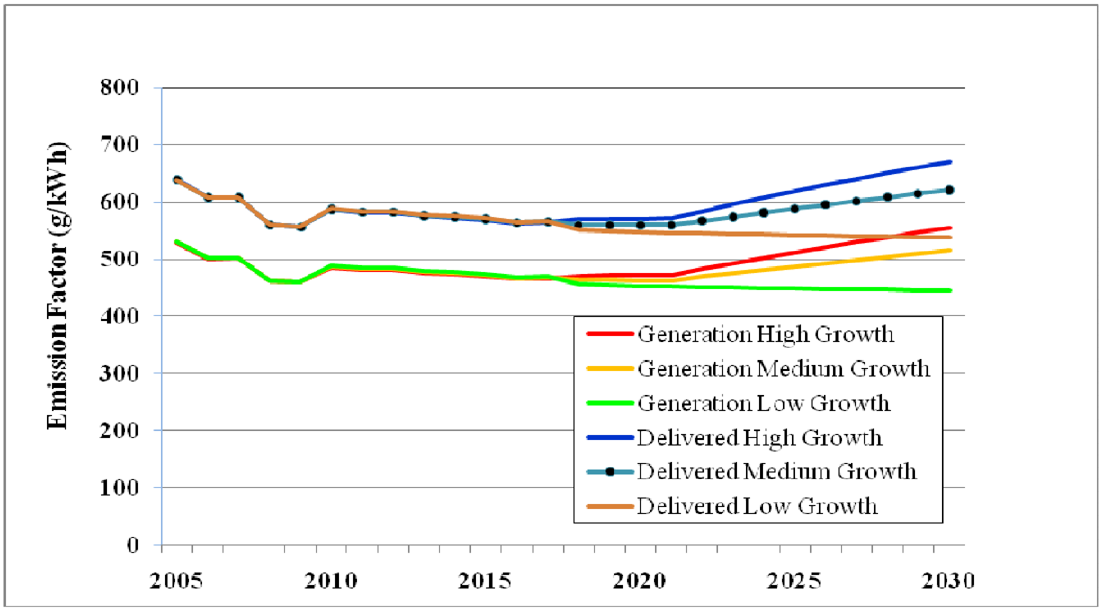


Figure 9.16 – Scenario 3, Carbon Emissisons from Coal Dominance in Electricity Generation, Mexico, 2005-2030

In the medium growth scenario, the coal generation capacity rises from 6,408 MW in 2017 to 14,800 MW in 2030 while the carbon emission factor which is projected to fall from 530 g/kWh in 2005 to 468.5 g/kWh in 2017 under current policies will then rise to 515.1 g/kWh almost negating the improvement over the next decade. The corresponding figures when transmission losses are taken into account are 639 g/kWh in 2005, 565 g/kWh in 2017 and 621 g/kWh in 2030. In the high growth scenario, the coal fired capacity will raise further to over 27000 MW and the emissions at 555g/kWh will significantly exceed the emissions in 2005.

It is clear that a switch to indigenous coal is not an option which is compatible with moving to a low carbon economy unless carbon sequestration is available, but as said previously it is unlikely to have a significant impact before 2025.

9.4.3.4 Scenario 4 – A Renewable Electricity Generation Regime

This scenario shows the outcome on carbon dioxide emission factors from reductions in the installed capacity of older fossil fuel plants (e.g. conventional fuel oil stations, turbo gas and coal), static levels of absolute capacity post 2017 for CCGT and nuclear, and growth in the installed capacity of renewable(s) to cover the reduction in the older fossil fuel and also further growth in demand for electricity. Many of the older fossil fuel power stations are likely to come to the end of their operating lives during this period and it is assumed that the installed capacity in coal and dual fuel plants, the conventional generation, and the open circuit gas turbine generation reduces from the relevant levels in 2017 to 1% in 2030. In the case of coal/duel fuel plant this corresponds to a change from around 10%. In this scenario, it is also assumed that installed capacity of FBC of pet coke (0.5%), and FBC of coal (2.1%) will remain stable over the period. In this scenario, any shortfall in capacity is accommodated by a steadily increasing in an appropriate mix of renewable technologies.

Emphasis is placed on wind and solar when modelling this renewable energy scenario regime. Wind, after hydro, is perhaps the most developed renewable technology world wide, and a major expansion in wind generation from 1% in 2007 to 15% is projected. However, to achieve such an increase may require the installation of large numbers of turbines, something which is covered in detail below.

Of the currently installed electricity generating capacity, hydro electricity currently (2007) represents 13% and according to Government projections is expected to rise to 20% of total installed capacity by 2017 (SENER, 2008). Thereafter it is assumed that this proportion will reach a maximum of 27% towards the end of the scenario period. Geothermal installed capacity slightly increases from 1.7% in 2017 to 2% in 2030 while a major expansion in solar generation increasing from 1% in 2017 to 9% in 2030 is expected. Nuclear capacity was assumed to remain constant in this scenario (i.e. any closures would be compensated by opening of equivalent capacity).

This scenario required a different approach to the formulation of algorithms for the projected emissions. This is because the generation of electricity from many of the different sources is expressed in percentage terms, and changing the capacity of one generation type automatically affects the others. The development of the approach was done in several stages as shown below:

- A pro-rata percentage generation of each generation type was determined for each year, for those energy source in which the capacity was varying (i.e. increasing percentage or decreasing), using the percentage information given above.

- A reconciliation of the generation capacity and the predicted demand was made in a similar manner to that explained in previous scenarios. In this case the adjustments were done for the CCGT plant, the two fluidized bed plants and also the internal combustion plant. Though the latter constitute a very small proportion of overall generation, their function is important to serve remote areas not adequately covered by the grid and also for standby generation in emergency situation.

  Once again, if there was any surplus/deficit in generation when estimates were used using average load factors, these factors were adjusted accordingly. However, if these load factors exceeded the maximum normally accepted load factors (e.g. 75% in the case of CCGT), the relevant capacities were increased in these generation sources accordingly.

- The amended capacities were then used to estimate the capacities of those generation sources which were specified as a percentage using the iteration facility within Excel The potential generation was estimated using these capacities and either the average load factors in the case of the renewable sources, nuclear or those sources which were closing (e.g. coal) while the load factor as amended above was used for the remaining sources.

- The total predicted generation was then compared with the projected demand according to the relevant growth scenario. In general these figures did not match – in some case the predicted generation exceed the projected demand and vice-versa. Let this mismatch demand be E.

  A difficulty now arose as to how to distribute the generation to resolve the imbalance bearing in mind that the percentage generation of each fuel type was different and so was its load factor. The approach taken was to evaluate the product of multiplying the load factor (L_i) by the proportion (p_i) of generation capacity for each electricity source by fuel type. This generated a weighting factor which when multiplied by a total capacity (C) should equate to the energy demand imbalance, and this indicates the total additional capacity needed. From this it is then possible to estimate the additional capacity for a particular generation source "C_i" according to the following equation:

$$C_i = p_i C = \frac{E_{imbalance}}{8.76 \cdot \sum_{i=1}^{n} p_i L_i} \qquad \dots (9.38)$$

Here the factor 8.76 arises from the number of hours in a year divided by 1000 to covert from GWh in which the demand was specified into MW.

- Using the revised capacity, a revised total generation was computed. However, since some of the energy sources such as nuclear had a fixed capacity, the resulting percentages were not always exactly correct, but after a second iteration of the procedure the discrepancies in potential generation from the capacity and the projected demand were less than 1% which was adequate for this modelling.

The results for this scenario are shown in Figure 9.17 where for clarity again the Medium growth lines have been omitted as they fall between those of the low growth and high growth.

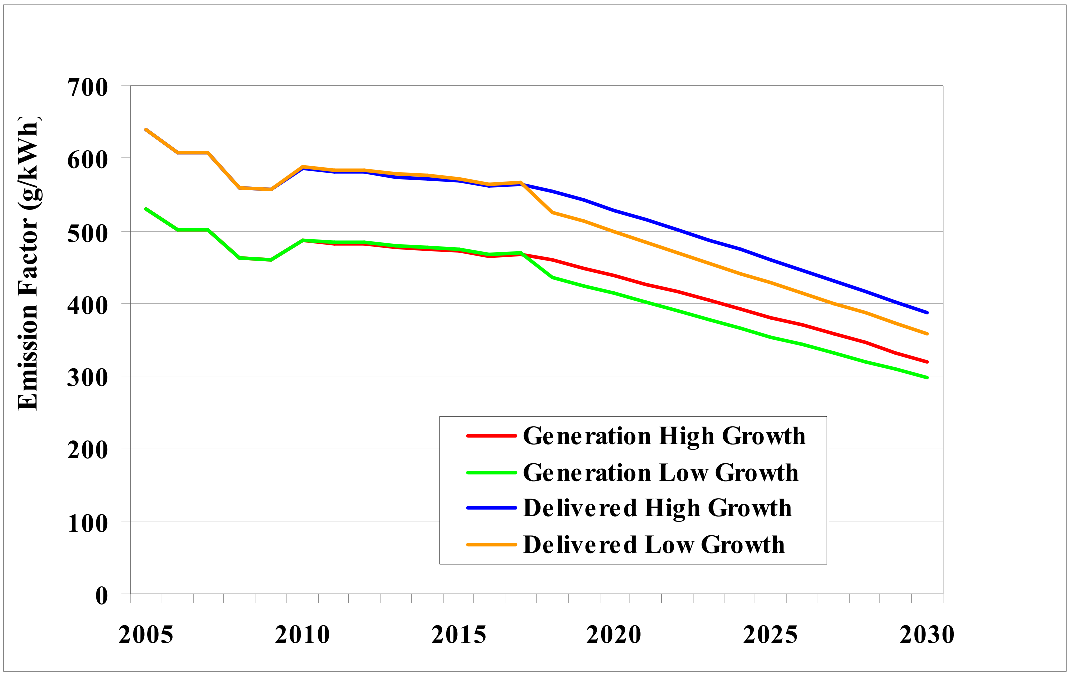


Figure 9.17 – Scenario 4, Carbon Emissions in a Renewable Electricity Generation Regime, Mexico, 2005-2030

In this scenario, the carbon emission factor for the low growth scenario falls from 468 g/kWh in 2017 to 297 g/kWh by 2030 compared to a factor of 320 g/kWh in the high growth scenario. To maintain the required percentage generation it was necessary to slightly adjust the CCGT geenration capacity in the medium and high growth scenarios: in the low growth, the CCGT capacity remains constant at 24,708 MW as in all previous scenarios.

Regarding the renewable generation, two technologies need review, namely wind and solar. These were indicated to have particularly high eventual percentage contributions to the overall capacity in 2030. It is thus relevant to examien whether the projected increase in installed capacity of both these technologies is feasible.

The growth rate in installed capacity of wind generation in Mexico was assumed to be higher than in the case of growth in solar radiation because wind energy is a more matured and commercially diffused technology. Under the low growth scenario, the wind generation capacity rises from under 1000 MW in 2017 to approximately 9,600 MW in 2030 while the figures for medium and high growth are 11,900 MW and 16,300 MW respectively in 2030.

A reference value for a typical wind turbine size was taken as 2 Megawatts with 80 meters blade diameter. In the low growth scenario this would require the installation of around 4300 turbines over the 13 years or at about 330 turbines a year (660 MW capacity per year). For the medium and high growth scenarios the corresponding figures are 420 turbines (840 MW capacity) and 590 turbines (1180 MW capacity) respectively. It is thus relevant to consider whether such installations rates are feasible bearing in mind that unlike the simple linear projection indicated here, there is likely to be a saturation type curve which would mean that in the middle years installation rates would need to be around double thus suggested above.

Countries such as Germany and Spain have had peak installation rates of up to 2,000 MW a year and these rates would thus seem possible. In addition, the Chinese Government has plans to increase its generation capacity from 2.6 GW in 2006 to 30 GW in 2020 (Pernick & Wilder, 2007). In this respect, the scenarios proposed for the Mexican situation are much more modest. However, no country has achieved continued high expansion rates over a number of years and with increasing interest worldwide in wind generation, there may be supply chain barriers to the implementation of the wind energy expansion proposed here. Nevertheless this does not invalidate the modelling as it aims to explore what might be technically feasible.

A further issue with regard to wind energy expansion relates to the area of land required. To avoid interactive effects the turbines should normally be spaced at 10 blade diameters but even at this spacing there will be a small reduction in cumulative output compared to individually spaced turbines. At such spacing the land area required for the full deployment of turbines will range from 2750 sq km in the low growth scenario to approximately 5000 sq km in the high growth scenario. As a matter of comparison, this last figure is a little less than the area of the county of Norfolk in the UK.

While current generation wind turbines have a rated output of around 2 Megawatts, state-of-the-art technology in Germany suggests 5 Megawatts per wind turbine with a 130 meter blade diameter (Pernick & Wilder, 2007) will be available in the near future. Thus in 2010, turbines with a capacity of 3MW have been installed in the UK and elsewhere. However, since the power from a given turbine is proportional to the square of its blade diameter, and the land area covered is also similarly related, the total area covered will be approximately the same irrespective of the turbine size. Of course, with larger turbines there will be fewer but large turbines, but will cover the same total area.

In the case of solar generation, an installed capacity of 5.8 GW would be required in the low growth scenario and 9.8 GW with high growth. Though the annual growth would be well under 1 GW, it does represent a continual rate of development which to date has not been achieved anywhere. However, from a low base there have been impressive increases such as the growth in installed capacity for solar collectors in Europe at an annual growth rate of 15% in the period 1980-1994 and global growth in installed capacity for wind energy at annual growth rate of 55% in the period 1980-1998 (Jacobsson & Johnson, 2000).

With the development of prototype centralised solar power plants in Spain there is the possibility of developing such power stations on a scale of 100s of MW in a relatively few locations rather than installing large arrays of photo-voltaic electricity and using distributed networks to supply the electricity. Overall it would appear that these proposals for solar energy are more ambitious than the wind developments.

9.4.3.5 Scenario 5 – Increasing Participation of Nuclear and Moderate Growth in Renewable(s)

This scenario concerns the expansion of non-fossil energy (nuclear, hydro, geothermal, wind, and solar radiation). This deployment regime is perhaps the most controversial in many respects. Installed capacity of nuclear energy in Mexico accounts for 1,365 Megawatts in 2008. Mexico relies on a single nuclear plant which started up operations in 1990 after nearly 20 years of construction. The design of this power station corresponds to a boiling water reactor (BWR-5) type of which manufacturing is currently discontinued (Lomelí & Tamayo, 2008; Martinez-Fernandez, 2007). Currently, there are 439 nuclear reactors for electricity generation in the world, of which 92 are boiling water reactors (BWR),[168] and 36 units under construction (SENER, 2008). The majority of these reactors are concentrated in the United States (104), followed by France (59), Japan (55), and Russia (31).

This scenario is highly controversial because nuclear energy in generally unpopular among the population's point of view. According to the results indicate in table 9.5, nuclear energy has the lowest carbon dioxide emission factor as compared to fossil energy. However, in terms of contingencies and technological risks, the acceptability of nuclear energy is not always straightforward from the positions adopted by the public.

The governmental energy deployment policy (i.e. scenario 2) assumes an increase in nuclear installed capacity from 1,365 Megawatts in 2008 to 1,634 Megawatts for the period 2010-2017. In general, an average nuclear power station has a 30+ year working life time with decommissioning taking place afterwards. In the proposed scenario in this chapter, decommissioning of current nuclear capacity is assumed to take place on a full basis in year 2017. In the following year, two pressurized water reactors (PWR) accounting for 1,360 Megawatts net capacity are added to the current capacity for electricity generation in Mexico. Afterwards, a linear progression occurs in the growth of nuclear energy adding up an additional nuclear reactor of the same type every subsequent year till 2030.

By year 2017 replacement reactors are in place to a capacity of 1,634 MW and thereafter the installed capacity rises at approximately 1000 MW per year. In the low growth scenario the nuclear capacity reaches 13,600 GW while in the high growth scenario it reaches 20,700 MW. The significant increase in the high growth scenario would be comparable with the growth of nuclear capacity in France during the 1980s and 1990s.

In this scenario, the CCGT installed capacity decreases from around 40% in 2017 to 35% in 2030 as the older plants are closed. However, a CCGT capability will still be required as the renewable generation is intermittent and nuclear power is largely based load and cannot respond rapidly to diurnal changes in demand. Once

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168 Operational & Long Term Shutdown Reactors by Type, Nuclear Power Plants Information, Power Reactor Information System. Summary Statistics at http://www.iaea.org/programmes/a2/, September 2009.

again the coal, conventional and open circuit gas turbine plant will decline in a similar manner to that in scenario 3. With regard to renewable energy, installed wind capacity will see a more moderate increase in relation to the previous scenario increasing to 6% of installed capacity by 2030. At the same time, hydro electricity remains around 21% along the period; whereas energy from solar radiation grows from 1% in 2017 to 4.5% in 2030.

In this scenario, the overall emission factor falls further despite the much lower proportion of renewable generation than in the previous scenario. The overall emission factor for generation falls to 197 g/kWh by 2030 for low growth and to 259 g/kWh for high growth.

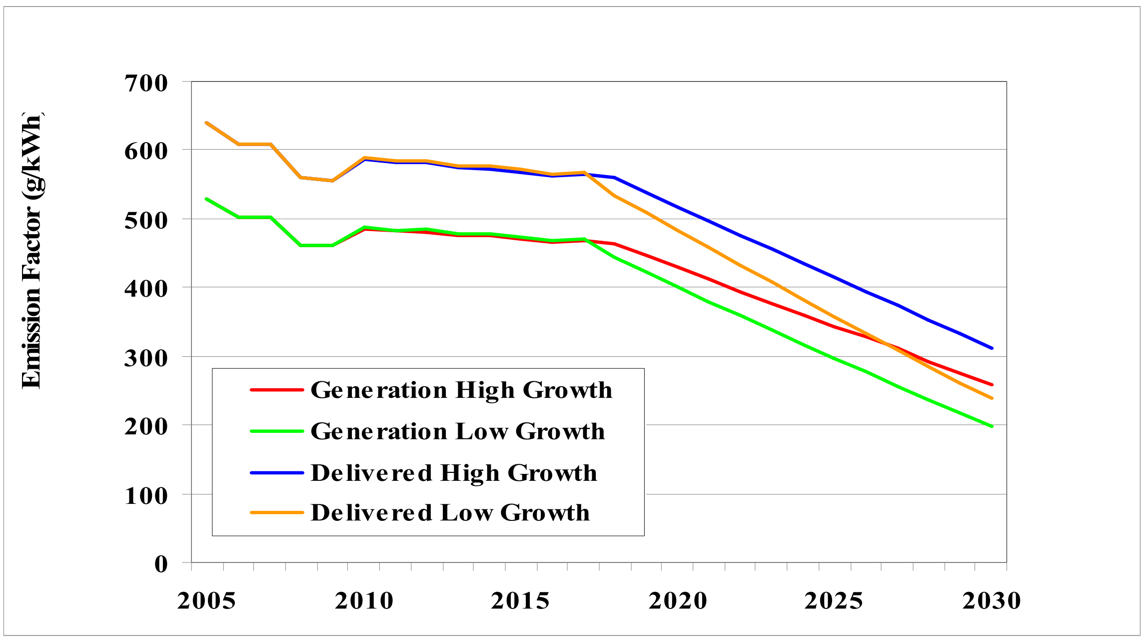


Figure 9.18 – Scenario 5, Carbon Emisisons from an Increasing Participation of Nuclear, Mexico, 2005-2030 (Nuclear)

9.5 A Review of the Three Growth Scenarios

Carbon intensities for each of the three growth scenarios can be multiplied by the total amount of electricity generated to estimate the total carbon emissions for each of the three growth scenarios. The results are shown in figures 9.19 to 9.21.

It must be remembered that though the carbon intensities in all scenarios are essentially fixed under current Government Policies, a difference in the growth rate will automatically mean an increased (or decreased) total carbon emission.

Figure 9.19 shows the total cumulative carbon emissions for the low growth scenario. Unlike the previous figures (9.14 – 9.18), this one shows the total emissions including the impacts of transmission losses. What is noteworthy is that the carbon intensity improvement between 2009 and 2017 just cancels the impact of increased growth. Thereafter there is little difference between the CCGT, coal, and current mix scenarios as the capacity already planned is sufficient to cope with any demand up to 2030. There is a slight difference in total emissions with the CCGT scenario being slightly better than the other two as emissions for CCGT generation are noticeably lower than for other fossil fuel. The reason for the small differences between the different scenarios arises purely for the priority given in load factor adjustment in the different scenarios. Essentially, there is little difference in final outcome irrespective of which mix of fossil fuel is used in this low growth scenario.

On the other hand, there is a noticeable improvement in total carbon emissions with the renewable energy scenario falling from 140 Mtonnes to under 100 tonnes by 2030. With the combined nuclear/renewable scenario, the improvement is even better as more fossil fuel generation is phased out with the inclusion of more low carbon nuclear generation. The total emissions for this scenario fall to around 60 Mtonnes by 2030 around 40% of the current level.

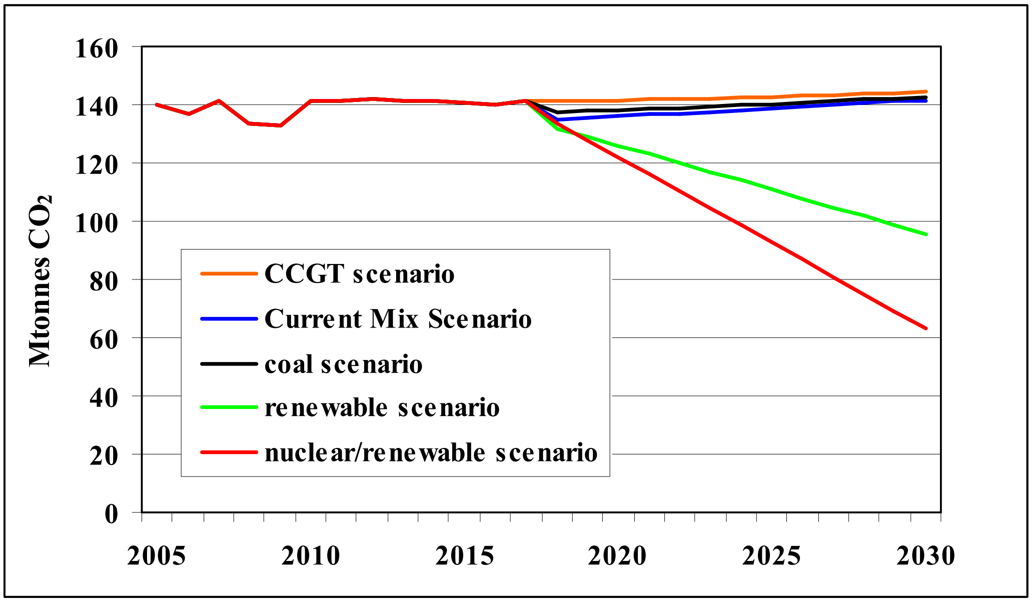


Figure 9.19 – Total Carbon Dioxide Emissions (including effect of transmission losses) for the Low Growth Scenario

In the medium growth scenarios shown in figure 9.20, there is an increase in total carbon emissions from the present day up to 2017. This seems to be a contradiction with what was said above about the low growth scenario. In both cases, irrespective of the generation type scenario, the carbon emission factor (including transmission losses) falls from 639 g/kWh to 567 g/kWh, but the growth rate in generation is higher than this improvement rate and there is a small increase over the period. Unlike the low growth scenario, there is a noticeable difference in the total emissions between the three fossil fuel scenarios.

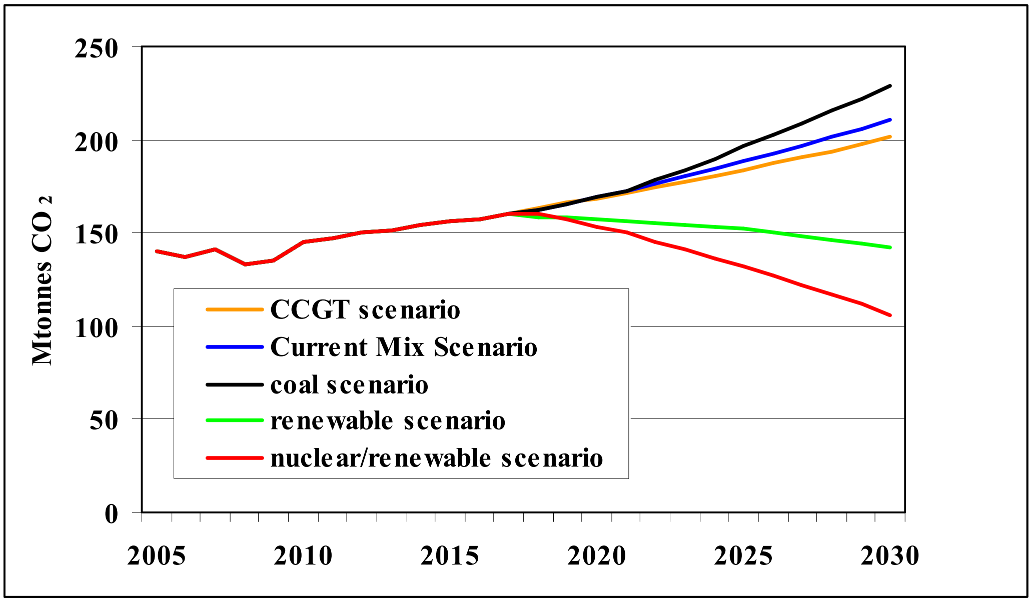


Figure 9.20 - Total Carbon Dioxide Emissions (including effect of transmission losses) for the Medium Growth Scenario

As expected the CCGT scenario shows the least increase in overall cumulative carbon emissions, but overall would see an increase of around 33% on 2005 levels. For the coal scenario, the situation is significantly worse. Interestingly, with the renewable scenario, carbon dioxide emissions essentially return to 2005 levels at around 140 Mtonnes. With the nuclear/renewable(s) scenario, the total emissions fall to just over 100 Mtonne, a fall of 25% on 2005 levels.

The impact of the high growth scenario on carbon dioxide emissions is shown in figure 9.21. The differences between the three fossil fuel scenarios are now more marked and the total emissions rise to between 270 and 340 Mtonnes of carbon dioxide, approximately double those in 2005. It is clear that such scenarios are not compatible with carbon reduction at the relatively modest growth rate for a developing country of 3.5%. While the renewable scenario stabilises emissions after 2017, these are still around one third higher than 2005. Even the nuclear/renewable scenario fails to return the total emissions to the 2005 level.

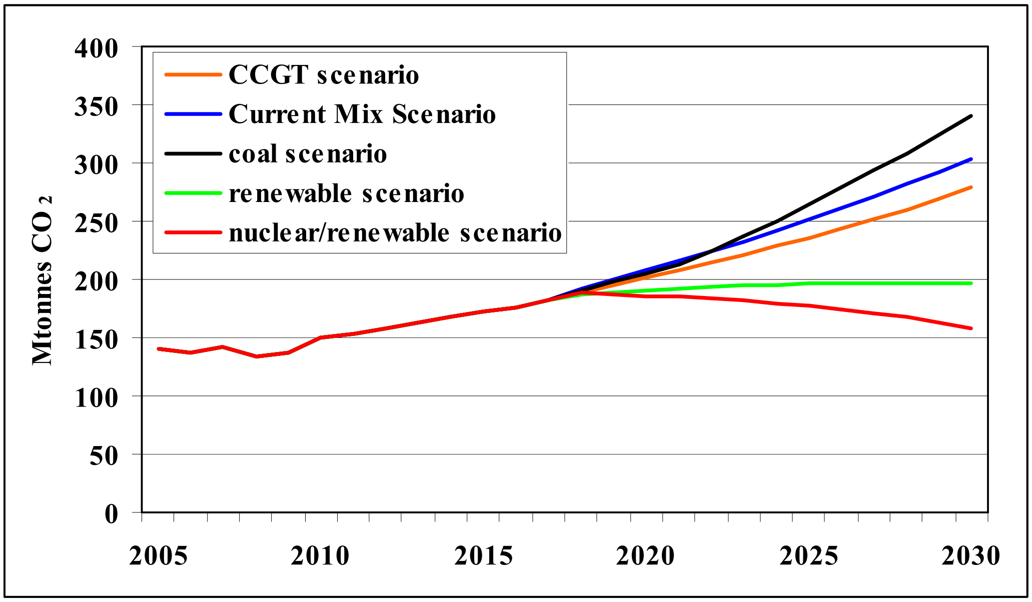


Figure 9.21 – Total Carbon Dioxide Emissions (including effect of transmission losses) for the High Growth Scenario

9.6 Summary of the Chapter

Overall, turbo gas and conventional thermal plants were found to have the highest carbon dioxide equivalent emission factors (i.e. 1098.2 and 998.5 g/kWh, respectively) whereas nuclear plants showed the lowest (i.e. 18.2 g/kWh) in 2005. These findings were arrived after taking into account both the fugitive emissions of gas, oil, and coal and the electricity loses after transmission and distribution.

An overall carbon dioxide equivalent emission factor for the Mexican electricity grid including transmission losses was found to be 638.7 g/kWh in 2005. This carbon emission factor reduced to 559.7 g/kWh in 2008.

The first electricity scenario of maintaining the current generation capacity after 2017 (i.e. the planned governmental energy policy) with variations in CCGT generation capacity will require 56,000 MW of CCGT in 2030 in a high growth electricity demand scenario (i.e. a 3.5% annual growth).

In the second energy scenario consisting of maintaining the current fuel mix constant after 2017, the CCGT capacity is somewhat less at 49,000 MW in 2030.

The third electricity future explores increases in coal and pet coke FBC installed capacity after 2017. In the high growth electricity demand scenario, the coal generation capacity will growth to over 27,000 MW by 2030 and the carbon emissions will largely exceed 555 g/kWh not taking into account the impact of transmission loses (i.e. the most carbon intensive scenario).

The fourth energy scenario considers a raise in renewable energy. Hydro generation capacity rises from 20% to 27% between 2017 and 2030. Geothermal capacity grows from 1.7% to 2% whereas solar capacity increases from 1% to 9% in the same period. In the high growth electricity demand scenario, the wind generation capacity rises from 1000 MW to 16,300 MW between 2017 and 2030 whereas the carbon emission factor falls from 468 to 320 g/kWh in the same period.

The fifth scenario sees a growth of nuclear generation capacity and is assumed to increase in 1,634 MW between 2010 and 2017. In 2018, 1,360 MW net capacity are added to the current capacity and afterwards nuclear capacity rises 1000 MW circa per year. In the high growth scenario, nuclear generation capacity reaches up to 20,700 MW by 2030 and the corresponding carbon emission factor drops to 259 g/kWh.

It is clear that the Mexican Government needs to address issues of carbon dioxide emissions from electricity generation urgently and that the present policies are inadequate to promote carbon reduction and at best retain the status quo only with a low growth scenario except where a high renewable(s) and/or nuclear generation scenario is adopted.

Chapter 10

Carbon Dioxide Emissions in the Mexican Iron & Steel Industry

Introduction

This chapter presents a methodology in regards to the third component of the carbon life cycle assessment model introduced in chapter 1, and completes the several strategies to mitigate climate change from a holistic point of view.

The carbon emission factors for electricity obtained in the previous chapter under different energy policy scenarios are incorporated in this chapter as changes in the carbon emission factor of purchased electricity may significantly affect emissions in the steel industry and this is reflected in the methodology of this chapter.

The energy policy scenarios in the previous chapter form a complementary strategy with regards to energy efficiency in the steel industry. Reducing the intensity of electricity uses in the steel industry is a specific strategy in the manufacturing sector. Not only may there be a lower carbon content of purchased electricity but a reduction in electricity use in steel making will further enhance the reduction by combining the lines of actions implemented in both power facilities and steel plants.

In instances where electricity generation capacity cannot be increased but there is a growing electricity demand in the manufacturing sector energy efficiency is a critical strategy to prevent a further expansion of installed capacity in electricity generation. Certainly, a higher energy demand will put a pressure in carbon emissions. Thus a holistic approach to carbon emissions needs to revise energy policy scenarios of renewable capacity in combination with energy efficiency in industry and this was done in the research of this thesis.

The chapter consists of the following five sections: section 10.1 presents the data sources used in this analysis. Section 10.2 elaborates on a characterisation of the steel industry in Mexico in regards to the relative importance of materials, by-products, fuels and electricity uses. Section 10.3 covers the methodology which comprises four sub-sections with:

- Section 10.3.1 presenting a general approach to the quantification of carbon emissions;
- section 10.3.2 defining a distribution of fuels and materials between primary and secondary steelmaking;
- section 10.3.3 presenting the quantification of average specific electricity consumption

while

- section 10.3.4 covers the calculation of carbon intensities by main steel technological route.

Section 10.4 elaborates on alternative carbon emissions scenarios in the steel industry while the final section 10.5 presents a summary of the main findings.

10.1 Data Sources

The following three sources of information were used in the methodology of this chapter:

1) National official statistics from the Institute of Statistics, Geography, and Informatics in Mexico (INEGI), period 1990-2006.
2) Energy Balance Tables from the Ministry of Energy in Mexico (SENER), period 1990-2007.
3) Aggregation of data reported at plant level in year 2005 from the Ministry of Environment and Natural Resources (SEMARNAT).

An alternative approach to using balance table data is to use data derived at the plant level. Aggregation of electricity and other fossil fuels (i.e. inclusive of natural gas, coal, pet coke and so on) reported by single plants should be equal to the total overall amount of fuels and electricity in the steel industry.

Data reported at plant level which is used in the aggregation analysis presented in this chapter and includes the following:

1) Raw materials employed in the production process and supportive manufacturing services (for instance, diesel for internal traffic in a plant).
2) Products and by-products in manufacturing.
3) Intermediate products (for instance, steel scrap and liquid steel which are used for the production of finished steels).
4) Energy inputs in the production process.
5) Aggregated electricity consumption and self-generation.

Data reported at plant level does not allow tracking back the amount of electricity and energy inputs allocated for specific stages in a production process. For instance, observation of data at plant level does not allow breaking down electricity requirements by coking plant, blast furnace, basic oxygen furnace, and a rolling mill in a single facility. This represents an information drawback which is tackled in the methodology section below. On the other hand, data at plant level permits identifying the amount of raw materials as feedstock (for instance, steel scrap and dolomite) which correspond to a specific stage of a production process. Plant data is used to specify and compare the amount of energy requirements at different stages of the production process and by main steel making technology.

10.2 Characterisation of the Steel Industry in Mexico

The iron & steel industry uses a combination of raw materials, fossil fuels, and electricity requirements in the production process. Figure 10.1 presents overall consumption of raw materials and intermediate products in the Mexican steel industry in 2005. The relative importance of these materials is as follows: iron ore (7,012.3 tonnes); sponge iron (5,973.2 tonnes); steel scrap (4,232.2 tonnes); pig iron (4,047.1 tonnes); coal (3,160.7 tonnes); coke (1,491.8 tonnes); sinter product (1,413.5 tonnes); limestone (1,261 tonnes); and dolomite (459.8 tonnes). Coal and coke consist of both feedstock and provide heat in combustion processes in a blast furnace. Pig iron and sponge iron are two intermediate products obtained during primary and secondary integrated steel making, respectively. Pig iron is produced in blast furnaces whereas sponge iron is produced in direct reduction reactors. Steel scrap is widely used in secondary steel making and sometimes mixed with sponge iron in the charge of an electric arc furnace.

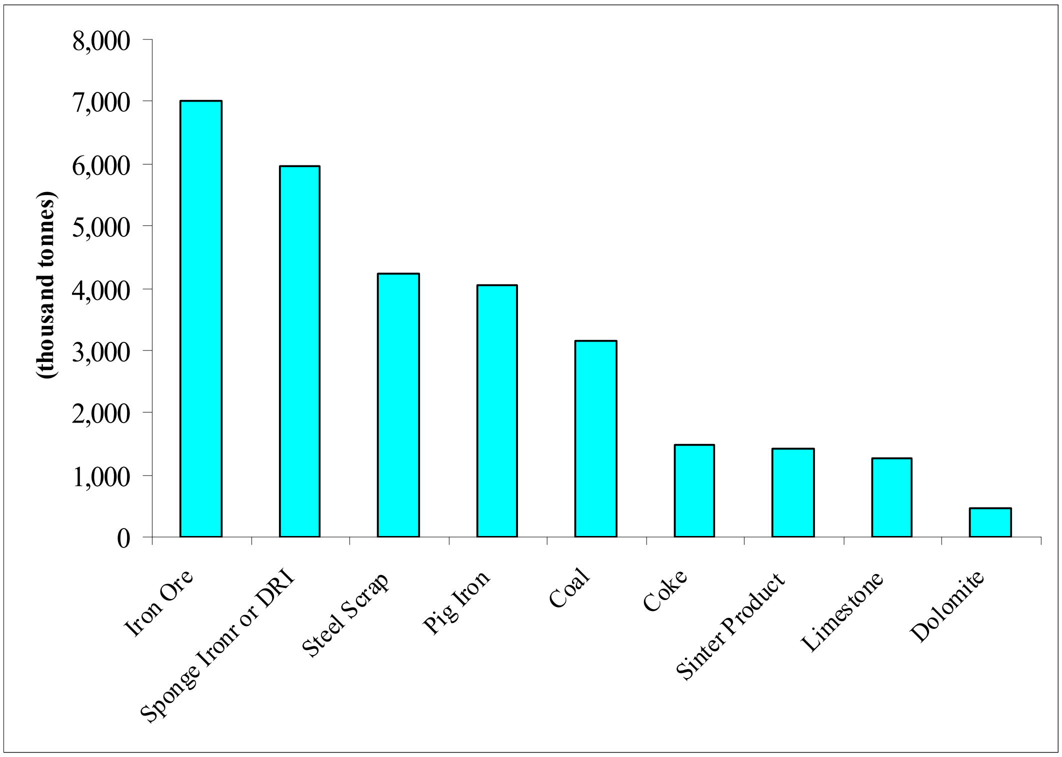


Figure 10.1 – Raw Materials Used in Integrated Primary and Secondary Steelmaking, Mexico, 2005 (thousand tonnes)

Source: INEGI and SEMARNAT, Mexico, 2005.

Figure 10.2 shows the overall consumption in TERA Joules of fossil fuels and electricity in the steel sector in 2005. Within the steel sector, dry gas is the most important fossil fuel in combustion and reduction processes in steel making (122,812 TJ), and is used both a fuel and as a reducing agent in DRI production. Electricity requirements in steel making are also significant (26,359 TJ) although they only account for 21.5 % of the energy provided by dry gas, while small amount of other fossil fuels also used in the steel sector are fuel oil (11,510 TJ), diesel (791 TJ) and liquefied petroleum gas (or LPG, 5 TJ). Overall the total energy provided by the addition of dry gas, electricity, fuel oil, diesel, and LPG amounted to 161,478 TJ in 2005.

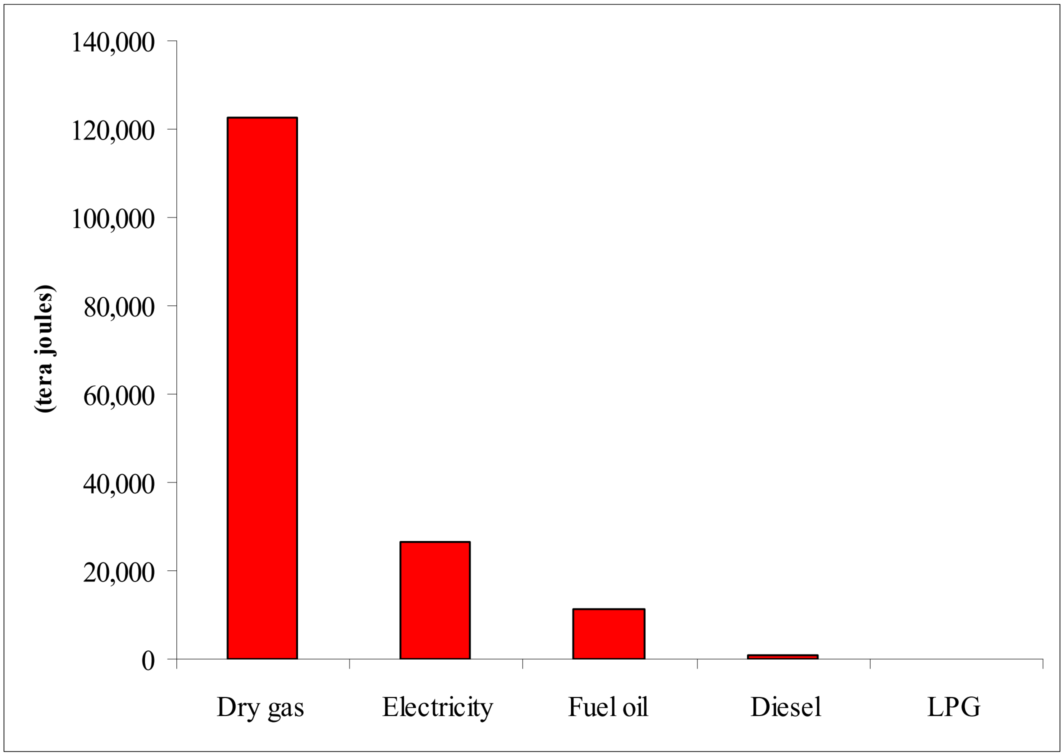


Figure 10.2 – Fuels Used in Integrated Primary and Secondary Steelmaking, Mexico, 2005 (TERA Joules)

Source: Energy Balance Tables, SENER, Mexico, 2005.

Bituminous coal is employed in the production of coke in coking plants. Afterwards, coke is part of the charge of a blast furnace for the production of pig iron. The requirements of these two raw materials are shown alongside other materials as part of the feedstock used in the steel industry (figure 10.1), and form important data values for the approach taken in this research. However, coal and coke also provide energy for combustion processes either in a blast furnace or an electric arc furnace. Figure 10.3 compares the distribution of energy (in TERA Joules) provided by each fuel including coal and coke and is derived from data in the energy balance tables which are based on a net calorific basis (see table 10.1). In practice, coal and coke are not consumed entirely as fuels (i.e. they are also part of a feedstock). To provide a consistent comparison all data in Figure 10.3 are converted to TERA Joules whereas in the primary data sources the information is sometimes given in thousand tonnes (e.g. data provided by INEGI) and sometimes in TERA Joules (e.g. data provided by SENER in the energy balance tables).

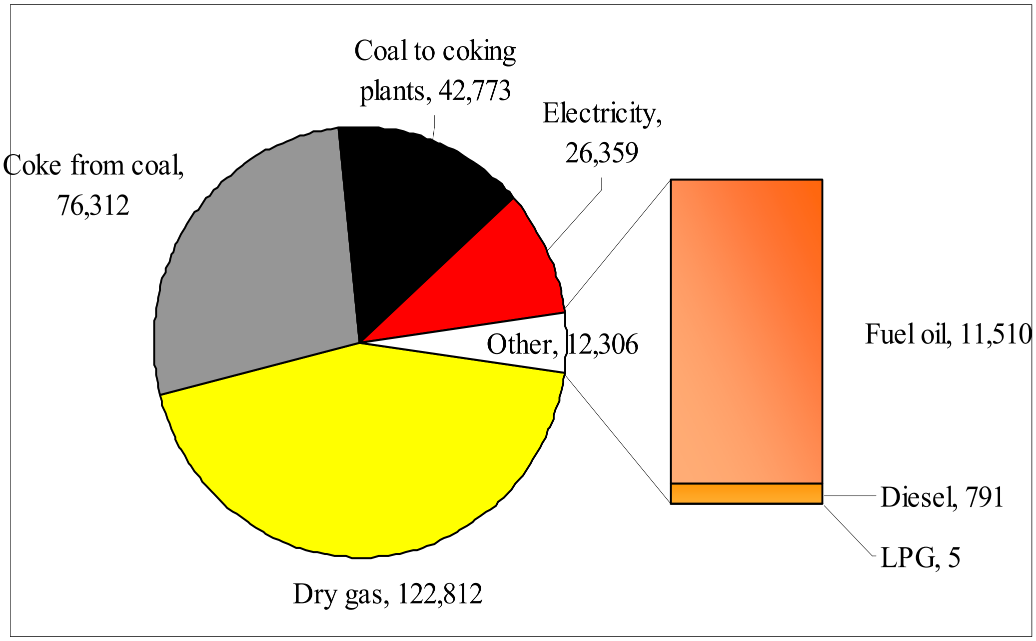


Figure 10.3 – Distribution of Fuels and Electricity Consumption in Overall Steelmaking, Mexico, 2005 (TJ)

Source: Energy Balance Tables, SENER, Mexico, 2005.

Dry gas is the most important energy source in the steel industry (43.8%), followed by metallurgical coke (27.2%), bituminous coal (15.2%), electricity (9.4%), fuel oil (4.1%), diesel (0.3%), and LPG (0.002%) in 2005 (figure 10.3).

Kerosene consumption in the steel industry in Mexico is not consistent over the period 1980-2007. According to reports in energy balance tables, the steel industry only consumes 260 and 20 TJ of kerosene in 1987 and 1988, respectively. In addition, pet coke consumption in the steel industry begins since 2000 with no consumption reported in 2003-2005. Overall, cumulative pet coke consumption in the steel industry accounts for 22,120 TJ in the period 2000-2007. This amount of energy is considered in the model specification for CO_2 calculations.

10.3 Methodology

The methodology presented in this chapter is structured in five main sub-sections:

1) General approach in the calculation of carbon dioxide intensities in the Mexican steel industry (section 10.3.1).
2) Specification of raw materials and production by main technological route in steel making (i.e. Blast Furnace – Basic Oxygen Furnace route (BF-BOF) and Direct Reduction – Electric arc furnace route or (DRI-EAF), section 10.3.2).
3) Specification of electricity requirements and energy intensities in BF-BOF and DRI-EAF (section 10.3.3)
4) Calculation of carbon dioxide intensities in BF-BOF and DRI-EAF (10.3.4).
5) Alternative scenarios in CO_2 emissions in the Mexican steel industry (10.4)

10.3.1 General Approach in the Estimation of CO_2 Emissions

This approach consists of an aggregated method of calculating CO_2 emissions. In this approach which involves an aggregated method for calculating CO_2 emissions, as opposed to the specific analysis done for each technology route as discussed in sections 10.3.2, 10.3.3, and 10.3.4, there is no distinction between the amount of fossil fuels and materials which correspond to primary and secondary steel making. In addition, there is no specification of the type of steel making technique employed (i.e. whether BOF or EAF), nor is there a distinction as to whether emissions arise from chemical processing of feedstock or fuels in combustion processes.

10.3.1.1 Specification of the Variables in the Model

The following materials, intermediate products and final steels, fuels, and sub-products enter the specification of the model to calculate carbon dioxide emissions:

a) Materials (feedstock measured in tonnes)

- Iron ore (IO_t)
- Coal (Cl_t)
- Coke (Ck_t)
- Sinter product (SI_t)

- Limestone (L_t)
- Dolomite (D_t)
- Electrodes (u_t)

b) Intermediate products and finished steels (measured in tonnes)

- Steel scrap (Sc_t)
- Sponge Iron (DRI_t)
- Pig Iron (Pig_t)
- Finished steel $(Q_{S,t})$

c) Fuels and Electricity (measured in TERA Joules)

- Dry gas (G_t)
- Electricity (E_t)
- Fuel oil (Fo_t)
- Diesel (Ds_t)
- LPG (LPG_t)

d) Sub-products from Combustion and Reduction Processes [measured in cubic meters (cum)]

This includes two major exhausted gases:

- Coke oven gas (COG_t)
- Blast furnace gas (BFG_t)

The definitions and the equations which provide estimations of CO_2 emissions have been adapted according to IPCC guidelines (2006a) which refer to National Greenhouse Gas Inventories in industrial processes and product use. In general, combustion and/or reduction of fuels and materials generate carbon emissions (figure 10.4) as do sub-products (i.e. exhausted gases) which are generated at the different stages of steel manufacturing. In particular, coke oven gas (COG) is a sub-product generated during the conversion of bituminous coal into metallurgical coke in coking operations while blast furnace gas is generated during the operation of a blast furnace in the production of pig iron. Iron ore *per se* does not generate carbon dioxide emissions in the iron and steel making process although there will embodied carbon issues associated with the extraction of such ore, but these are beyond the scope of this research. Sinter and pellets are obtained from iron ore of which heating processes generate carbon emissions while intermediate products such as pig iron and sponge iron also contain a certain amount of carbon. The following properties are considered in the current modelling approach:

1) All steel scrap consumed in a facility is taken into account when calculating carbon emissions. Otherwise, if there is a fraction (δ) of steel scrap which is sent outside a facility (i.e. exports), the carbon content accounting for this fraction is deducted.
2) The process described in point 1) also applies for sponge iron and pig iron.
3) At the aggregate industry level, the calculation of carbon content corresponds to the total amount of steel scrap, pig iron, and sponge iron consumed within the steel industry.
4) A fraction of intermediate products (Fe and steel scrap) may be purchased from abroad (i.e. imports) and in this case the corresponding carbon content is included in the calculations.
5) There is a carbon content incorporated in final steel product. This amount is deducted from the total overall carbon dioxide emissions.

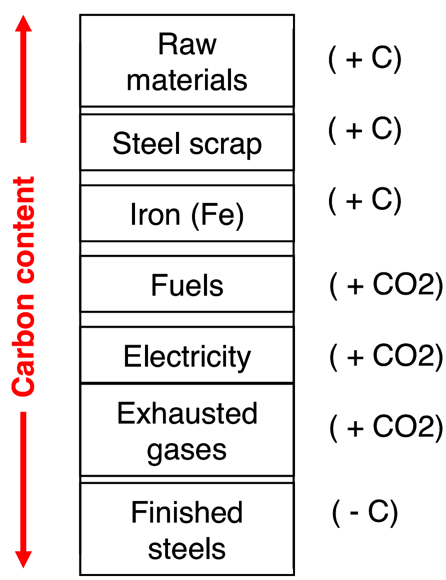


Figure 10.4 – A Cycle of Carbon Content in the Steelmaking Process

Frequently references to greenhouse emissions are presented in terms of either carbon (C) or carbon dioxide (CO_2), and this can lead to confusion especially among the non-specialised readers. Such confusion is observed in both the specialised technical literature and the daily media press. Furthermore, transformation activities in manufacturing involve chemical reactions and reductions which relate to carbon (C), carbon monoxide (CO), and carbon dioxide (CO_2). Although representing a different meaning in terms of emissions, C and CO_2 can be standardised with the following generic equation:

$$a\frac{CO_2 kg}{raw.material.kg} = a\frac{C.kg}{raw.material.kg} * \left(\frac{m.w.CO_2}{m.w.C}\right) \qquad \ldots (10.1)$$

Where,

- $m.w.CO_2$ stands for molecular weight of carbon dioxide [i.e. 44]
- $m.w.C$ stands for molecular weigh of carbon [i.e. 12.01]

In the standardisation of the use of emission factors, the use of specific calorific values (CV_x) and densities (ρ_x) of fuels is sometimes necessary. This is so because fuel consumption and emission factors are reported in different units. The selection of net calorific values in the standardisation of emission factors and energy units takes into account the properties of domestic fuels. These fuels refer to the use of natural gas, oil derivatives, and coke mining produced in Mexico, (Chapter 8). The following two generic equations are employed in the standardisation of emission factors:

a) For a fuel which is reported in units of mass (i.e. tonnes), conversion from mass to energy units consists of:

$$fuel.(TJ) = \left((fuel).tonnes * (CV_x)\frac{MJ}{tonne}\right)/10\text{^}(6) \qquad \ldots (10.2)$$

b) For a fuel which is reported in units of volume (i.e. cubic meters), conversion from volume to energy units consists of:

$$fuel.(TJ) = \left((fuel).cum * \frac{(\rho_x)kg}{cum} * \frac{(CV_x)MJ}{kg}\right)/10\text{^}(6) \qquad \ldots (10.3)$$

For instance, coal consumption in the steel industry is reported in tonnes by INEGI whereas natural gas is reported in PETA Joules or cubic meters (cum) by SENER. More importantly, there is a subtle but worth of mentioning difference between the calorific value of natural and dry gas. A list of calorific values used in the calculations of the model presented in this chapter is presented in table 10.1 (section 10.3.1.2). In the case of aggregate industry data, fuels are reported in PETA Joules. However, in the majority of cases fuels are reported in cubic metres (cum) or sometimes litres at plant level. In this example, after applying unit standardisation in the amount of coal and natural gas employed in the steel industry, the amount of carbon dioxide emissions is calculated as follows:

$$CO_2.emissions_{coal}(tonnes) = \left[A.coal.(TJ) * 94{,}600 \left(\frac{kg.CO_2}{TJ_{coal}} \right) \right] / 10\hat{}(3) \quad \ldots$$

(10.2.1)

$$CO_2.emissions_{natural.gas}(tonnes) = \left[B.gas.(TJ) * 56{,}100 \left(\frac{kg.CO_2}{TJ_{natural.gas}} \right) \right] / 10\hat{}(3) \ldots$$

(10.3.1)

The terms 94,600 Kg CO_2/TJ and 56,100 Kg CO_2/TJ in equations 10.2.1 and 10.3.1 are default emission factors for coal and natural gas, respectively, reported in IPCC Guidelines (2006). Similar iterations on the use of generic equations (10.2) and (10.3) are performed for each of the raw materials, inter-mediate products, by-products, fuels, electricity, and steels defined in equations 10.4-10.8. $(A.coal)$ and $(B.gas)$ refer to quantities of coal and gas respectively declared in TERA Joules.

At the industry level, CO_2 emissions (units measured in tonnes) in iron and steel making are calculated as follows:[169]

$$CO_2,_{materials} = \left[Cl_t * EF_{CL} + Ck_t * EF_{Ck} + SI_t * EF_{SI} + L_t * EF_L + D_t * EF_D + u_t \right] * (44/12) \quad \ldots (10.4)$$

$$CO_2,_{products} = \left\{ (1-\delta) * \left[Sc_t * EF_{Sc} + DRI_t * EF_{DRI} + Pig_t * EF_{Pig} \right] \right\} * (44/12) \ldots (10.5)$$

[169] A definition of the terms included in equations 10.4 – 10.8 is listed in section 10.3.1.1.

$$CO_{2,sub-products} = COG_t * EF_{COG} + BFG_t * EF_{BFG} \quad \ldots (10.6)$$

$$CO_{2,fuels} = G_t * EF_G + E_t * EF + Fo_t * EF_{Fo} + Ds_t * EF_{Ds} + LPG_t * EF_{LPG} \quad \ldots (10.7)$$

$$Overall.CO_2 = CO_{2,materials} + CO_{2,products} + CO_{2,sub-products} + CO_{2,fuels} - (44/12) * Q_{S,t} * EF_{Q_S} \quad \ldots (10.8)$$

Where,

- *EF_x is the relevant carbon emission factor of the fuel, raw material, by-product, and steel.*
- u_t is the material in the electrodes in the electric arc furnace which are consumed and is given by:

  $$u_t = f(Q_S) = 0.0015 * (Q_{EAF,t}) * (44/12) \quad \ldots (10.4.1)$$

- $0 \leq \delta < 1$, is the fraction of intermediate products not consumed domestically (i.e. "exports" outside a plant)
- $Q_{EAF,t}$ is the liquid steel produced with EAF technology

The amount of electrode consumption and the associated carbon dioxide emissions is a constructed variable (u_t) and on average, 0.0015 metric tonnes of carbon are released due to electrode consumption per metric ton of EAF steel production (USEPA, 2003). In principle, emissions due to electrode consumption should not be included in an aggregated approach because there is no distinction between steel making technologies. At this stage of the model, there is no specification between BOF and EAF liquid steel but overall steel production in the industry. However, including this factor in the equation will allow greater accuracy in the current calculations.

Carbon intensity refers to overall CO_2 emissions per tonne of finished steel produced in a given year (t). In the methodology presented in this chapter, carbon intensity is calculated on the basis of:

a) Overall emissions in the steel industry:

$$\bar{c} = f(CO_{2,OVERALL.STEELS}) = \frac{Overall.CO_2}{Q_S} \quad \ldots (10.9)$$

b) Emissions in the steel industry without taking into account emissions associated to purchased electricity from the Mexican grid:

$$\bar{c}' = f(CO_{2,materials,fuels}) = \left[\frac{(Overall.CO_2) - (E * EF)}{Q_S}\right] \quad \ldots (10.10)$$

Where $\bar{c}'$ is used to denote the steel carbon intensity after subtracting the carbon emissions from electricity uses as opposed to a total overall carbon intensity in the steel industry $\bar{c}$.

The purpose of equation (10.10) is to identify the amount of carbon dioxide emissions attributed to the consumption of raw materials and fuels and to isolate the effect of electricity consumption on the amount of CO_2 emissions as the electricity emission factor will vary depending on factors outside the control of the industry (see chapter 9). The impact electricity carbon emissions can be accomplished by comparing results obtained from both equation (10.9) and (10.10).

The amount of CO_2 embedded in finished steels is deducted in the calculations defined in equation 10.8 (i.e. the final term… $\boldsymbol{(44/12)*Q_{S,t}*EF_{Q_S}}$). This amount of emissions is calculated on the basis of a default carbon emission factor for steels. However, this aggregated approach has a limitation as in practice, carbon incorporated in steels differs according to the exact production technique, and this is explored further in section 10.3.4 where there is a focus on the calculation of carbon intensities by a single major steel making technological route (i.e. BOF and EAF).

The overall iron and steel industry shows a decreasing trend in the carbon intensity of steelmaking processes during 1980-2007 (figure 10.5). CO_2 intensity reduced from 3.8 to 1.5 tonnes of CO_2 per tonne of finished steel between 1980 and 2007 when electricity consumption is not considered. Also, the CO_2 decreased from 4.4 to 1.8 tonnes of CO2 per tonne of finished in the same period when electricity consumption is included. The gap between the two lines plotted in figure 10.5 indicates the amount of CO_2 emissions due to electricity uses in steel works.

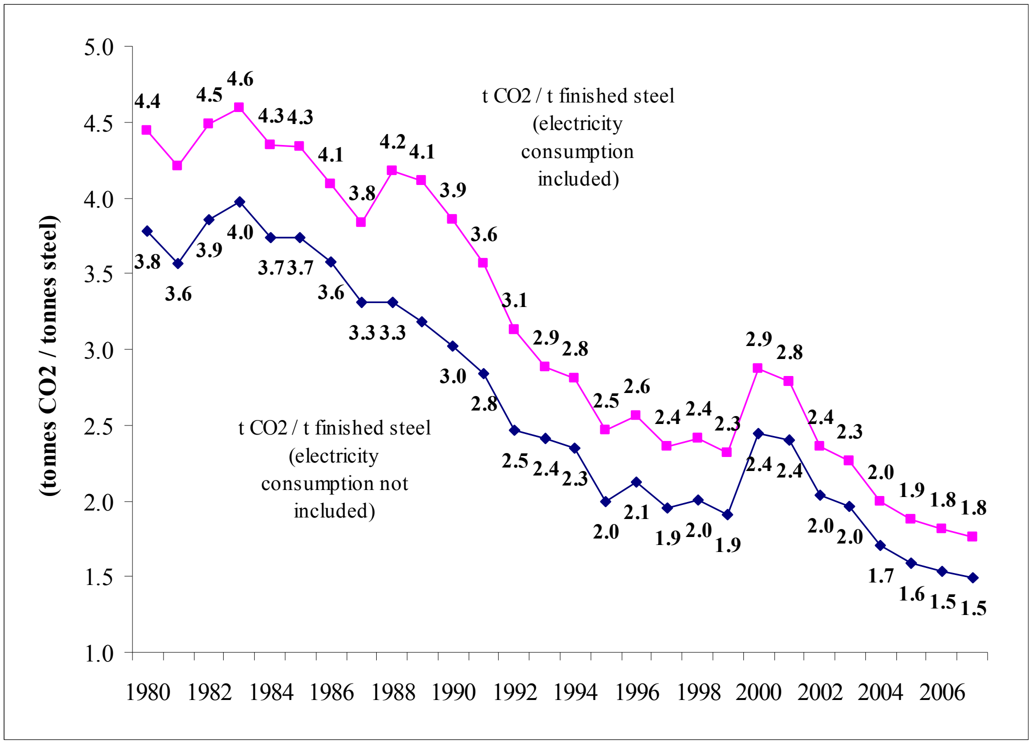


Figure 10.5 – Carbon Dioxide Intensity of the Total Overall Iron & Steel Industry, Mexico, 1980-2007 (t CO_2e/t finished steel)

A re-composition in the mix of raw materials and change in the relative share of specific steelmaking techniques give an account of the observed trend of CO_2 intensity. In general, this consists of the following:

a. Production of sponge iron (DRI) has gained a relative larger importance as compared to pig iron production. Growth in sponge iron production represented 5% whereas growth in pig iron production represented 0.15% on a compound annual basis during 1980-2007.

b. Growth in steel scrap production accounted for 6% in the same period.

c. A negative growth in the production of metallurgical coke (-2.4%)

d. Improvements in the productivity of the blast furnace. The ratio of coke to pig iron decreased from 84% to 40% between 1980 and 2007.

e. Growth in steel production with electric arc furnace represented 5.2% whereas growth in steel production with basic oxygen furnace accounted for 1.64% on a compound annual basis in the same period.

10.3.1.2 Properties of Materials, Fossil Fuels, and Electricity

Raw materials, intermediate products, sub-products, fuels, electricity, and final steels, all have different degrees of physically embedded carbon. During any material transformation process, part of this carbon is released to the atmosphere in form of CO_2 due to combustion and/or reduction processes with the carbon emission factors (EF_x) being indicative of the quantity (i.e. a metric) of the carbon released in the combustion of these materials. There are three attributes on emission factors which need to be taken into account in the building of a consistent methodology:

1) Carbon (C) and carbon dioxide (CO_2) emission factors are not the same: the latter is 44/12 times the former.
2) Emission factors are reported on the basis of fuel and raw material consumption. This involves units such as kg C per TERA Joule (TJ) of fuel oil; kg C per tonne of coke; and so on.
3) Standardisation of emission factors among fuels and materials requires an adequate knowledge of calorific values and densities. The overall accuracy of such parameters depends on the availability of domestic fuels where the specific values are known or fuel imports when there will be some uncertainty over precise values.

Emission factors used in the model presented in this chapter were obtained from three different sources:

1) Metal Industry Emissions, Chapter 4, IPCC, (2006a) for raw materials, intermediate products, and finished steels.
2) Energy Industries, Vol. 2, IPCC, (2006b) for fossil fuels inclusive of coal to coking plants as feedstock.
3) Greenhouse Gas Inventory Protocols, American Iron & Steel Institute, (1998) for sub-products (i.e. exhausted gases) inclusive of coke oven gas (COG) and blast furnace gas (BFG).

There is a group of raw materials in which the carbon content is significantly high. This includes coke, EAF charge carbon (which consists of oven coke (IPCC, 2006a), and carbon electrodes used in EAF operations (figure 10.6). On the other hand, intermediate products in the production of steel such as pig iron and sponge iron (or direct reduced iron – DRI) have very low carbon content. In particular, the carbon content in DRI is lower than carbon content in pig iron and steel scrap (i.e. 0.02 Kg CO_2 per tonne of DRI or 20 grams CO_2 per tonne of DRI less than in pig iron). Although this is a subtle difference, this is an important characteristic of the steel industry in Mexico when calculating carbon dioxide emissions and future scenarios.

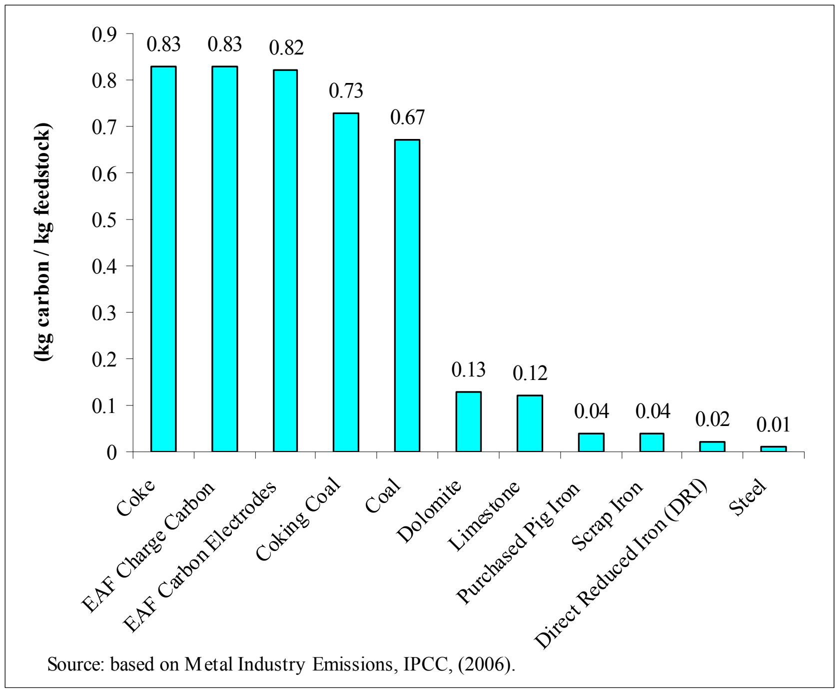


Figure 10.6 – Carbon Content of Raw Materials, Inter-mediate Products, and Final Steel, 2006 (kg C/kg raw material)

Petroleum coke (or pet coke) has the highest CO_2 emission factor among the fuels employed in the steel industry (i.e. 97,500 kg CO_2 / TJ of pet coke, figure 10.7). On the other hand, natural gas corresponds to the fuel with the lowest CO_2 emission factor (i.e. 56,100 kg CO_2 / TJ of natural gas). The use of pet coke in the steel industry only began recently. However, a growing dependence on this fuel would imply a significant growth in carbon dioxide emissions.

Given the relative importance of natural gas in steel production (figure 10.3 above), this implies a lower impact on the amount of CO_2 emissions as compared to the rest of fuels. In the reduction process for the production of sponge iron (DRI), alternative gases (and not natural gas) comprise gases obtained from coal gasification processes and COREX waste gases among other sources. Even in these cases, there is an associated amount of carbon dioxide due to combustion, for instance, of coal. There is an amount of natural gas which is imported in Mexico, however, at present time the majority of natural gas which is consumed domestically in industrial sectors is obtained in Mexican oil fields (see Chapter 8).

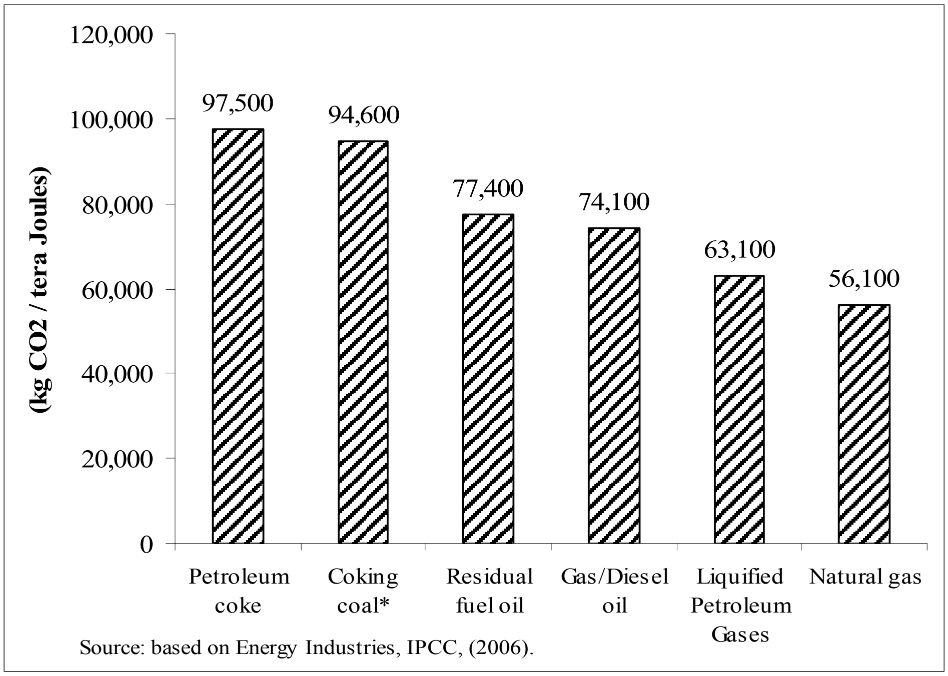


Figure 10.7 – Default Emission Factors for Stationary Combustion in Energy Industries, 2006 (kg CO_2e/TJ on a net calorific value)

Other CO_2 emissions factors reported in figure 10.7 correspond to combustion of coking coal, residual fuel oil, gas/diesel oil, and liquefied petroleum gases. An emission factor for bituminous coal represents an alternative value to coking coal. Indeed, the default value for both bituminous coal and coking coal is the same (i.e. 94,600 kg CO_2 per TJ) according to IPCC Guidelines for GHG Inventories (2006b). Data for emission factors for coal does appear to vary depending on the source of statistics. In some cases, specific information regarding coal as used for coking coal is indicated as a separate item, whereas in other cases, the information is lumped under the general heading "mechanical washed" coal which covers total overall uses in the steel industry. The definition of mechanical washed coal consists of the removal of sulphur content in coal. In the aggregate approach, this latter category of coal is used because this gives an indication of coal employed either in coking plants or other uses in the steel sector.

Fuel	NCV	unit
Associate natural gas	44,077	kJ/cum
Non-associated natural gas	38,116	kJ/cum
Domestic metallurgical coal	22,187	MJ/tonne
Pet coke	30,675	MJ/tonne
Liquified gas	3,765	MJ/barrel
Kerosene	5,223	MJ/barrel
Diesel	5,426	MJ/barrel
Fuel oil	6,019	MJ/barrel
Dry gas	33,913	kJ/cum
Intenrational metallurgical coal	29,559	MJ/tonne
Coke from coal	26,521	MJ/tonne

Source: SENER, Balance Nacional de Energia, Mexico, 2006

Table 10.1 – Net Calorific Values by Fuel Type, Mexico, 2006

10.3.1.3 A CO_2 Emission Factor for Purchased Electricity from the Mexican Grid

CO_2 emissions arising from electricity consumption in steel making facilities in Mexico are directly related to the modelling work presented in chapters 8 and 9 in this thesis. The use of CO_2 emission factors for electricity consumption in steel facilities deserves special attention. There is a fundamental difference between CO_2 emission factors of fuels and materials and the CO_2 emission factor of purchased electricity. This difference points out constant or otherwise changing values for each emission factor as follows:

1) CO_2 emission factors for fuels and materials do not change along time and, if they do so, variations are originated in the assumptions made on reported emission factors (i.e. if lower, upper, or default values).

2) A CO_2 emission factor for electricity from the Mexican grid is not constant. It may evolve gradually along time or, in *sui generis* circumstances,[170] change drastically as shown in chapter 9.

[170] Imagine a given country located along the Equator where 15% of total electricity comes from wind turbines. 10% of wind turbine installed capacity is located off-shore. Suddenly, there are unusual

An overall CO_2 emission factor for purchased electricity depends on:

1) The fuel mix of energy sources (i.e. fossil and non fossil energy sources) and,
2) Inefficiencies due to electricity losses through the transmission network.

Once purchased electricity from the Mexican grid is used in an industrial facility, CO_2 emissions from electricity requirements are dependent on energy efficiency practices. Hence from a holistic approach CO_2 emissions due to electricity uses in steel plants depend on:

1) CO_2 emissions from the fuel mix in electricity generation (m) which is dependent on the share of each electricity generation technology in overall installed capacity (Chapter 9).
2) Losses (L) in the delivery of electricity through the network. The functional form of electricity losses is defined in equation 9.29 in Chapter 9.
3) Energy efficiency in the use of electricity in steel plants (eff_S); this consists of the amount of kWh per tonne of finished steels (section 10.3.3).
4) Electricity generation on-site (i.e. combined heat and power or cogeneration, (CHP_S).

These four conditions are specified in the following function:

$$CO_{2,Steels,electricity} = f\left[m * \left(\frac{1}{1-L}\right) * (eff_S) + CHP_S\right] \ldots (10.11)$$

Within the limits of an organisation, variations in the content of carbon dioxide in electricity generation are not a competence of steel facilities. In other words, steel manufacturers have no flexibility in reducing the amount of CO_2 emissions originating from electricity which is purchased from power plants. This is a variable under the control of power plants where an increasing participation of non-fossil fuel technology lowers CO_2 emissions per kWh. On the other hand, energy

tropical storms and hurricanes during two days in the autumn in such a way that 10% of wind turbine installed capacity get damaged and are no longer available for generation.

efficiency improvements in electricity uses are an exclusive competence of steel facilities and, in this regard, this has a direct impact on total overall CO_2 emissions $(CO_{2,Steels,electricity})$. In addition, combined heat and power (CHP) may be present in some steel facilities. In this latter case, this would mean that part of electricity generated on-site complements overall electricity requirements in a steel plant. A fraction of electricity generated on-site can be compared to the amount of CO_2 emissions given up otherwise this electricity being purchased from the Mexican grid.

Figure 10.8 outlines a functional relationship defined in equation (10.11). Strategies to control carbon dioxide emissions in electricity generation and consumption are classified according to three types of organisations. The first group of organisations consists of oil, gas, and coal mining producers in energy industries. In this case, a *"line of action"* to prevent climate change consists of reducing fugitive emissions, and emissions associated to venting and flaring practices in oil and gas production, processing, transmission, and distribution, bearing in mind that a significant amount of gas and oil products go to uses in the steel industry and electricity generation (Chapter 8). The second group of organisations relates to power plants located in electricity generation and transmission. Lines of action to control climate change consist of:

1) Increasing the thermal efficiencies in the combustion of fossil fuel technology for electricity generation[171]
2) Growth in non-fossil fuel installed capacity (i.e. renewable(s) and nuclear)
3) Reductions in electricity transmission losses

Steel plants represent the third group of industry organisations. In this case, steel plants are large industrial electricity consumers. The two critical lines of actions consist of the diffusion and improvements of practices which target energy efficiency growth (Chapters 6, and 7) and on-site electricity generation. Hence, overall total

[171] In the Mexican case, this has taken place by adding CCGT new installed capacity in IPP plants.

CO_2 emissions concerning electricity requirements in steel making consist of the following compound function:

$$Overall.CO_{2,electricity,S} = \begin{cases} \mathbf{f_1 = \left(m * \dfrac{1}{1-L}\right) \text{....}(unit\,(CO_2 / kWh)} \\ \quad \text{- Public electricity supply} \\ \mathbf{f_2 = (eff_s)\ \text{.............}\ (unit\,CO_2 / Q_{steel})} \\ \quad \text{- Efficiency of electricity use in steel production} \\ \mathbf{f_3 = (CHP_s)\ \text{.............}\ (unit\,CO_2 / Q_{steel})} \\ \quad \text{- CHP generation on site} \end{cases}$$

i.e. $Overall.CO_{2,electricity,S} = \mathbf{f_1 * f_2 + f3}$

For simplicity in this exposition, assume $f = (CHP_S) = 0$ at the moment. Hence,

$$CO_2 = f\left(m * \frac{1}{1-L}\right) * f(eff_S) * (Q_{Steels}) = \left(\frac{CO_2}{kWh}\right) * \left(\frac{kWh}{Q_{Steels}}\right) * (Q_{Steels}) \ldots (10.11.1)$$

(Q_{Steels}) stands for the amount of industrial production of steel in physical units (i.e. tonnes). Equation (10.11.1) represents the synthesis of a holistic approach in carbon dioxide energy-based emissions presented in this chapter.

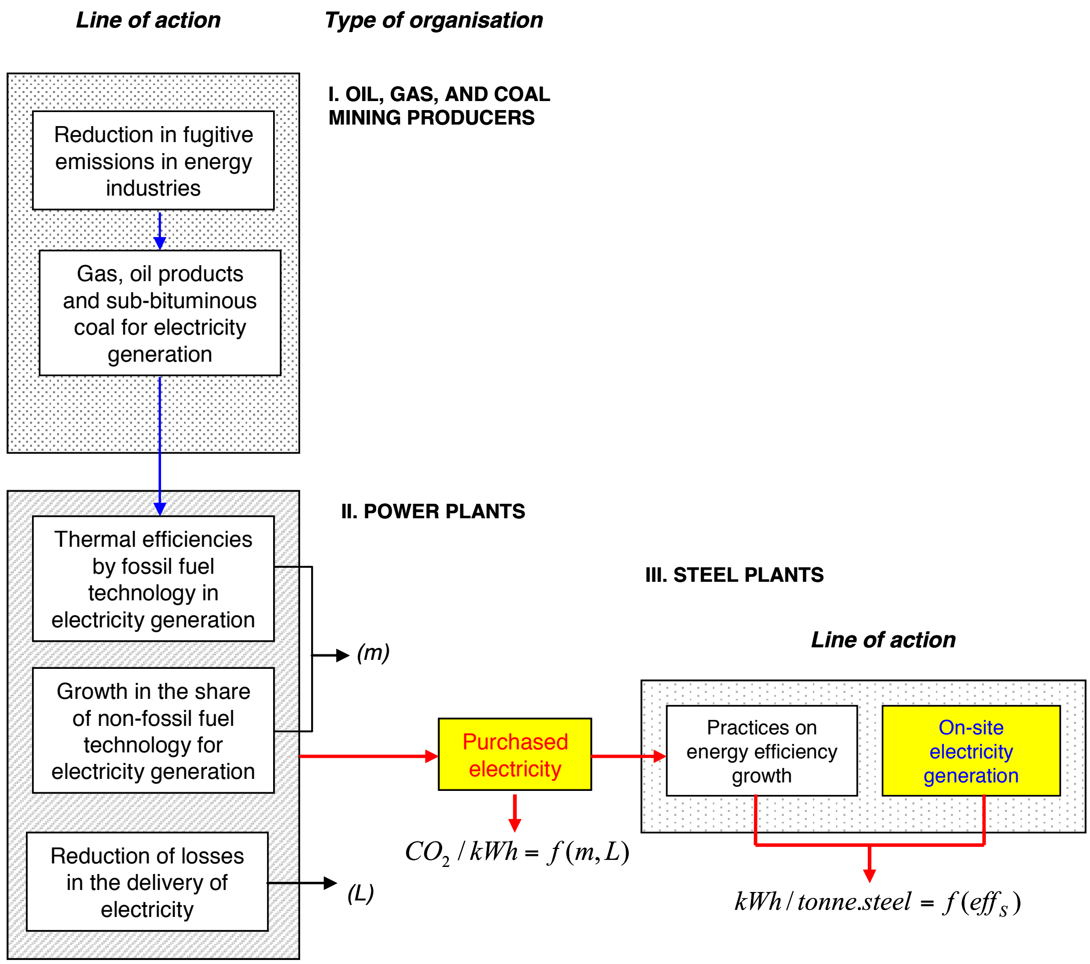


Figure 10.8 – Strategies to Control CO_2 Emissions in Electricity Generation and Uses

10.3.2 Distribution of Materials between Integrated Primary and Secondary Steel Making

In remaining of this chapter, calculation of carbon dioxide intensities concerns the following technological routes:

1) Blast furnace (BF) → Basic oxygen converter (BOF).

2) Direct reduction (DRI) + Steel scrap → Electric arc furnace (EAF).

In practice, there is a fraction of steel scrap which may be used in blast furnaces in primary steel making. This fraction is taken into account when estimating CO_2 intensities for the route BF-BOF.

The total number of plants (X_{2005}) in the analysis of this chapter consists of:

$$X_{2005} = \sum_{i=1}^{2} BF\_BOF_i + \sum_{i=1}^{4} DRI\_EAF_i + \sum_{i=1}^{12} SC\_EAF_i + \sum_{i=1}^{6} rm_i \quad \ldots (10.12)$$

Where,

- BF_BOF_i : primary integrated plants with BF and BOF.
- DRI_EAF_i : secondary integrated plants with DRI and EAF.
- SC_EAF_i : secondary steel making with steel scrap (SC) and EAF.
- rm_i : single rolling mills.

Energy uses and associated CO_2 emissions were calculated on the basis of 24 iron and steel plants with DRI – EAF and SC – EAF plants incorporated into a single category. In addition, rolling mills (rm) plants employ mostly electricity and, to a lesser extent, natural gas. Equation (10.12) can be re-written as follows:

$$X_{2005} = \sum_{i=1}^{2} BOF_i + \sum_{i=1}^{16} EAF_i + \sum_{i=1}^{6} rm_i \quad \ldots (10.12.1)$$

Where,

- $EAF_i = \sum_{i=1}^{4} DRI\_EAF_i + \sum_{i=1}^{12} SC\_EAF_i$

In Mexico, there are two large plants with integrated primary steel making (i.e. BF-BOF), and in this case, each material, intermediate product, and fuel used is calculated by adding up plant data as follows:

Iron ore consumed in BF-BOF steel: $IO_{BOF} = \sum_{i=1}^{2} BOF_{i,IO}$ … (10.13)

Coal consumed in BF-BOF steel: $CL_{BOF} = \sum_{i=1}^{2} BOF_{i,CL}$ … (10.14)

j material used in BF-BOF steel: $j_{BOF} = \sum_{i=1}^{2} BOF_{i,j}$ … (10.15)

Equations (10.13)-(10.15) consist of a matrix arrangement where rows $(i=1,2)$ stand for the number of BF-BOF plants and columns $(j=1,2...,n)$ stand for each of the materials and fuels used in BF-BOF steel making. The following raw materials $(Rawmat_{BOF})$ are used in the BF-BOF steel making route:

$$\begin{bmatrix} & IO & Cl & Ck & SI & L & D \\ BOF_1 & (1,1) & (1,2) & (1,3) & (1.4) & (1,5) & (1,6) \\ BOF_2 & (2,1) & (2,2) & (2,3) & (2,4) & (2,5) & (2,6) \end{bmatrix} = BF\_BOF_{raw.materials} \quad \ldots (10.16)$$

The following intermediate products and by-products are used in BF-BOF:

$$\begin{bmatrix} & Pig & Feh & Sc & COG & BFG \\ BOF_1 & (1,1) & (1,2) & (1,3) & (1,4) & (1,5) \\ BOF_2 & (2,1) & (2,2) & (2,3) & (2,4) & (2,5) \end{bmatrix} = BF\_BOF_{products,by\_products}$$

(10.17)

The following fuels $(Fuel_{BOf})$ and electricity (E_{BOF}) are consumed in BF-BOF:

$$\begin{bmatrix} & G & E & Fo & Ds & Pck \\ BOF_1 & (1,1) & (1,2) & (1,3) & (1,4) & (1,5) \\ BOF_2 & (2,1) & (2,2) & (2,3) & (2,4) & (2,5) \end{bmatrix} = BF\_BOF_{fuels,electricity} \ \ldots (10.18)$$

Where,

- Feh : hot metal from cupola furnace.
- Pck : petroleum coke.

Data grouped in the BF-BOF route in the above matrixes correspond to 2005. Surprisingly, energy balance tables do not report pet coke consumption in 2005 for overall consumption in the steel industry and is an important source of discrepancy which was identified while revising plant data. Regarding the use of hot metal, this is an intermediate product obtained in a cupola furnace which is pre-heated with the use of COG and BFG. Afterwards, hot metal is part of a charge in a BOF the main function of which is to add heat to the basic oxygen conversion process.

The addition of raw materials and fuels used in both BF_BOF and DRI_EAF routes accounts for total overall industry consumption as represented in the following three equations:

$$Rawmat_{BOF} + Rawmat_{EAF} = Overall.Rawmat_{STEELS} \quad \ldots (10.19)$$

$$Fuels_{BOF} + Fuels_{EAF} = Overall.Fuels_{STEELS} \quad \ldots (10.20)$$

$$E_{BOF} + E_{EAF} = E_{STEELS} \quad \ldots (10.21)$$

The addition of each column in matrix (11.16) gives a value for the $\left(Rawmat_{BOF}\right)$ variable in equation (10.19). Similarly, the addition of each column in matrix (11.18) provides a value for $\left(Fuels_{BOF}\right)$ and $\left(E_{BOF}\right)$ in equations (10.20) and (10.21), respectively. A general approach for the calculation of CO_2 emissions was then built with the use of this aggregated data for the steel industry (section 10.3.1). At the aggregate industry level, the amount of each raw material, fuel, and electricity consumption using both technology routes in the steel industry is a known parameter (i.e. specification of these variables is provided in section 10.3.1.1). Hence the amount of materials, fuels, and electricity required in DRI-EAF route (which information is not directly known) can be determined as follows:

$$Rawmat_{EAF} = Overall.Rawmat_{STEELS} - Rawmat_{BOF} \quad \ldots (10.19.1)$$

$$Fuels_{EAF} = Overall.Fuels_{STEELS} - Fuels_{BOF} \quad \ldots (10.20.1)$$

$$E_{EAF} = E_{STEELS} - E_{BOF} \quad \ldots (10.21.1)$$

Equations (10.19.1)-(10.21.1) provide with an alternative iteration in order to calculate material and fuel consumption in EAF plants.

10.3.3 Average Specific Electricity Consumption (SEC) in the Mexican Steel Industry

One of the fundamental differences between BOF and EAF steelmaking routes is the intensity of electricity incorporated in each process. It is important to specify the amount of electricity requirements in each stage of both BF-BOF and DRI-EAF steel making routes. Specific electricity consumption in the overall industry (SEC) consists of the amount of kWh required per tonne of finished steel, and this parameter is an indicator of the efficiency in electricity requirements in the overall steel making process.

Production and overall electricity consumption (in kWh or Joules) are two critical variables in the measurement of SEC. Table 10.2 contains a definition of the variables and equations in the calculation of SEC in the steel industry. Worrell et al., (1995) indicate that the assessment of energy consumption in terms of thermal energy and electricity (in kWh or Joules and not monetary values) and the associated amount of industrial production (in tonnes) reflect structural changes in an industry. These structural changes concern the properties of technology, changes in the composition of a fuel mix and electricity (sometimes a switch in the use of fossil fuels whereby this is possible), and improved managerial practices.

Steel production in the overall iron and steel industry is specified in equation 10.22 in table 10.2. Composition of steel production in Mexico changed significantly during the 1990s with steel production from open hearth furnaces shutting down operations in 1992 as part of a process of privatization, trade liberalisation, and modernization of the steel sector (Guzmán, 2002; Ozawa et al., 2002). Thus after 1992, overall steel production in industry (equation 10.22 in Table 10.2) consists only of electric arc furnace (EAF) and basic oxygen furnace steel (BOF).

The SEC in the overall iron and steel industry shows dramatic decreases between 1990 and 2007 reducing from 937.5 to 447.1 kWh/tonne of finished steel over the period (figure 10.9).

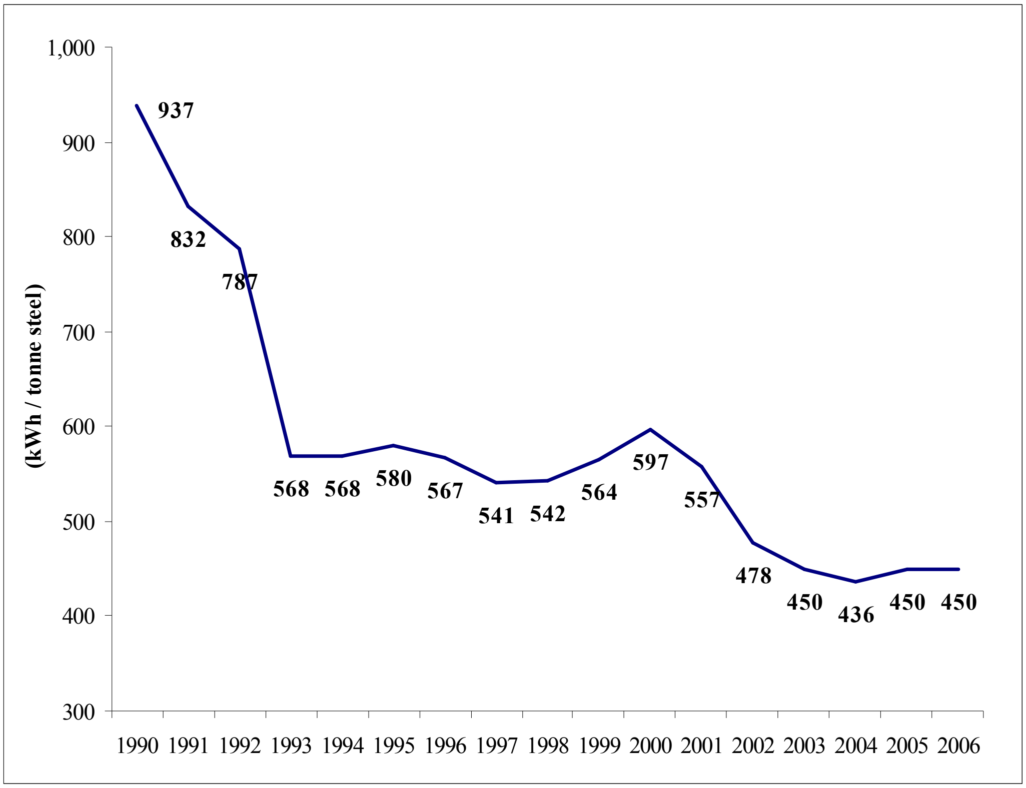


Figure 10.9 – Average Specific Electricity Consumption in the Iron and Steel Industry, Mexico, 1990-2007 (kWh/tonne of steel)

Variable	Specification	Source of information/equations
Overall steel production industry	$Q_{S,t}$	$Q_{S,t} = Q_{EAF,t} + Q_{BOF,t} + Q_{OHF,t}$ (10.22) National official statistics (INEGI) 1990-2006
Steel production with electric arc furnace technology (EAF)	$Q_{EAF,t}$	INEGI, 1990-2006
Steel production with basic oxygen furnace technology (BOF)	$Q_{BOF,t}$	INEGI, 1990-2006
Steel production with open hearth furnace (OHF)	$Q_{OHF,t}$	INEGI, 1990-2006
Total electricity consumption in iron and steel industry	$E_{S,t}$	Energy balance tables, Ministry of Energy (SENER), 1990-2007
Average specific electricity consumption (SEC) in overall steel industry	$SEC_{e,S,t}$	$SEC_{e,S,t} = \frac{E_{S,t}}{Q_{S,t}}$ (10.23) or $SEC_{e,S,t} = \frac{E_{S,t}}{(Q_{EAF,t} + Q_{BOF,t})}$ (10.24)
Electricity consumption in BOF steel production	$E_{BOF,t}$	$E_{BOF,t} = \sum_{i=1}^{2} e_{BOF,i}$ (10.25); plant level data.
Electricity consumption in EAF steel production	$E_{EAF,t}$	$E_{EAF,t} = \sum_{i=1}^{16} e_{EAF,i}$ (10.26); plant level data.
Total electricity consumption by process	$E_{S,t}$	$E_{S,t} = E_{BOF,t} + E_{EAF,t}$ (10.27)
Total gas consumption by process	$G_{S,t}$	$G_{S,t} = \sum_{i=1}^{18} g_{i,t}$, (10.28)
Specific electricity consumption in EAF	$SEC_{EAF,t}$	$SEC_{EAF,t} = \frac{E_{EAF,t}}{Q_{EAF,t}}$, (10.29)
Specific electricity consumption in BOF	$SEC_{BOF,t}$	$SEC_{BOF,t} = \frac{E_{BOF,t}}{Q_{BOF,t}}$, (10.30)

Table 10.2 – Variables in the Calculation of Specific Electricity Consumption in the Steel Industry

Specific electricity consumption (SEC) in the steel industry can be calculated in relation to overall steel production (equation 10.23) or separately with respect to

EAF and BOF steel production (equation 10.24). The same energy accounting principle is applied to the rest of fuels allocated between EAF and BOF steel production. The amount of electricity consumed in BOF steel production is specified in equation 10.25 which is a particular representation of the generic equation defined in equation (10.15) (i.e. all raw materials and energy inputs in BF-BOF plants are calculated by adding up plant data). This data is only available for 2005 and thus specification of energy consumption in the model corresponds to 2005.

Electricity consumption in EAF plants is specified in equation (10.26), although the purpose of this last equation is only illustrative as in the approach suggested in this model, electricity in EAF technology is calculated as a difference between overall electricity requirements in the steel industry and electricity consumption in BOF plants (equation 10.21.1 and 10.27). This is because there is a lack of detailed specific data for EAF plant. Using this approach ensures that the amount of electricity allocated between both BOF and EAF processes corresponds to overall electricity for the steel industry as reported in energy balance tables. The same iteration on data validation is applied for overall gas consumption in the steel industry (equation 10.28).

Specific electricity consumption in EAF and BOF plants is calculated using equations (10.29) and (10.30), respectively. Electricity consumption in EAF steel making route is by far more intensive than in BOF route. On average, 527.7 kWh/tonne are required in EAF steelmaking whereas 250.9 kWh/tonne are required in BOF steel making in 2005 (figure 11.10). The DRI-EAF technology route for steel production consumes 6,192 GWh of electricity (85% of total electricity in the steel industry) compared to 1,130 GWh for the BF-BOF route (figure 11.10). In the case of the BF-BOF route, 250.9 kWh/tonne includes electricity requirements in coking and sinter plants, blast furnace, continuous casting, and rolling mills. Similarly, in the DRI-EAF route, 527.7 kWh/tonne also includes electricity requirements in DRI, continuous casting, and rolling mills. In this latter case, the majority of electricity goes for the operation of EAF. A breakdown of electricity requirements by specific stage in steelmaking is defined in section 10.3.3.2.

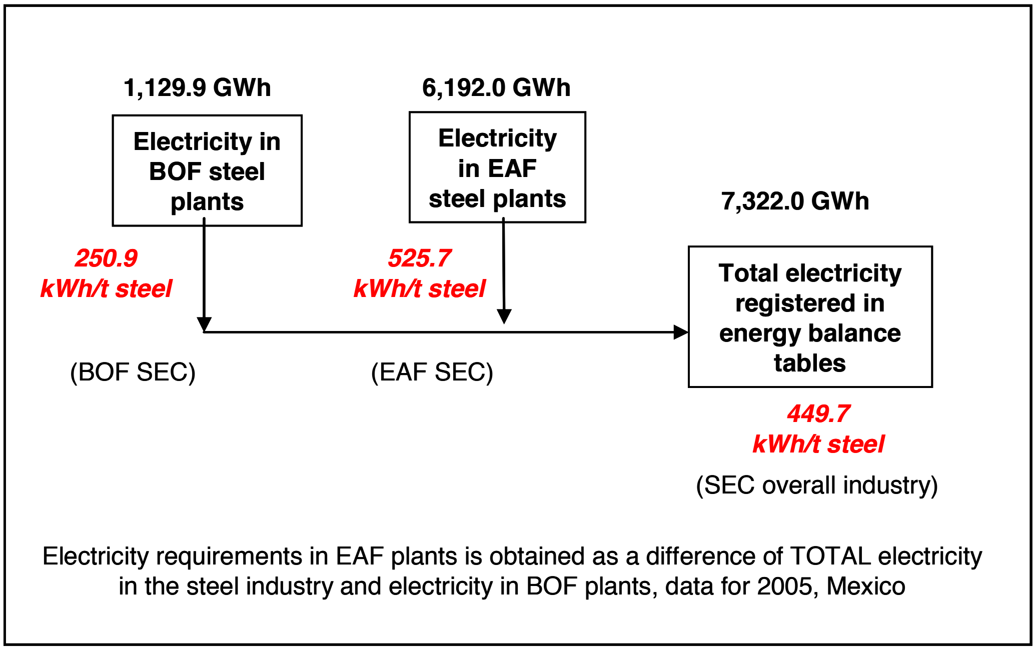


Figure 10.10 – Specific Electricity Consumption in BOF and EAF Steel Plants in Mexico, 2005 (GWh)

10.3.3.1 Distribution of Electricity Requirements and Fuels by Specific Stage in BF-BOF and DRI-EAF Steelmaking

Unlike the previous section which considers the overall electricity requirements in the two steel making technologies, the purpose of this section is to specify the amount of electricity in each separate segment through the BF-BOF and DRI-EAF steelmaking routes. The following equation is used in the calculation of electricity requirements by segment of steel making process:

$$E_{Segment} = Q_{product}(tonnes) * \left(\frac{kWh}{Q_{product}(tonnes)} \right) \qquad \dots (10.31)$$

$$E_{Segment} = Q_{Rawmat}(tonnes) * \left(\frac{kWh}{Q_{Rawmat}(tonnes)} \right) \qquad \dots (10.32)$$

- $Q_{product}$: amount of intermediate products in steel making (i.e. pig iron, sponge iron, etc.)
- Q_{Rawmat} : amount of transformed raw materials in steel making (i.e. from bituminous coal to metallurgical coke)

Equations (10.31) and (11.32) contain electricity intensity parameters which consists of the number of kWh required per tonne of raw material (for instance, metallurgical coke from coking plants). These parameters are values taken from the technical literature on steel making technologies and values registered from observations of some Mexican plants. Table 10.3 comprises electricity intensity parameters which are substituted in the two equations presented above. The amount of electricity requirements is determined as a function of the level of production activity of the relevant raw material or intermediate product. For instance, the amount of electricity requirements in a blast furnace in 2005 consists of:

$$E_{BF,2005} = 4{,}047{,}122.\text{tonnes.pig.iron} * \left(\frac{25.kWh}{tonne.pig.iron} \right) \qquad \ldots (10.31.1)$$

Process segement	USA (1994)	Mexico	year (Mexico)		unit
Sinter making	45.9	45.0	1983	a	kWh/t iron ore
Coke making	33.5	33.0	1993	b	kWh/t coke
Iron ore making (BF)	22.5	25.0	1993	b	kWh/t pig iron
Direct iron making					
Direct reduction iron	n.a.	60.0	2001	c	kWh/t DRI
Hot briquetted iron	n.a.	75.0	2001	c	kWh/t HBI
HYTEMP	n.a.	55.0	2001	c	kWh/t HYTEMP
Basic oxygen furnace	30.1	30.0	1993	b	kWh/t steel
Electric arc furnace	479.7	525.7	2005	d	kWh/t steel
Continuos casting	61.7	15.0	1993	b	kWh/t semifinished product
Hot rolling	195.5	67.4	2005	d	kWh/t hot rolled steel
Cold rolling and finishing	131.4	113.2	2005	d	kWh/t cold rolled steel

Source: Worrell et al., (2001) for USA; a, b, c, and d for Mexico, several years.[172]

Table 10.3 – Electricity Uses in the Steelmaking Process

The energy-CO_2 model presented in this chapter is relevant insofar it provides a benchmark of energy requirements for the whole steel industry in Mexico. Different sources have been consulted in order to choose a representative parameter of electricity consumption for the different stages of steelmaking as follows.

- Electricity consumption in a sinter plant in Mexico is taken from the study of Guzmán et al., (1987) in table 10.3.

[172] (a) Guzmán et al., (1987); b) Meyers and Odón de Buen, (1993); c) HYLSA, (2001) ; and d) own calculations based on plant data, on-site fieldwork visits in Mexico (2005, 2006, 2007).

- Values of electricity consumption in coking plants, blast furnace, BOF, and continuous casting correspond to the study of Meyers and Odón de Buen, (2006).
- Electricity consumption in direct iron reduction processes, hot briquetted iron (HBI), and HYTEMP iron, all are variants of direct iron making correspond to the HYL-III steel making technology (HYLSA, 2001).

A main assumption in the values presented in table 10.3 is that electricity requirements of the majority of steel making segments remain with little variation over time. However, there are three critical stages of steel making where electricity requirements appear to decrease considerably:

1) The replacements of ingot casting for continuous casting (i.e. 28 kWh/tonne ingot casting versus 15 kWh/tonne continuous casting steel, Meyers and Odon de Buen, 2006).
2) Electricity requirements in direct reduction reactors (DRI) sometimes are met with a self-sufficiency electricity scheme ranging from 60 kWh/tonne DRI on average (HYLSA, 2001) to nearly zero kWh/tonne DRI (Quintero, 1995).
3) Dramatic reductions in electricity requirements per tonne of liquid steel in the electric arc furnace process.

In this respect, relevant electricity intensity parameters for DRI production and ingot casting were obtained through consultation of the technical literature and personal communication during on-site fieldwork visits. In addition, electricity intensity for hot and cold rolling was obtained as the ratio of the overall electricity requirements and total finished steel production in six single rolling mills in Mexico.

10.3.3.2 Overall Electricity Requirements in BOF and EAF Technologies in Mexican Plants

According to the methodology presented in this chapter, 250.9 kWh per tonne of finished steel are required in the BF-BOF route in 2005 (equation 10.30). This amount of electricity is distributed across the following stages in the BF-BOF route:

a) On-site electricity generation (CHP)

b) Coking plants
c) Sinter plants
d) Blast furnaces
e) BOF
f) Casting
g) Hot rolling
h) Cold rolling and finishing

The above formulation is represented as follows:

$$E_{BF\_BOF} = E_{CHP} + E_{UTILITIES} + E_{BF} + E_{BOF} + E_{Semifinished} \quad \ldots (10.33)$$

Where,

- E_{BF_BOF} : overall electricity in BF-BOF steel making route (i.e. 1,129.9 GWh in 2005).
- E_{CHP} : On-site electricity generation by means of combined heat and power.
- $E_{UTILITIES} = E_{Coking.plant} + E_{SINTER.plant} + E_{Blast.furnace} \quad \ldots (10.34)$
- E_{BOF} : amount of electricity exclusively consumed in BOF.
- $E_{Semifinished} = E_{Casting} + E_{hot.rolling} + E_{Cold.rolling,finishing} \quad \ldots (10.35)$

The amount of electricity consumed in semi-finished products includes electricity uses in continuous casting, hot, and cold rolling. There is a split between electricity requirements for semi-finished steels according to the share of BOF and EAF steel in overall total production in industry. From national industry statistics, the total BOF steel production accounts for 27.7% of total steel industry in 2005. In addition, data at plant level for BOF facilities indicates that 26.2% of total BOF steel production corresponds to hot rolling. This latter value $(26.2/100)$ is used as a reference in the share of electricity in BOF semi-finished steels in equation 10.35.1:

$$E_{Semifinished} = \left(E_{Casting} + E_{hot.rolling} + E_{Cold.rolling,finishing}\right) * (0.262) \ldots (10.35.1)$$

In addition, the remaining of electricity for semi-finished products in EAF steel consists of the difference $(1 - 0.262 = 0.738)$. This latter proportion is employed to calculate the amount of electricity required in the production of semi-finished steel products ($E_{Semifinished}$) using the route DRI-EAF (in equation 10.37).

Overall electricity consumption in the BF-BOF route is a known value according to the specification of equations (10.13)-(10.15). In addition, substituting the generic equations (10.31) and (10.32) into (10.33) defines a value for each electricity requirements in every stage of BF-BOF steelmaking route. E_{BOF} is an unknown parameter in (11.35). The electricity intensity parameter for BOF (30 kWh/tonne steel) given by Meyers and Odon de Buen, (1993) is not used as a reference value. Instead, E_{BOF} is endogenously calculated in the model specified in this chapter. Hence E_{BOF} Is obtained using equation (10.33) as follows:

$$E_{BOF} = \frac{E_{BF\_BOF} - E_{CHP} - E_{UTILITIES} - E_{BF} - E_{Semifinished}}{Q_{BOF}} \quad \text{… (10.36), or}$$

$$E_{BOF} = \frac{1{,}129.9 * 10\hat{}(6) kWh - \left(E_{CHP} + E_{UTILITIES} + E_{BF} + E_{Semifinished}\right) kWh}{4{,}504{,}541\,tonnes} \quad \text{… (10.36.1)}$$

According to equation (10.36), 38.7 kWh/tonne steel are required, on average, in BOF process in Mexican plants. This value indicates a rise in the amount of electricity in BOF per tonne of liquid steel as compared to the value reported by Meyers and Odon de Buen, (2006). Notice, indeed, that E_{BOF} is dependent on the values taken by each of the independent variables in (11.38.1). The larger the amount of electricity provided by CHP, the lower the amount of electricity per tonne of liquid steel in a BOF. Similarly, an increase in the use of electricity in utilities such as sinter and coking plants and in rolling mills would imply a decrease in the amount of electricity in BOF per tonne of liquid steel.

The stages with a relative larger demand for electricity in the BF – BOF route correspond to sinter making (322 GWh), the basic oxygen converter (304.2 GWh), and the hot rolling mills (161.9 GWh), figure 10.11.

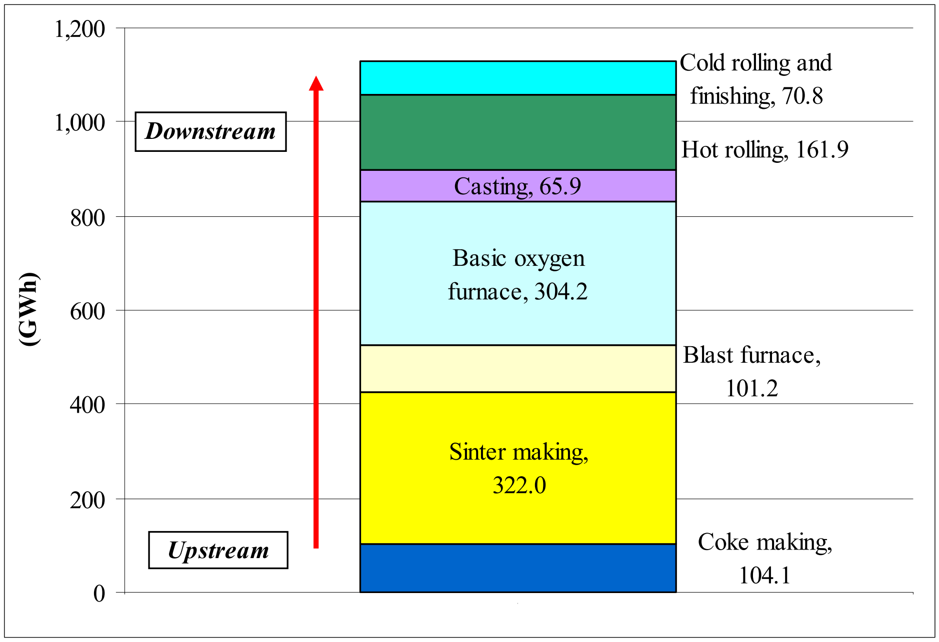


Figure 10.11 – Distribution of Electricity Uses in the Blast Furnace – Basic Oxygen Furnace Route, Mexico, 2005 (GWh)

Similarly, the amount of overall electricity used in the DRI-EAF route is defined in equation (10.29). This electricity is distributed through the following direct iron making stages:

a) On-site electricity generation
b) Direct reduction reactor
c) Electric arc furnace
d) Continuous casting
e) Hot rolling mills
f) Cold rolling and finishing

Electricity through the DRI-EAF route consists of:

$$E_{DRI\_EAF} = E_{CHP} + E_{DRI} + E_{EAF} + E_{Semifinished} \quad \ldots (10.37)$$

Where,

- E_{CHP} : on-site electricity generation with a self-sufficiency scheme (i.e. sponge iron production with HYL-III and/or MIDREX technologies)

- $E_{DRI-EAF}$: overall electricity consumption in the DRI-EAF route (i.e. 6,192 GWh in 2005)
- E_{DRI} : electricity consumption in the direct reduction iron process
- E_{EAF} : electricity consumption exclusively in EAF
- $E_{Semifinished} = \left(E_{Casting} + E_{hot.rolling} + E_{Cold.rolling,finishing}\right) * (1 - 0.262)$ … (10.38)

Electricity in EAF per tonne of liquid steel after taking into account electricity requirements in other stages of the DRI-EAF route consist of:

$$E_{EAF} = \frac{E_{DRI\_EAF} - \left(E_{DRI} + E_{Semifinished}\right)}{Q_{EAF}} \quad \ldots (10.39), \text{ or}$$

$$E_{EAF} = \frac{6{,}192 * 10\text{^}(6)\text{kWh} - \left(E_{DRI} + E_{Semifinished}\right)}{11{,}777{,}758.tonnes} \quad \ldots (10.39.1)$$

DRI plants with self-sufficiency in electricity generation do not require electricity imports from the Mexican grid in the production of pig iron. Not all DRI plants in the Mexican case have a self-sufficiency scheme, but for those plants which do, electricity requirements in DRI are nearly zero. In the representation of this model, the amount of electricity consumed in a DRI process cancels out the amount provided by CHP:

$$E_{DRI} = E_{CHP}, E \to 0 \quad \ldots (10.40)$$

One of the assumptions in DRI-EAF steel production consists of no self-sufficiency scheme in electricity generation. However, in practice, there are two DRI plants in Mexico with a self-sufficiency scheme. In this route, the majority of electricity requirements are concentrated in the operation of electric arc furnaces (5,027.3 GWh), followed by hot rolling mills (455.5 GWh), and the direct reduction of iron (328.5 GWh) figure 10.12.

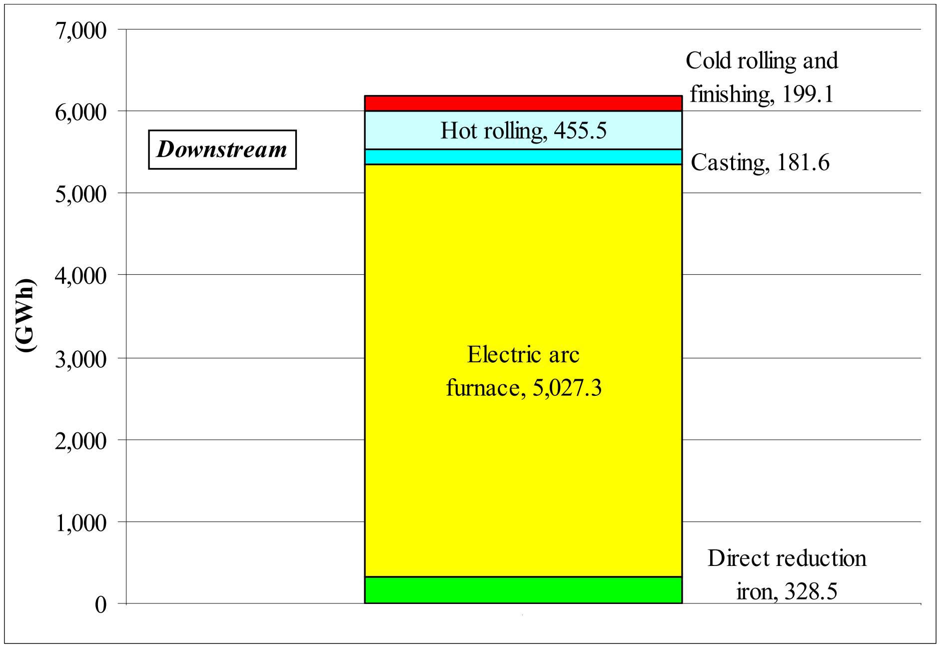


Figure 10.12 – Distribution of Electricity Uses in the Direct Reduction of Iron – Electric Arc Furnace Route, Mexico, 2005 (GWh)

A summary of results of energy consumption and the amount of CO_2 emissions in each stage of the BF-BOF and DRI-EAF technological routes are presented in figures 10.13 and 10.14, respectively. In the BF-BOF route, energy requirements (GWh) due to consumption of fossil fuels (i.e. coal, coke, pet coke, natural gas, diesel, and fuel oil) are relatively larger in the early stages as compared to the latter stages.

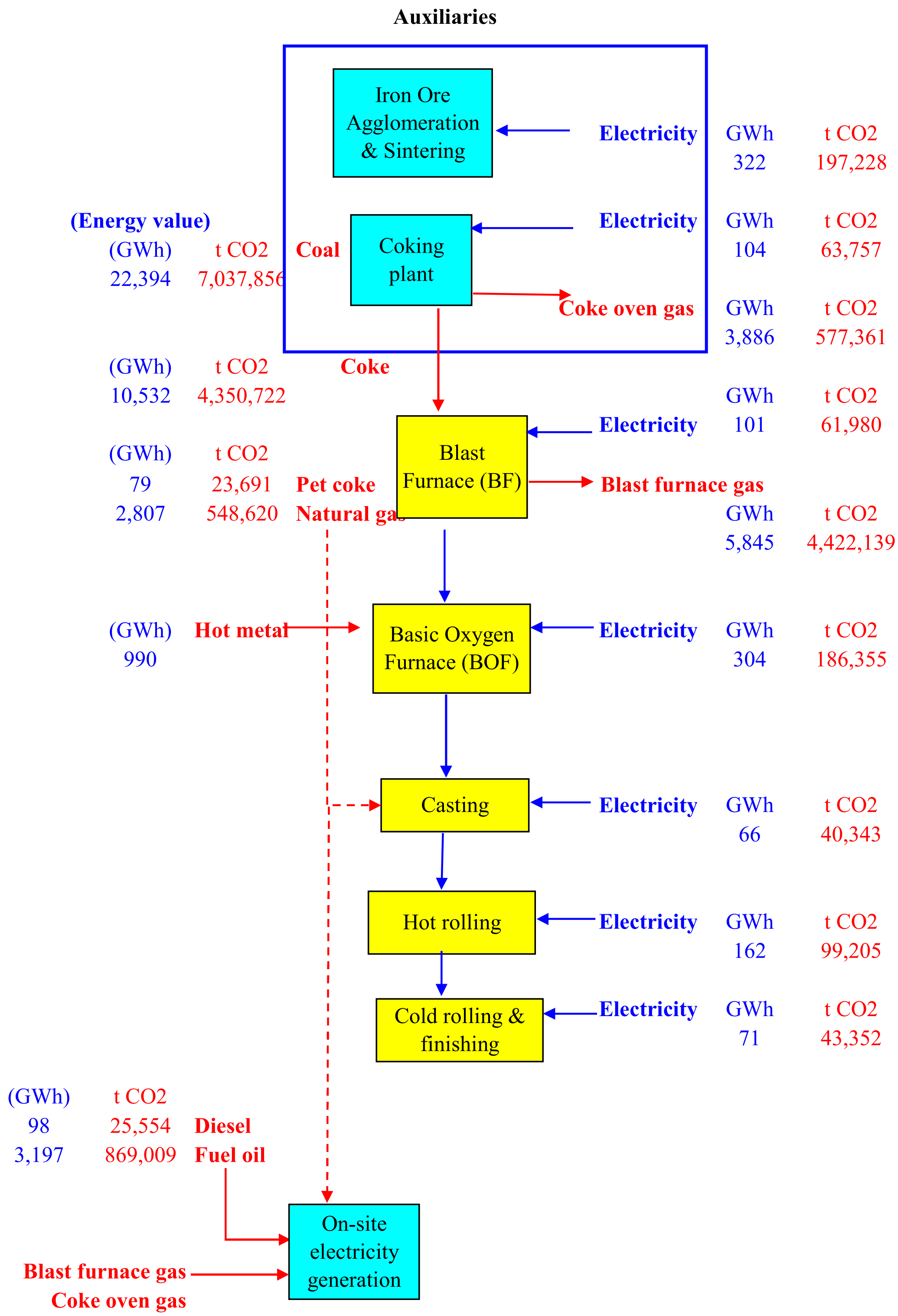


Figure 10.13 – Energy Consumption and CO_2e Emissions by Stage in BF-BOF Route, Mexico, 2005 (GWh and tonnes of CO_2e)

This is the result of the quantity of fossil fuels employed but also the calorific value of each fossil fuel. The only exception is the energy embedded in fuel oil for on-site electricity generation which is located at the bottom of the layout although this location is only for explanatory purposes (figure 10.13).

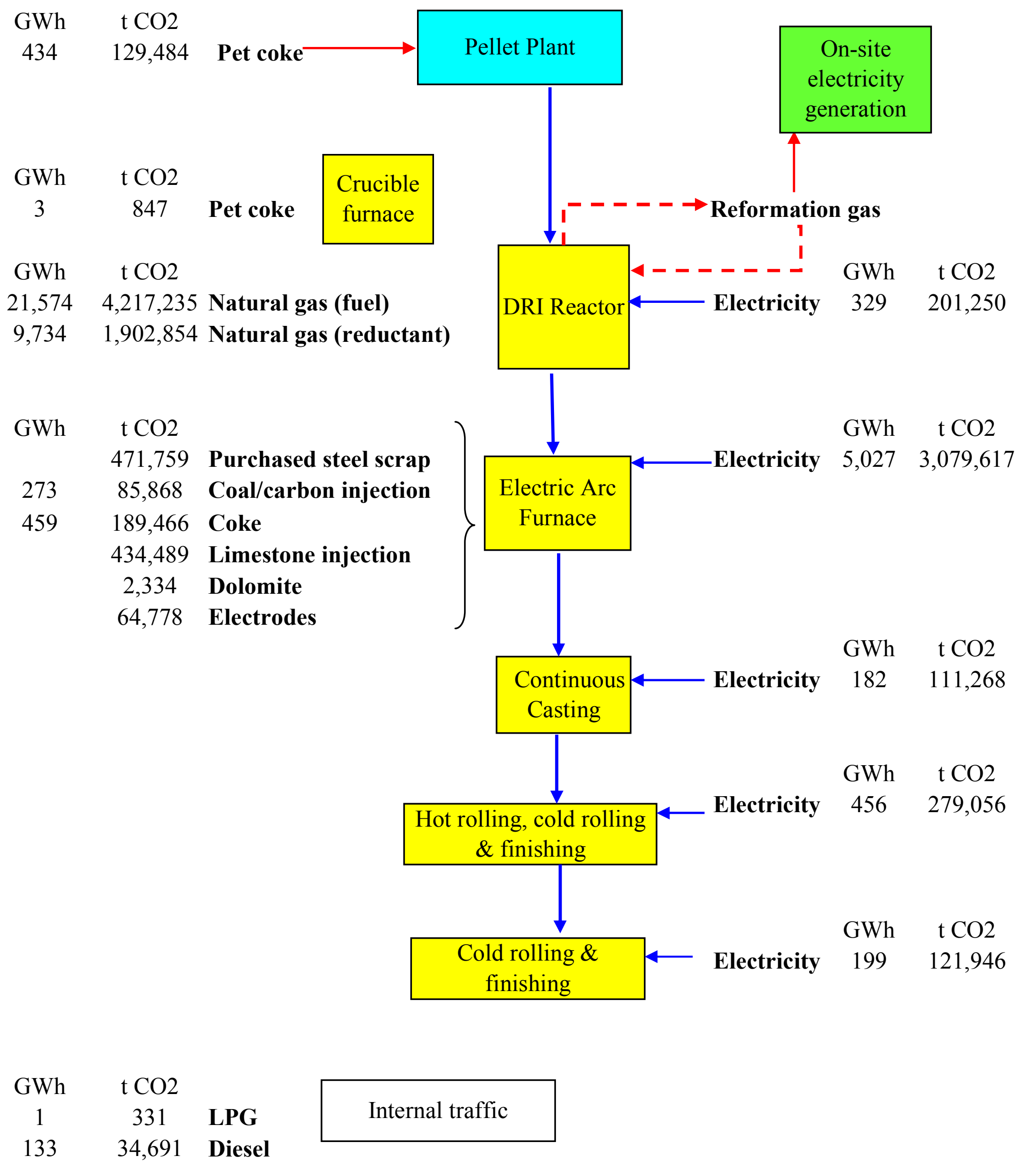


Figure 10.14 – Energy Consumption and CO_2e Emissions by Stage in DRI-EAF Route, Mexico, 2005 (GWh and tonnes of CO_2e)

In the DRI-EAF route, total energy provided by natural gas amounted for 31, 308 GWh in 2008. Of this amount, 21,574 GWh (68.9%) are used as heat whereas 9,734 GWh (31.1%) are used in the reduction process. Energy provided by pet coke

(434 GWh) as heat in the pellet plant is also significant. The use of coke represents an important source of energy (459 GWh) in the operation of electric arc furnaces. LPG and diesel are mostly used for internal traffic in the plants.

10.3.4 Calculation of CO_2 Intensities in DRI-EAF and BF-BOF Steelmaking

Carbon dioxide intensity is calculated for the specific materials/energy consumption through the BF-BOF route as follows:

$$\frac{CO_2(tonnes)}{BOF.steel(tonnes)},_{2005} = \left(\frac{CO_2,_{materials} + CO_2,_{by-products} + CO_2,_{fuels} + CO_2,_{electricity} - CO_2,_{finished.steel}}{Q_{BOF}}\right)$$

… (10.41)

Similarly, carbon dioxide intensity for the specific materials/energy consumption through the DRI-EAF route is calculated as follows:

$$\frac{CO_2(tonnes)}{EAF.steel(tonnes)},_{2005} = \left(\frac{CO_2,_{materials} + CO_2,_{by-products} + CO_2,_{fuels} + CO_2,_{electricity} - CO_2,_{finished.steel}}{Q_{EAF}}\right)$$

… (10.42)

Notice that both equations (10.41) and (10.42) are specific versions of the general equation (10.9) which corresponds to the aggregated method for CO_2 emissions calculations in the total overall steel industry. Notice also that the amount of carbon dioxide embedded in final steel products is subtracted from the overall emissions in each technological route.

Figures 10.15 and 10.16 compare the amount of CO_2 emissions originated in the consumption of each material and fuel per tonne of BOF and EAF finished steel, respectively, and are calculated in relation to the amount of final BOF and EAF steel. The value of carbon intensity is affected by both the value of the corresponding emission factor and the quantity of material/fuel employed in each technological route. For instance, transformation of coking coal into coke and uses of coke in blast furnaces are the most CO_2 intense activities. On average, 1.52 tonnes of CO_2 per tonne of BOF steel are generated in the use of coking coal whereas 0.97 tonnes of CO_2 per tonne of BOF steel are produced in the consumption of coke in the Mexican BF-BOF technological route. In addition, blast furnace gas (BFG) is found as the most CO_2 intensive by-product (i.e. 0.98 tonnes of CO_2 per tonne of BOF steel) as opposed to coke oven gas (COG) in primary steel making (i.e. 0.13 tonnes of CO_2 per tonne of BOF steel). A CO_2 emission factor for BFG and COG is very similar. However, the large discrepancy in the CO_2 intensity between the two exhausted gases is due to a much larger volume of BFG. Similarly, electricity consumption in the BF-BOF routes accounts for 0.15 tonnes of CO_2 per tonne of finished BOF steel whereas natural gas consumption accounts for 0.13 tonnes of CO_2 per tonne of BOF steel.

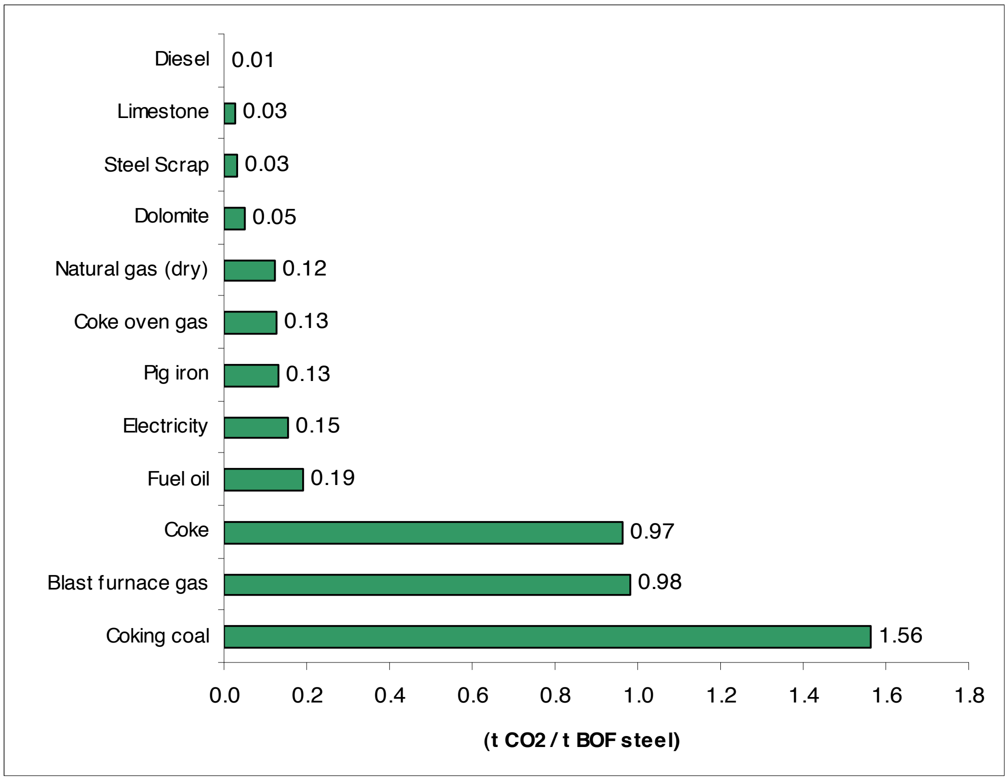


Figure 10.15 – Carbon Intensity of Fuels, Materials & Electricity Used in Primary Integrated Steel Making Obtained from Equations 10.36.1 and 10.41, Mexico, 2005 (t CO_2e/t BOF steel)

Source: own calculations based on the methodology developed in this Chapter.

Results presented in figure 10.15 can be used as an ***industry benchmark*** for each material, fuel, and the corresponding amount of electricity in the BF-BOF technological route in Mexico.

BFG is among the most CO_2 intensive regardless of its application (i.e. pre-heating purposes, on-site electricity generation, and/or venting practices). There is a potential to reduce imported electricity from the Mexican grid to the extent that on-site electricity is generated with a mix of BFG, COG and other fuels. A CO_2 intensity of electricity requirements in BF-BOF facilities could be reduced whereby a certain amount of purchased electricity is replaced with the use of recovery gases for on on-site electricity generation.

CO_2 intensities of each material/fuel in the DRI-EAF route are presented in figure 10.16. Dry gas is the most CO_2 intensive among the fuels used in integrated secondary steel making. A CO_2 emission factor for dry gas is the lowest amongst the fuels employed in steel making in Mexico. However, high carbon dioxide intensity for dry gas is explained, in this case, due to the vast amounts of dry gas used in the DRI-EAF steelmaking route. More importantly, two CO_2 intensities for dry gas are calculated in relation to a different allocation given to this fuel. On average, 0.16 tonnes of CO_2 per tonne of EAF steel are generated in the consumption of dry gas as a reducing agent (RA in figure 10.16). In addition, 0.36 tonnes of CO_2 per tonnes of EAF steel are produced in the consumption of dry gas as source of heat.

In the first case, dry gas is employed as a chemical reducing agent in the reduction of pellets in order to produce sponge iron in DRI reactors, whereas in the second case, dry gas is mostly employed as a fuel in the heating and pre-heating of boilers, EAF furnaces, and rolling mills. Adding the CO_2 intensities of dry gas both as a reducing agent (RA) and as a fuel, gives an overall CO_2 intensity for dry gas of 0.52 tonnes of CO_2 per tonne of BOF steel.

Regarding electricity uses, 0.32 tonnes of CO_2 are generated per tonne of EAF steel through the BF-EAF route compared to 0.15 tonnes of CO_2 per tonne of BOF steel. Sponge iron production (in the DRI-EAF steel route) is significantly larger (i.e. 5,973.2 thousand tonnes) than pig iron production in 2005 (i.e. 4,030.3 thousand tonnes). However, the CO_2 intensity for sponge iron (i.e. 0.04 tonnes of CO_2 per tonne of EAF steel) is lower than the CO_2 intensity for pig iron (i.e. 0.13 tonnes of CO_2 per tonne of BOF steel). Bearing in mind that EAF steel production (11,777.8 thousand tonnes) was 2.6 times as much as BOF steel production in 2005 (4,504.5 thousand tonnes) producing a larger volume of EAF liquid steel explains the lower CO_2 intensity of sponge iron in comparison to that of pig iron.

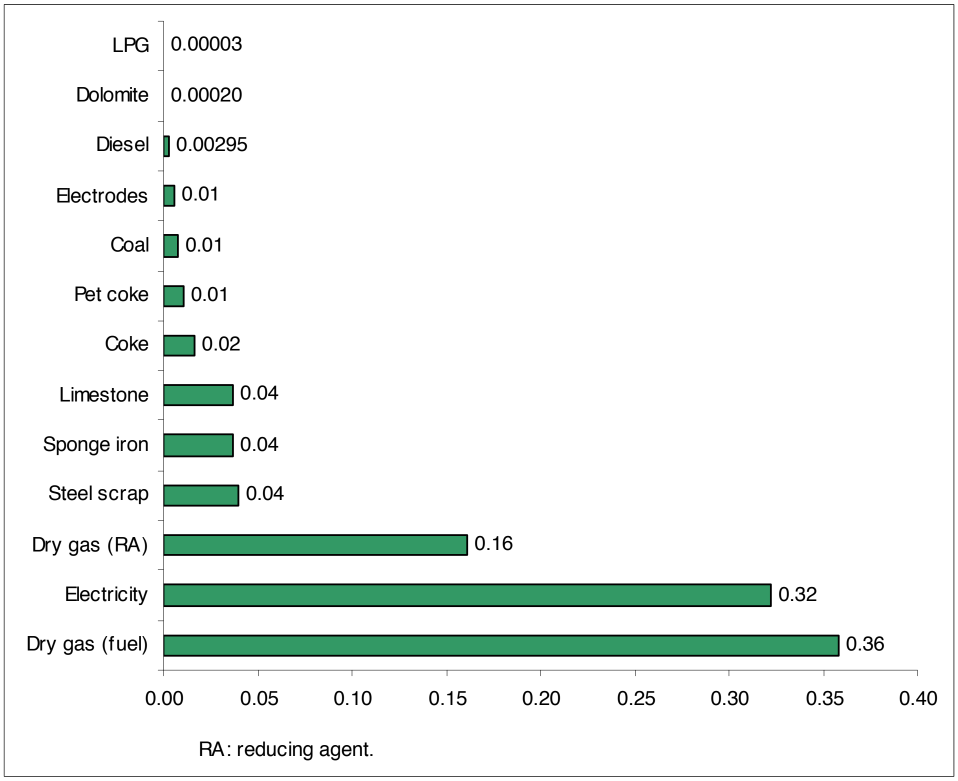


Figure 10.16 – Carbon Intensity of Fuels, Materials & Electricity Used in Secondary Steel Making Obtained from Equations 10.39.1 and 10.42, Mexico, 2005 (t CO_2e/t EAF steel)

Source: own calculations based on the methodology developed in this chapter.

The addition of separate CO_2 intensities of each fuel and material is used in the accounting of the overall CO_2 intensity of the BF-BOF and DRI-EAF steelmaking routes. There are three factors which affect the value of the overall CO_2 intensity:

1) The relative amount of each material, fuel, and electricity requirements.

2) The relevant CO_2 emission factor of each material, fuel, and electricity uses.

3) The amount of final steel production with both BOF and EAF steelmaking.

CO_2 emissions in the BF-BOF and DRI-EAF arising from the component emissions from materials, intermediate products, by-products, fuels, and electricity requirements amounted to 19,461.7 and 11,333.5 thousand tonnes of CO_2 respectively in 2005 (i.e. rows a and b2 in table 10.4). Table 10.4 also presents CO_2

emissions in the DRI-EAF route after subtracting dry gas used as a reducing agent. In this latter case, overall total emissions in the DRI-EAF routes amount to 9,430.6 thousand tonnes of CO_2 in 2005 (i.e. row b1 in table 10.4).

Dry gas as a reducing agent is used in direct iron making such as the HYL-III and MIDREX technologies, and a critical novelty in these processes is the selective removal of CO_2 in the flux of reducing gases which, in turn, is delivered to other industrial activities for commercial applications.

Steel making route / Parameters		Carbon emissions	Carbon intensity	Energy intensity
		t CO2	t CO2 / t steel	kWh/t steel
a)	Emissions from route BF - BOF	19,461,729	4.320	250.9
b1)	Emissions from route DRI - EAF	9,430,604	0.801	525.7
b2)	Emissions from route DRI - EAF	11,333,458	0.962	525.7
c)	Emission in overall industry*	30,392,747	1.867	449.7

(b1, no natural gas used as reducing agent)

(b2, including natural gas used as a reducing agent)

Table 10.4 - CO_2e Emissions, CO_2e intensities, and SEC intensities in BF-BOF and DRI-EAF Steelmaking Routes in Mexico, 2005

CO_2 emissions considered in the calculation of CO_2 intensities for the two steel making routes correspond to rows a) and b2) in table 10.4. Overall CO_2 intensities (i.e. CO_2 per tonne of steel), these correspond to 4.32 and 0.96 tonnes of CO_2 per tonne of BOF and EAF steel, respectively (column 4 in table 10.4). This is an important finding in the research presented in this thesis as it appears that a CO_2 intensity in the BF-BOF was around 4.5 times that of the DRI-EAF in 2005. Hence, opportunities to curb CO_2 emissions are relatively larger in primary integrated steel making in the Mexican case.

In addition, row c in table 10.4 presents an overall CO_2 intensity of the iron and steel industry in Mexico using the aggregated methodology specified in sections 10.3.1 and 11.3.1.1. According to the aggregated methodology, 11,333.5 thousand tonnes of CO_2 are generated in the manufacturing of steels in the overall iron and steel industry in 2005. This result is obtained on the basis of observed aggregated parameters for both technologies for materials, fuels, and electricity consumption in the overall still industry in Mexico.

Consequently, an overall CO_2 intensity in the iron and steel industry corresponds to 1.87 tonnes of CO_2 per tonne of finished steel (column 4 in table 10.4). It is important to validate these results in a sense that the model presented for each different steelmaking routes is self-contained and validation means that adding up a CO_2 intensity for each steelmaking route (weighted according to tonnage produced) should be close or equal to the overall total CO_2 intensity for the whole steel industry. A validation of these results consists of representing an overall CO_2 intensity for the whole steel industry as follows:

$$Overall\frac{CO_2}{Q_S} = \left(\frac{Q_{EAF}}{Q_S}\right)*\left(\frac{CO_{2,EAF}}{Q_{EAF}}\right)+\left(\frac{Q_{BOF}}{Q_S}\right)*\left(\frac{CO_{2,BOF}}{Q_{BOF}}\right) \quad \ldots (10.43)$$

Where,

- $\frac{Q_{EAF}}{Q_S}$: the share of EAF steel production in overall total steel production in the industry.
- $\frac{Q_{BOF}}{Q_S}$:the share of BOF steel production in overall total steel production in the industry.
- $\frac{Q_{EAF}}{Q_S}+\frac{Q_{BOF}}{Q_S}=1$ (i.e. industrial production constraint).
- $\frac{CO_{2,EAF}}{Q_{EAF}}$:carbon dioxide intensity in the DRI-EAF steelmaking route.
- $\frac{CO_{2,BOF}}{Q_{BOF}}$:carbon dioxide intensity in the BF-BOF steelmaking route.

The above analysis is summarised in table 10.5 and yields and overall carbon intensity of 1.891 tonnes CO_2 per tonne of steel.

Steelmaking route	Share of steel produced	Carbon intensity (tonnes CO_2 per tonne steel)	Share * CO_2 intensity product
EAF steel production	0.7233	0.962	0.696
BOF steel production	0.2767	4.320	1.195
Overall carbon intensity - tonnes CO_2 per tonne steel = 1.891			

Table 10.5 –CO_2e Intensities of EAF and BOF Steelmaking, Mexico, 2005 (t CO_2e/t steel)

Alternatively the same result can be obtained by cancelling out the same variables (i.e. amount of EAF and BOF steel production) which are defined in both the numerator and denominator of equation (10.43) yields:

$$Overall\frac{CO_2}{Q_S} = \left(\frac{CO_2,_{EAF} + CO_2,_{BOF}}{Q_S}\right) \quad \ldots (10.44)$$

$$Overall\frac{CO_2}{Q_S} = 1.891 \quad \ldots (10.44.1)$$

A level of uncertainty was calculated for both absolute emissions (measured in tonnes of CO_2) and carbon dioxide intensities (measured in tonnes of CO_2 per tonne of finished steel). A level of uncertainty may be calculated in two different ways as follows:

$$u = f(CO_2) = \left(\frac{CO_2,_{EAF} + CO_2,_{BOF}}{Overall.CO_2}\right) \quad \ldots (10.45), \text{ and}$$

$$u_2 = f\left(\frac{CO_2}{Q_S}\right) = \frac{\left(\frac{CO_2,_{EAF}}{Q_{EAF}} + \frac{CO_2,_{BOF}}{Q_{BOF}}\right)}{\left(Overall\frac{CO_2}{Q_S}\right)} \quad \ldots (10.46)$$

Calculated uncertainties of the CO_2 intensity using an aggregated methodology and a specific steelmaking technological route are presented in table 10.6. Both measures of uncertainty give the same value and the error in estimation from the two approaches give values which differ by just over 1% (i.e. 1 – 0.9869).

CO_2 Emissions (u)	CO_2 Intensities (u_2)
0.9869	0.9869

Table 10.6 – Uncertainty in CO_2e Emissions and Intensities Using Aggregated and Technology Specific Methodologies, Mexico, 2005

10.4 Alternative CO_2 Emissions Scenarios in the Mexican Steel Industry

Carbon dioxide intensities in the production of steel from the direct use of a given amount of fossil fuels and materials are likely to change little as any modifications in the emission factor of each material/fuel or changes in the calorific value of fuels are likely to be relatively small. Densities of materials and fuels are assumed to be constant since this is more a matter of a physical property and not a dependent variable in the exposed model. On the other hand, a changing fuel mix in electricity generation could significantly affect the overall emission factor for steel production even though it is largely outside the control of the industry. Another important variable affecting CO_2 intensities is the relative distribution of steel production between BF-BOF and DRI-EAF.

Overall changes in CO_2 emissions will be proportional to the changes in growth in steel production unless:

1) Technological and energy efficiency gains take place in a specific steelmaking route.
2) The penetration of one technological route, for instance, the DRI-EAF route is more pervasive than the other (i.e. BF-BOF).

The CO_2 intensities and SEC for each technological route in 2005 are used in the following four alternative CO_2 emission scenarios in the Mexican steel industry:

1) Overall growth in steel production in the period 2005-2030.
2) Growth in steel production by EAF and BOF technology in 2005-2030.
3) A reduction in SEC and reduction in the CO_2 emission factor of purchased electricity in 2005-2030.

4) Overall growth in steel production and reduction in the CO_2 emission factor of purchased electricity in 2017-2030.

10.4.1 Scenario 1 – Overall Growth in Industrial Production

Growth in steel production was analysed in two scenarios. In the first scenario, growth in steel production reduces each consecutive year from 3% to 1.5% between 2008 and 2030 as follows:

$$\boldsymbol{growth\,in\,CO_2(tonnes) = f(\Delta Q)} \quad \ldots (10.47)$$

$$growth\,in\,CO_2(tonnes) = \left[\left(\frac{CO_{2},_{BOF}}{Q_{BOF}}\right) * (Q_{BOF}) + \left(\frac{CO_{2},_{EAF}}{Q_{EAF}}\right) * (Q_{EAF})\right] * \Delta Q \ldots$$

(10.47.1), or

$$\boldsymbol{growth\,in\,CO_2(tonnes) = \left(4.32\frac{CO_2(t)}{Q_{BOF}(t)} * (Q_{BOF}) + 0.962\frac{CO_2(t)}{Q_{EAF}(t)} * (Q_{EAF})\right) * \Delta Q}$$

… (10.47.2)

Where,

- $\Delta Q = \left(\frac{Q_t}{Q_{t-1}}\right)$ *if and only if* $\frac{\partial \Delta Q}{\partial t} > 0$ and $\frac{\partial^2 \Delta Q}{\partial t^2} < 0$, (condition 1)

Steel production is assumed to rise from 17,640,126 tonnes to 28,181,371 tonnes between 2008 and 2030 but at a diminishing growth rate each consecutive year. The annual compound growth rate over the period 2008-2030 is 2.1%. CO_2 intensities of both BF-BOF and DRI-EAF steel production remains constant as of 2005. The amount of steel production (i.e. BOF and EAF steel) is multiplied by the same growth rate every consecutive year (ΔQ). This means that the share of BOF and EAF steel in overall steel production remains constant to the distribution in 2005 (i.e. 25% and 75% of BOF and EAF steel, respectively).

In the second scenario, steel production raises gradually each consecutive year from 3% to 4.5% between 2008 and 2030. The annual growth rate is controlled by the following condition:

$$0.06 \le \frac{\partial^2 \Delta Q}{\partial t^2} \le 0.08$$ in the period 2008-2030 (condition 2).

Steel production is assumed to rise from 17,640,126 tonnes to 39,466,941 tonnes between 2008 and 2030. The annual compound growth rate over the period 2008-2030 is 3.6% i.e. at a rate 75% higher than in the first scenario.

According to observed steel production between 2005 and 2008, carbon emissions in the iron and steel industry in Mexico rose from 30,795.2 to 31,651.8 thousand tonnes. There is not current but simulated data for steel production in 2008. Steel production rose at a 1.7% growth rate in the period 2005-2007. Under a 2.1% growth scenario of steel production, carbon emissions rise from 32,572.9 thousand tonnes to 50,566.0 thousand tonnes between 2009 and 2030. Under a 3.6% growth scenario of steel production, carbon emissions raise from 32,618.9 thousand tonnes to 70,815.8 thousand tonnes in the same period (figure 10.17).

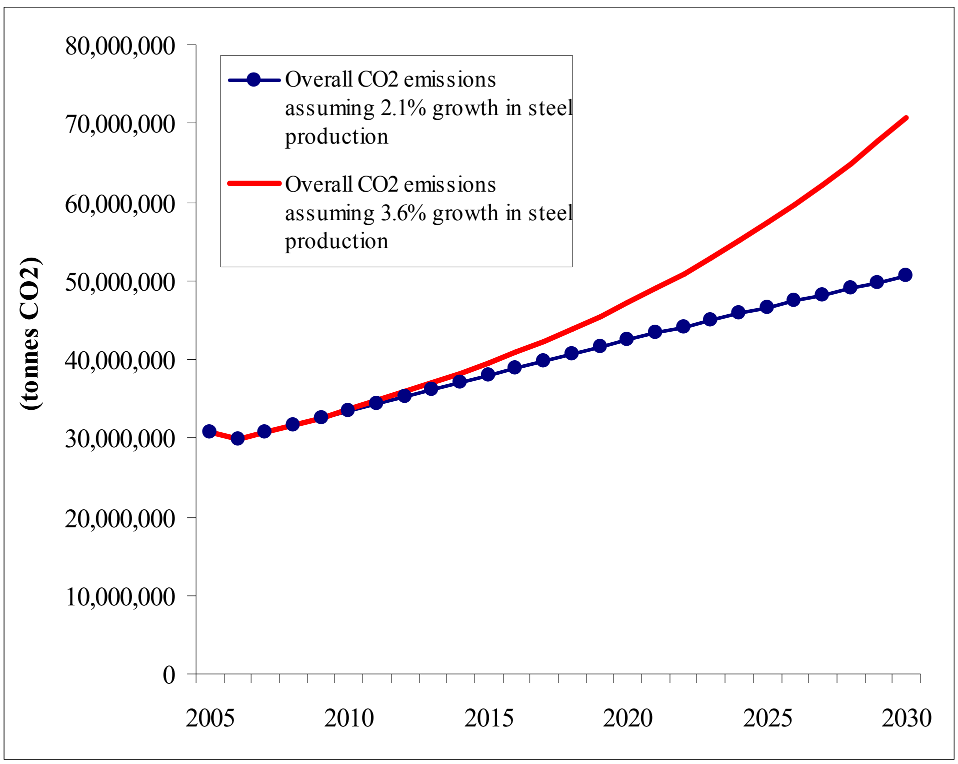


Figure 10.17 – CO_2e Emissions in Overall Steel Production, Scenario1, Mexico, 2005-2030 (tonnes CO_2e)

10.4.2 Scenario 2 – Differentiated Growth in Steel Production by EAF and BOF Technology

Over the years, the composition of EAF and BOF steel production in Mexico has changed. Production of steel with BF-Open Hearth Furnace (Siemens Martin technology) was terminated in 1992. This is a factor which has re-enforced the dominance of EAF and BOF steelmaking technologies in the Mexican industry. Interestingly, in the Mexican case EAF technology has shown a more pervasive penetration in steelmaking as compared to BOF technology. EAF steel production grew up 6.58% whereas BOF steel production only rose at 0.75% between 1992 and 2006. Overall steel production in the industry (i.e. no difference between EAF and BOF steel) increased 4.53% in the same period on a compound annual growth rate. Several studies have documented an ever increasing diffusion of the EAF technique in Mexico (i.e. Castillo-Ramos and Tovey, 2008; Mercado-García, 2008; Barton and Mercado-García, 2005; Guzmán, 2002; Ozawa et al., 2002; Guzmán et al., 1987; and Tizcareño-Velasco, 1986). The dominance of the EAF technology in Mexico makes a difference as compared to the U.S. steel industry. In this latter case, Worrell et al., (2001) show that BOF steel production in the United States was much more significant than EAF steel production between 1965 and 1995.

The calculated growth rates for EAF and BOF steel production between 1992 and 2006 are used as a reference in this second scenario. Growth in CO_2 emissions related to the diffusion of EAF and BOF is defined as follows:

$$Growth..inCO_2(tonnes) = 4.32\frac{CO_2(tonnes)}{Q_{BOF}(tonnes)}*(Q_{BOF})*(\Delta Q_{BOF})+...$$

$$...+0.962\frac{CO_2(tonnes)}{Q_{EAF}(tonnes)}*(Q_{EAF})*(\Delta Q_{EAF}) \quad ... (10.48)$$

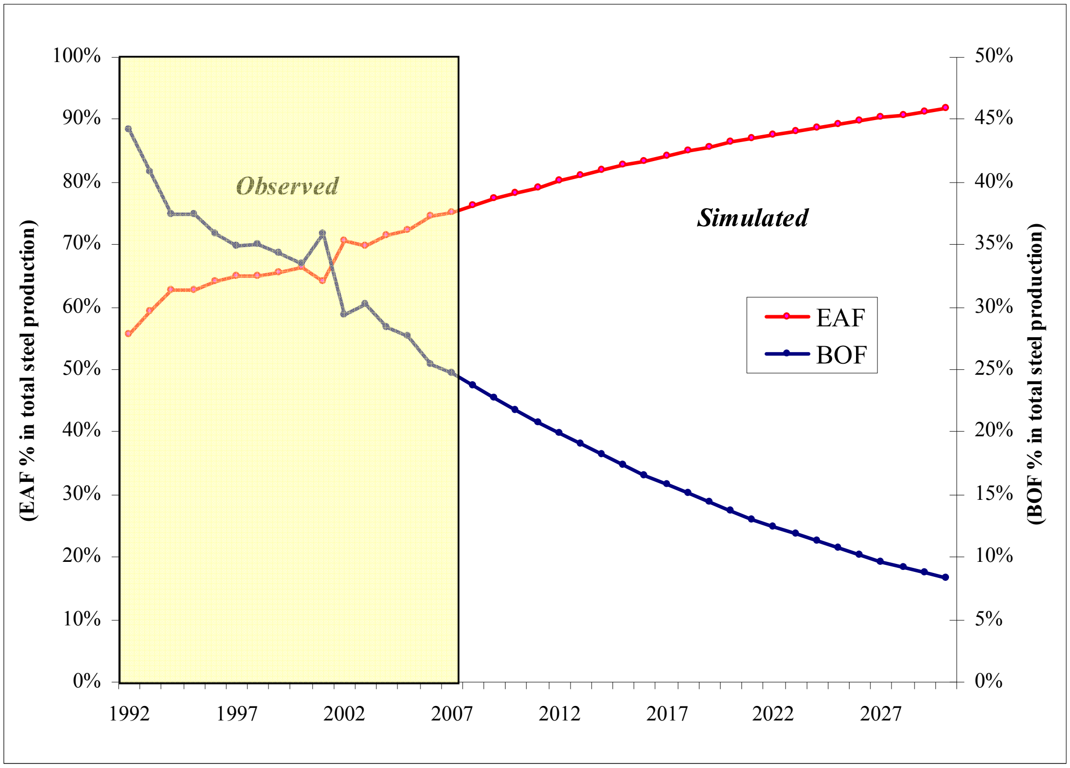
Where,

- Where 4.32 tonnes CO_2/tonne BOF steel and 0.962 tonnes CO_2/tonne EAF steel are the carbon intensities of the blast furnace – basic oxygen furnace and direct iron reduction – electric arc furnace routes, respectively, in 2005 as obtained in the analysis of section 10.3.4.

- $\Delta Q_{BOF},_t = (Q_{BOF},_t)*\left(1+\frac{0.75}{100}\right)$, for every *t*.

- $\Delta Q_{EAF},_t = (Q_{EAF},_t)*\left(1+\frac{6.58}{100}\right)$, for every *t*.

Different growth rates of BOF and EAF steel production specified in equation (10.48) result into changes in the share of BOF and EAF steel production in the total overall steel production.



.**Figure 10.18 – Share of EAF and BOF Steel in Overall Steel Production, Mexico, 1992-2030 (% of total steel production)**

The share of BOF steel lowers from 23.7% to 8.3% between 2008 and 2030. EAF steel production share increases from 76.3% to 91.7% between 2008 and 2030 (figure 10.18).

Carbon emissions associated to growth in BOF steel production raise from 18,608.3 thousand tonnes to 21,763.5 thousand tonnes between 2009 and 2030. Carbon emissions associated to growth in EAF steel production increase from

14,081.5 thousand tonnes to 53,656.7 thousand tonnes n the same period (figure 10.19).

The observed level of CO_2 emissions from BOF steel production is larger than in the case of EAF steel production during the period 1992 to 2013. However, by 2014, CO_2 emissions in EAF steelmaking (i.e. 19,363.2 thousand tonnes) overtake those from BOF steelmaking (19,315.3 thousand tonnes) as a result of a further diffusion of the EAF technology. However, since the electricity requirements for EAF are 548% higher than those for BOF, changes in the fuel mix in electricity generation in Mexico in the future while have a more significant proportional effect on carbon emissions than it had in the past.

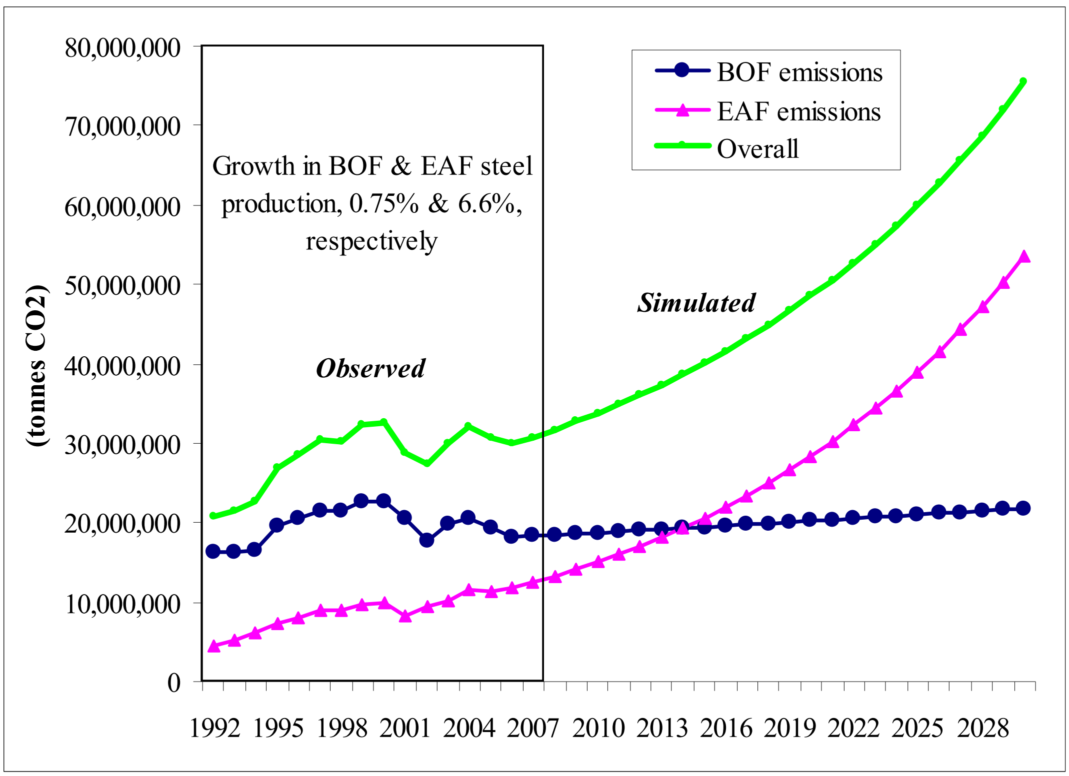


Figure 10.19 – CO_2e Emissions by Steel Making Technology, Mexico, 2005-2030 (tonnes CO_2e)

10.4.3 Scenario 3 –Energy Efficiency in Electricity Uses and CO_2 Emissions from Purchased Electricity

Reducing CO_2 emissions in regards to electricity uses are possible insofar:

1) The CO_2 emission factor in electricity generation reduces through a coherent and adequate national energy policy (i.e. energy futures in chapter 9).

2) The specific energy consumption (SEC) in the steel industry reduces either through a change in the relative proportions of the steel making technologies or by a continued or through more energy efficient deployment of those technologies..

Equation (10.49) takes into account the effect of variations of the SEC in BOF and EAF and changes in the carbon emission factor of purchased electricity on overall carbon emissions as follows:

$$Growth..in.CO_2(tonnes) = \left[\Delta\left(\frac{kWh}{Q_{BOF}}\right)*(Q_{BOF}) + \Delta\left(\frac{kWh}{Q_{EAF}}\right)*(Q_{EAF})\right]*\Delta\left(\frac{CO_2}{kWh}\right)$$

… (19.49)

$\left(\frac{kWh}{Q_{BOF}}\right)$ and $\left(\frac{kWh}{Q_{EAF}}\right)$ consist of specific electricity consumption (SEC) in BOF and EAF technologies, respectively. These values consists of $250.85\frac{kWh}{BOF.(tonne)}$ and $525.74\frac{kWh}{EAF.(tonne)}$, in 2005.

It is assumed (SEC_{BOF}) gradually reduces from $(250.85\,kWh/tonne.steel)$ to $(238.61\,kWh/tonne.steel)$ between 2005 and 2030 implying a negative growth rate in BOF electricity requirements of 0.2% every consecutive year. Conventional estimates on improvements in the BOF performance suggest reductions in electricity consumption in the range $[45 > 30]\boldsymbol{kWh/tonne.steel}$ (Energy Technologies, 2009). Hence there is a margin of flexibility for improvements in BOF electricity requirements of $(15\,kWh/tonne.steel)$.

In DRI-EAF steel production, (SEC_{EAF}) reduces from $(525.74\,kWh/tonne.steel)$ to $(250.0\,kWh/tonne.steel)$ between 2005 and 2030. This implies a compound negative growth rate in EAF electricity requirements of around 3.5% over the period.

CO_2 emissions are also dependent on a CO_2 emission factor of purchased electricity from the Mexican grid. This is represented by the amount of (CO_2/kWh) which is multiplied by the amount of electricity requirements in BOF and EAF steelmaking in equation (10.50). Variations in the CO_2 intensity of purchased electricity are part of the results on energy futures (Chapter 9). In this particular case, $\Delta(CO_2/kWh)$ corresponds to the amount of CO_2 in electricity generation and distribution under a renewable(s) energy policy taking place in 2017-2030 (i.e. s renewable electricity generation regime, section 9.4.3.4, chapter 9).

Carbon dioxide emissions reduce from 3,954.9 thousand tonnes to 1,241.6 thousand tonnes between 2005 and 2030 as a result of decreases in specific electricity consumption in EAF and reduction in the carbon emission factor of purchased electricity under a renewable energy policy. Carbon dioxide emissions also reduce from 721.7 thousand tonnes to 390.3 thousand tonnes in the same period as a result of reductions in specific electricity consumption in BOF and reduction in the carbon emission factor of purchased electricity (figure 10.20).

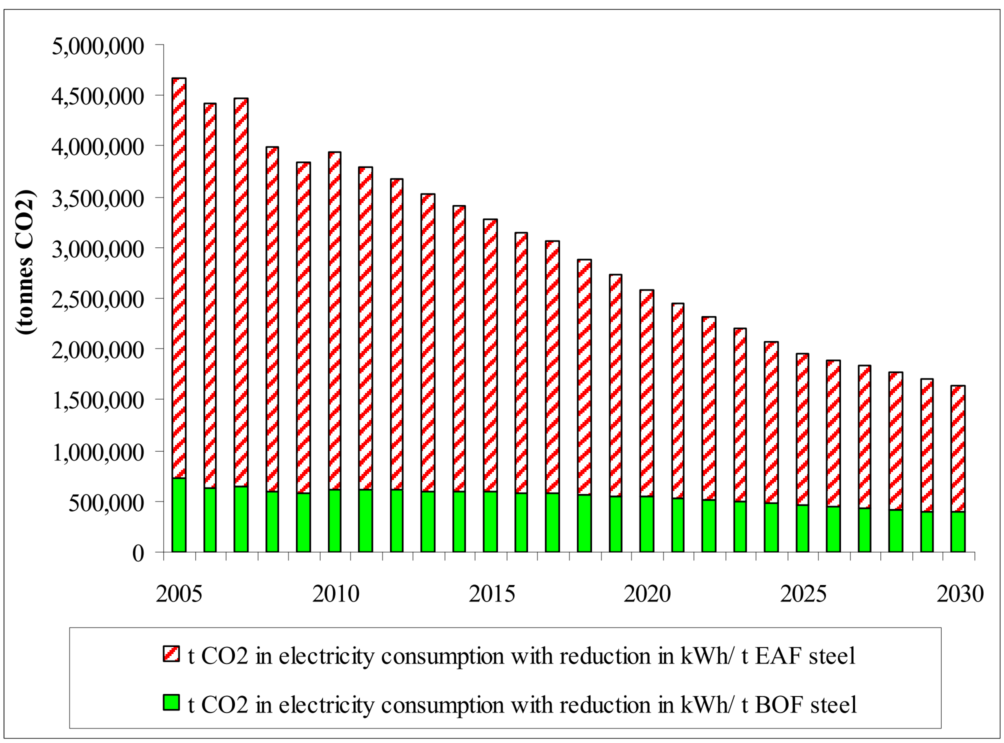


Figure 10.20 – CO_2e Emissions from Electricity Uses in BOF and EAF Steelmaking, Mexico, 2005-2030 (tonnes)

10.4.4 Scenario 4 – Reduction in the CO_2 Content of Purchased Electricity Used in Steels

This scenario incorporates the effect of a carbon emission factor of purchase electricity under alternative energy policies in regards to electricity uses in the steel industry. Unlike the previous scenario, CO_2 emissions arising from electricity consumption in the steel industry under three different energy policy scenarios are compared to those emissions of the overall steel industry associated only to fuels and materials.

Growth in steel production in these scenarios is modelled as follows:

$$Growth..in.CO_2(tonnes) = \left[SEC_{e,S,t} * Q_S * \Delta Q_{S,t}\right] * \Delta\left(\frac{CO_2}{kWh}\right)_{Scen,i} + ...$$

$$+\left[4.17\frac{CO_2(t)}{Q_{BOF}(t)} * Q_{BOF} + 0.64\frac{CO_2(t)}{Q_{EAF}(t)} * Q_{EAF}\right] * \Delta Q \qquad \ldots \qquad (10.50)$$

Growth in steel production $(\Delta Q_{S,t})$ is part of both components of equation 10.50 and hence this can be re-written as follows:

$$Growth..in.CO_2(tonnes) = \left\{\left[SEC_{e,S,t} * Q_S * \Delta\left(\frac{CO_2}{kWh}\right)_{Scen,i}\right] + ...\right\}$$

$$\left\{..... + \left[4.17\frac{CO_2(t)}{Q_{BOF}(t)} * Q_{BOF} + 0.64\frac{CO_2(t)}{Q_{EAF}(t)} * Q_{EAF}\right]\right\} * \Delta Q_{S,t} \qquad \ldots(10.50.1)$$

Where,

- $SEC_{e,S,2005} = \left[250.85\frac{kWh}{BOF(t)} + 525.74\frac{kWh}{EAF(t)}\right]$
- $\Delta\left(\frac{CO_2}{kWh}\right)_{Scen,i}$: carbon emission factor of purchased electricity according to energy policy scenarios analysed in Chapter 9.

- $4.17\dfrac{CO_2(t)}{Q_{BOF}(t)}$ consists of the carbon intensity in the BOF route and is obtained as the summation of CO_2 emissions from the consumption of fuels and materials after subtracting emissions from electricity. This amount of CO_2 emissions is divided by total BOF steel production. Similarly,

- $0.64\dfrac{CO_2(t)}{Q_{EAF}(t)}$ consists of the carbon intensity in the EAF route and is obtained as the summation of CO_2 emissions from the consumption of fuels and materials after subtracting emission from electricity. This amount of CO_2 emissions is divided by total EAF steel production.

The SEC in the BOF and EAF steelmaking routes is held constant to 2005 levels. Electricity demand in the steel sector and the corresponding CO_2 emissions are dependent on growth in steel production $\left(\Delta Q_{S,t}\right)$. A low growth rate (2.1%) of steel production is used on a compound annual basis over the period 2005-2030. Electricity consumption is obtained as the summation of electricity requirements in BOF and EAF steel production each year. Overall electricity requirements in the overall iron and steel industry are multiplied times the carbon dioxide emission factor of purchased electricity $\Delta\left(\dfrac{CO_2}{kWh}\right)_{Scen,i}$ according to each energy policy scenario.

Equation 10.50 defines CO_2 emissions from electricity consumption in the steel industry in comparison to those emissions from fuels and materials. Emissions are calculated under four alternative energy policy scenarios in electricity generation (figure 10.21) and an appraisal of these results are presented in table 10.7.

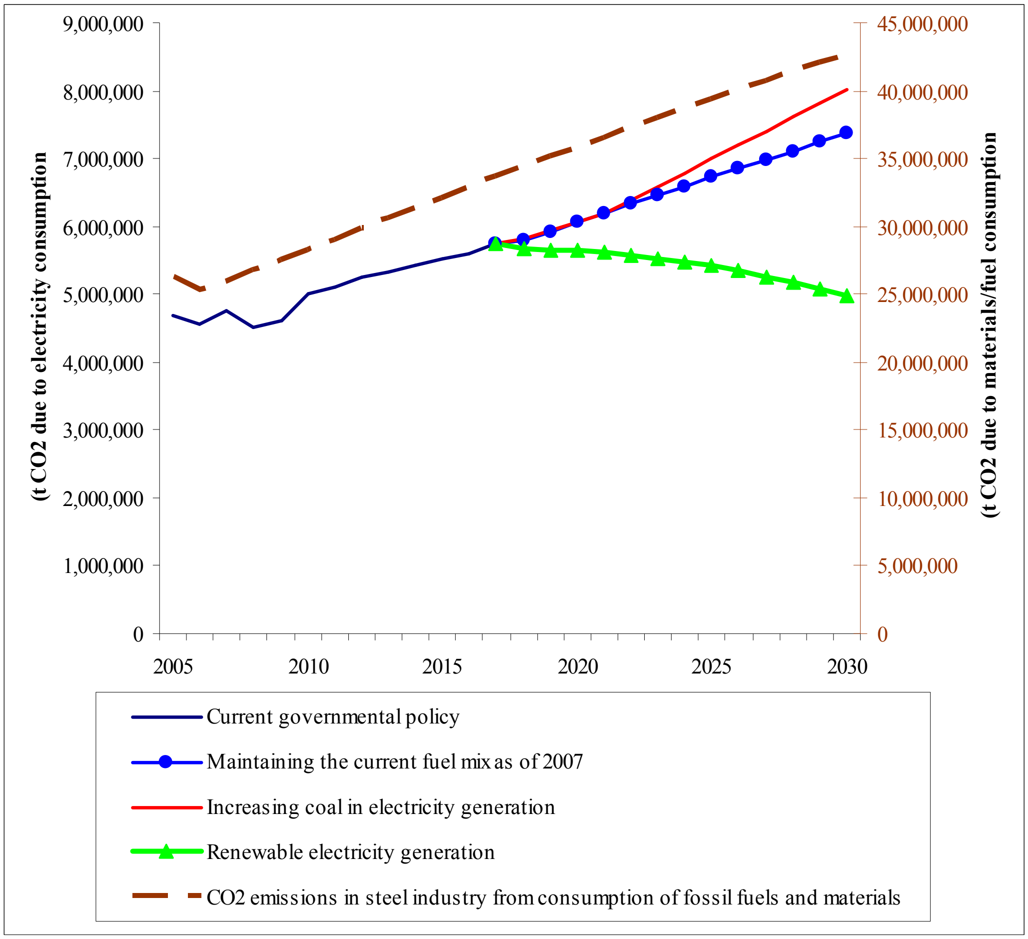


Figure 10.21 – CO_2e Emissions in the Iron & Steel Industry from Purchased Electricity, Fuels and Raw Materials, Scenarios up to 2030, Mexico (tonnes of CO_2e)

Carbon emissions from the consumption of raw materials and fossil fuels in the overall steel industry increase from 26,309.8 thousand tonnes to 42,665.7 thousand tonnes between 2005 and 2030 (i.e. dotted line in secondary axis in figure 10.21). A significant proportion of emissions are associated to consumption of raw materials and fuels such as natural gas, coal and metallurgical coke in integrated steel plants. CO_2 emissions due to electricity consumption represented 17.8% the emissions associated to uses of raw materials and fuels 2005.

	Carbon Dioxide Emissions Equivalent (thousand tonnes)			
Energy Policy Scenario	2005	2017	2018	2030
1) Current governmental policy	4,676.6	5,739.3		
2) Continuation of scenario 1			5,739.4	7,367.6
3) Dominance of coal in electricity generation			5,813.6	8,012.3
4) A renewable generation regime			5,659.8	4,971.6

Table 10.7 – CO_2e Emissions from Purchased Electricity in the Steel Industry under Alternative Electricity Futures, Mexico, 2005-2030 (thousand tonnes)

10.5 Summary of the Chapter

Overall the carbon intensity of the steel industry reduced from 4.4 to 1.8 tonnes CO_2e/tonne of steel between 1980 and 2006. Among the factors contributing to a lower carbon intensity of the steel industry are:

1) A growing importance of sponge iron production in comparison to pig iron.
2) A growing importance of steel crap production.
3) A decrease in the production of metallurgical coke.
4) Improvements in the productivity of blast furnaces.
5) A growing importance of steel production with electric arc furnaces in comparison to basic oxygen furnaces.

With regards to improvements in the efficiency of electricity uses, the SEC reduced from 937.5 to 447.1 kWh/tonne finished steel between 1990 and 2006. Of the overall 7,321.9 GWh used in the steel industry, 85% (6192 GWh) of total electricity were used in the direct iron reduction (DRI) – electric arc furnace (EAF) route whereas the remaining 15% (1129.9 GWh) were used in the blast furnace (BF) – basic oxygen furnace (BOF) route in 2005. The SEC in the BF – BOF route amounted to 250.9 kWh/tonne finished steel whereas in the DRI – EAF route amounted to 525.7 kWh/tonne finished steel in the same year.

The methodology used in this chapter permitted the estimation of a carbon intensity for each of the raw materials, fuels, and by-products used in each of the main steelmaking technological routes in 2005. In the BF – BOF route, coking coal, blast furnace gas, and coke are the most important contributors to carbon emissions the carbon intensity of which amounted to 1.56, 0.98, and 0.97 tonnes CO_2e/tonne of finished steel, respectively, in 2005. In the DRI – EAF route, dry gas as a fuel, electricity, and dry gas as a reduction agent are the most significant precursors to carbon emissions the carbon intensity of which amounted to 0.36, 0.32, and 0.16 tonnes CO_2e/tonne of finished steel, respectively, in the same year.

Of the overall 30,795,187 tonnes CO_2e in the steel industry, 63% (19,461,729 tonnes CO_2e) corresponds to the BF – BOF route whereas the remaining 37% (11,333,458 tonnes CO_2e) corresponds to the DRI - EAF route in 2005. The carbon intensity in BF-BOF amounted to 4.32 tonnes CO_2e/tonne of steel whereas in DRI-EAF amounted to 0.96 tonnes CO_2e/tonne of steel in the same year.

In the first scenario of a 2.1% growth in steel production carbon emissions rise from 32,572.0 thousand tonnes to 50,566,0 thousand tonnes between 2009 and 2030 as compared to a 3.6% growth in steel production in which carbon emissions reach up to 70,815.8 thousand tonnes at the end of the period.

In the second scenario of a 0.75% and 6.58% growth in BOF and EAF steel production, respectively, carbon emissions from BOF steel rise from 18,608.3 thousand tonnes to 21,763.5 thousand tonnes whereas carbon emissions from EAF steel increase from 14,081.5 thousand tonnes to 53,656.7 thousand tonnes between 2009 and 2030. Thus the overall total carbon emissions amount to 75,420.2 thousand tonnes at the end of the period.

In the third scenario of a reduction of specific electricity consumption in EAF and a lower carbon content of purchased electricity (under a scenario of renewable energy policy, section 9.4.3.4, chapter 9), carbon emissions reduce from 3,954,894.1 thousand tonnes to 1,241,583.3 thousand tonnes between 2005 and 2030. Similarly, carbon emissions in the BOF route reduce from 721,738.1 thousand tonnes to

390,305.8 thousand tonnes in the same period. Hence the overall reduction in carbon emissions from electricity uses in the steel industry amounts to 1,631,889 thousand tonnes at the end of the period.

In the fourth scenario of a 2.1% growth in steel production carbon emissions consist of the following:

1) Under a current governmental energy policy scenario, carbon emissions from electricity uses in the steel industry rise from 5,793.4 thousand tonnes to 7,367.6 thousand tonnes between 2018 and 2030.
2) Under a coal energy policy scenario in electricity generation, carbon emissions from electricity uses in the steel industry increases from 5,813 thousand tonnes to 8,012.3 thousand tonnes in the same period.
3) Under a renewable energy policy scenario in electricity generation, carbon emissions in the steel industry reduce from 5,659.8 thousand tonnes to 4,971.6 thousand tonnes in the same period

Carbon dioxide emissions from the use of raw materials and fossil fuels rise from 26,309.8 thousand tonnes to 42,665.7 thousand tonnes in the period 2005-2030.

Chapter 11

Conclusions

The holistic approach of this thesis addressed several aspects of electricity generation and energy efficiency in regards to carbon industrial emissions in the steel industry. Each finding was summarised at the end of each chapter and now the discussion turns to the conclusions.

Several barriers and drivers were identified through the revision of the energy literature in chapter 3 and these were grouped into: market, institutional, technological, managerial, priority strategies, and lack of governmental support/intervention. For instance, among the market barriers was the lack of sufficient information in organisations affecting an optimal level of energy efficiency investments while from a technical standpoint a barrier was the lack of specialised and trained personnel in regards to energy issues. On the other hand, a positive institutional driver was identified in the availability and access to capital to finance energy efficiency projects.

From an organisational perspective, it was noted that energy efficiency in some instances is part of the strategic resources within firms the contribution of which leads to sustain competitive advantage. The strategic attributes of the knowledge of energy efficiency and specific firm-based capabilities were a central concern in the resource-base approach of chapter 4. The theoretical approaches sketched in chapters 3 and 4 guided the analysis around the five research questions stated in this thesis and the following conclusions are presented around the research questions.

11.1 Main Conclusions from the Case Studies

The drivers and barriers explored in this thesis explored energy efficiency as part of many goals and strategies within organisations. Economic considerations greatly influence whether energy efficiency decisions go ahead. In some instances, energy efficiency is benefited as a result of capacity expansion as the new technology is more advanced with consequential reductions in energy uses. When incorporating new technology as was the case of the pellet plants and the steel rolling mills (in chapters 6 and 7), energy efficiency is only one among the many parameters of performance. However, capacity expansion is mostly an economic decision and firms do not decide putting additional steel capacity just because of energy efficiency. Hence energy efficiency may in some cases benefit from capacity expansion but the former does not determine the latter.

Energy efficiency cannot be tackled as an isolated aspect in decision making taken in an organisation. Energy efficiency is often found in combination with environmental, health, safety, and social responsibility goals in the definition of corporate policies. On the other hand, it was noted that in the two steel firms used as case studies market orientation of energy efficiency was important. These two steel companies are international competitors and they have a strong incentive to lower the energy costs thus looking at energy efficiency as an important resource.

With regards to the environmental side of energy efficiency, it can be concluded that energy efficiency is an ongoing process in the definition of guidelines to address climate change mitigation at the corporate level. This situation applies to the Mexican context and may be different in other steel companies.

The following drivers and barriers were identified as the most relevant in relation to energy efficiency according to the cases of two steel firms which included company Centaury and Perseus Mexico facilities.

11.1.1 Market Drivers

Market drivers are among the most important in the decisions of steel companies to lower energy consumption as this affects the overall cost structure. Firstly, steel manufacturers are large energy users the use of which represent a large share in the overall cost structure. In the Mexican steel industry, raw materials and electricity accounted for ~74% and 8% of overall input costs in 2007. Basic raw materials used in the two selected case study companies are pig iron, pellets, coal related products and steel scrap whereas the main energy inputs consists of coal, natural gas, and electricity. The relative price of energy and raw materials affect energy decisions and the use and future exploration of these commodities.

For instance, investing in iron ore exploration in Mexico depends on the rise of the relative price of iron ore in international markets. Before 2004, exploration of iron ore reserves was not significant in Mexico and this affected the production of pellets with consequential decreases in the production of sponge iron.

Secondly, in the Mexican context the price of natural gas and electricity show a long term increase in the steel industry (i.e. a two-fold increase in the period 2003-2010 based on a 2003 price index) hence creating a strong incentive among steel manufacturers to lower energy consumption and to find alternative energy sources.

Thirdly, the combined cost of raw materials, energy commodities, and prices of final steels are critical aspects in energy related decisions. Steel scrap is used in electric arc furnaces for producing liquid steels. In view of an increasing cost of steel scrap, the top management in the case of company Centaury may choose to use sponge iron of high carbon content in the load of an electric arc furnace. However, vast amounts of natural gas are needed in the reduction process for producing sponge iron.

As the price of natural gas shows an increasing long term trend, producing sponge iron may also put a pressure on production costs and in this instance the top management makes the most economical choice. This may result in a reverse effect of reducing the production of sponge iron in a plant in favour of larger uses of steel scrap. In the overall steel industry, the majority of gas is used in the direct reduction process for producing sponge iron (92% circa) where the remaining is used in blast and electric arc furnaces. Hence the relative price of energy inputs and raw materials plays a critical role in energy related decisions and sometimes choosing specific fuels and materials may be a barrier to lower energy consumption.

11.1.2 Priority Strategies

Energy efficiency involving retrofit projects were found to receive sufficient attention during stages of expansion of steel production capacity in company Centaury. It also appeared that expansion of production capacity projects which incidentally might enhance efficiency was given more support compared to energy efficiency projects alone when considering a pay back period. This barrier relates to the priority strategy given to additional production capacity. In this case two million tonnes of additional steel capacity was part of the committed investment taking place after 2007 following the acquisition of company Centaury in 2005. A longer payback period of energy efficiency projects as compared to increasing production capacity works as a barrier sometimes leading top management to limit the number of potential energy efficiency measures.

The case of Perseus Mexico facilities on the other hand is different as the need to increase two million steel tonnes of production capacity at the beginning of the 1980's resulted from operative inefficiencies and the corresponding economic loses. With the collected evidence in this research it is not possible to conclude that energy efficiency projects were less important than expansion of production capacity. However, the lack of a pellet plant and a rolling mill truncated an integrated production process and hence the corresponding energy gains at different stages of steel manufacturing were not possible. This is seen as technical barrier the overcoming of which was possible with financial investment (i.e. two million tonnes additional steel capacity) during 1996 and 1997.

Also, the financial crisis of 2009 showed how priority strategies in the Perseus Group were placed with regards to fixed cost reductions, managing cash, lowering levels of operation and thus delaying or stopping other long term projects including those incorporating energy efficiency. Thus periods of financial adjustment as a result of an economic downturn act regressively as a barrier in the full deployment of energy efficiency measures.

11.1.3 Technological Drivers

A way to characterise changes in energy efficiency was to give appraisals of the technical improvements in each critical stage of steelmaking in each organisation. A relative shortage of energy and steel scrap led company Centaury to carry out in-house R & D in the 1940's and the main outcome of this strategy was the use and commercialisation of HYL-I and HLY-III technologies during the last 40 years. Patenting technology improvements is seen as a large incentive to lower energy consumption and reduce further investments by the top management in company Centaury. Many of the improvements in the HYL technology look to lower energy consumption and integrate energy gains through different stages of the direct reduction of iron (DRI) – electric arc furnace (EAF) steelmaking route.

Overall, specific energy consumption (SEC) in company Centaury lowered from 800 to around 460 kWh/tonne of steel as a result of energy integration at different segments of steelmaking in a ten year period (mostly during the 1990's).

Interestingly, some of the technical improvements in steelmaking in company Centaury were also found in Perseus Mexico facilities. The energy contained in sponge iron of high carbon was used in combination with electricity to lower the energy consumption in electric arc furnaces. Personnel in both companies experiment with the use of techniques to lower electricity consumption in electric arc furnaces thus working as a technical driver to energy efficiency.

Unlike the case of company Centaury, Perseus Mexico facility does not conduct in-house R & D in steelmaking processes. This is not found to be a technical barrier to energy efficiency for two reasons. Firstly, improvements in the operation of an HYL-III reactor also use the benefits of high carbon content in sponge iron in relation to electricity savings in the subsequent operation of electric arc furnaces. Secondly, lowering energy uses is also pursued in the operation of a Midrex reactor which is an alternative technology for producing sponge iron. Perseus Mexico facilities produce sponge iron using either Midrex and HYL-III reactors but in this latter case the company pays the rights of using the patented technology. Hence this company has gained wider experience in the operation of different technologies the performance of which is assessed in terms of energy consumption.

11.1.4 Managerial and Organisational Drivers

Organisational drivers to energy efficiency were found to be of large importance in company Centaury. Energy uses are not unnoticed in the definition of corporate policy guideless. The normative aspects of energy uses are found to play a role as they look to improvements in energy uses in this company and indeed are integrated in the definition of corporate policy guideless.

The top management delegates the definition of energy related guidelines to specialized personnel at higher levels of the organisation. Energy efficiency capabilities within organisations rely on the involvement of operational personnel and commitment; training in new energy efficiency programmes; continuous monitoring of energy consumption parameters by steel process; and a large emphasis on the cultural domain of continuous improvement of energy uses. The organisational drivers to energy efficiency largely depend on the participation of staff at the bottom-line of production.

Energy uses and efficiency are included in the definition of eco-efficiency principles of the corporate environmental, safety, and health policy of company Centaury. This instance gives energy efficiency an environmental purpose wherein the observance of the corporate policy ensures that energy efficiency is not neglected.

In Perseus Mexico facilities, the definition and operation of a corporate responsibility and governance structure form an important part of the organisational and institutional drivers towards energy efficiency. The reporting of information goes from the bottom-line to the Corporate Responsibility Team before any energy efficiency related decision is made. It can be concluded from this particular case that much of energy efficiency management is a matter of measuring and reporting from the base (i.e. the bottom-line of production) to the top (i.e. the corporate team). Also, the inclusion of energy efficiency as part of the criteria of corporate leadership works proactively towards a continuous revision of energy related issues.

While other institutional barriers to energy efficiency are not widely addressed in the case studies, the corporate structure of Perseus Group is an instance on how the decisions within an organisation affect energy efficiency. In this regard, the flexibility of the corporate responsibility governance structure works as an organisational driver facilitating the decision-making in energy decisions.

This part of the conclusions relates exclusively to the cases of company Centaury and Perseus Mexico facilities. They do not necessarily apply to the whole iron and steel industry in Mexico and they should be regarded as particular cases of energy efficiency in organisations. The remaining of the conclusions are obtained from the quantifiable assessment of carbon emissions in relation to the total overall iron and steel industry.

In many respects, the drivers and barriers previously discussed above, and in particular, the corresponding technical capabilities, and the related energy decisions in these two organisations, give a meaningful interpretation to the remaining conclusions which are quantitative in nature. For instance, a decrease in the specific energy consumption in terms of kWh per tonne of steel in the overall industry is partly related to the qualitative characterisation of the technical and market drivers as presented in the two case studies. Using this approach provides a good theoretical advantage as a result of the previous exploration of how energy efficiency drivers and barriers give a social background with regards to carbon industrial emissions. The following conclusions can thus be generalised to the steel sector in Mexico.

11.2 Main Conclusions from the LCA of Carbon Industrial Emissions

11.2.1 The Relative Importance of Fugitive Emissions

The relative importance of fugitive emissions with respect to carbon emissions in the steel sector is presented in table 11.1. The carbon dioxide fugitive emissions of the fuels for electricity generation represented 34.4% the carbon emissions in the overall steel industry in Mexico in 2005. Carbon emissions in the steel industry are larger than the carbon emissions of the fuels used in the electricity sector thus offering alternative baselines in regards to the opportunities to reduce carbon dioxide.

Unit: thousand tonnes	CO_2e	CH_4e
Fugitive emissions	10,607.5	13,746.0
Iron and steel industry	30,795,187	

Table 11.1 – Fugitive Emissions in Energy Industries and Carbon Emissions in the Steel Sector, Mexico, 2005 (thousand tonnes)

The previous findings are very general conclusion as it is more appropriate to notice the relevance of fugitive emissions factors as part of the LCA. Firstly, the fugitive emissions of fuel oil + diesel amount to 144.9 g CO_2e/kWh whereas the gas and coal amounted to 31.5 and 8.17 g CO_2e/kWh, respectively, in 2005. These fugitive emissions make part of the emissions originating in power plants where the use of oil related products, coal and gas put a significant pressure on carbon dioxide.

Emissions in the steel industry do not only correspond to electricity uses but other fossil fuels and materials. Nevertheless, significant opportunities to reduce emissions from electricity uses in the steel industry correspond to strategies in energy and electricity generation.

An overall carbon intensity in the steel industry amounted to 1.89 tonnes of CO_2e/tonne of steel in 2005. When electricity is not considered the carbon intensity reduces to 1.6 tonnes of CO_2e/tonne of steel and thus emissions from electricity representing around 16% of the total carbon intensity. Interestingly, the fugitive emissions discussed above do not give a complete account as the majority of carbon emissions correspond to electricity generation itself for which more specific conclusions are given below.

11.2.2 Carbon Emissions in Electricity Generation

The main contribution using a LCA is to understand how a carbon emission factor for electricity generation changes under different energy policy scenarios. As a result, carbon emissions from electricity uses in the steel industry may in some cases be reduced with some national policy on electricity production although in other cases these emissions may raise. Clearly, the strategies for electricity generation correspond to variations in the fuel mix of electricity generation in power facilities but they can also have a significant consequential impact in the steel sector.

The observed emission factor in electricity generation amounted to 638.7 g CO_2e/kWh (in 2005) after taking into account both the fugitive carbon emissions and transmission loses. As noted above the relative significance of the carbon fugitive emissions from natural gas and coal is small as the majority of the emissions in these power plants arise during the combustion of fossil fuels. A rather different case is the carbon fugitive emissions of fuel oil and diesel as the carbon emissions factor (i.e. 144.9 g CO2e/kWh) represents around 23% the overall carbon emission factor of the Mexican electricity grid in 2005. Obviously, this comparison is only illustrative as the fugitive emissions were weighted according to the share of installed generation capacity for each of the fossil fuels. As for the transmissions losses, carbon emissions increase proportionally to the raise in transmission loses and these represented 17.1% of total electricity output in 2005.

Reducing fugitive carbon emissions upstream operations in energy industries cannot be overlooked as they represent an important strategy in climate change mitigation. Clearly, a strategy to reduce carbon fugitive emissions in fuel oil and diesel industries would translate into a lower overall carbon emission factor in electricity generation. This type of mitigation strategy needs to be implemented by oil and gas producers. On the other hand, increasing the efficiency of the electricity transmission network would be reflected in lower energy loses and the consequential carbon emissions. It should be noted that transmission losses in Mexico are double those in the UK and most other European Countries.

Nevertheless, the greatest of the opportunities for carbon emission reduction are localised in the power plants the strategies of which need to include alternative energy sources in the fuel mix and this is suggested in the future expansion of generation capacity. The energy policy in Mexico has several alternatives with regards to carbon emissions as was shown in the alternative electricity futures in chapter 9. However, not every future scenario for electricity generation sees a reduction in carbon emissions.

In the worst case scenario carbon emissions correspond to a growing share of coal-based technology in the future installed generation capacity and clearly, the energy policy would do better as maintaining the already planned Mexican governmental policy after 2017. There also appear to be better strategies for future electricity generation through an increasing participation of renewable energy. As hydro electricity is currently a large source of renewable energy in Mexico (~13% in 2007), a strategy must target a rise in the share of wind and solar generation capacity and appraisals of such strategies were given in chapter 9.

The most critical implication under such a renewable scenario is a fall in the carbon emission factor by the year 2030 from the current 638.7 g CO_2e/kWh to 297 and 320 g CO_2e/kWh in low and high growth electricity demand scenarios, respectively. The inclusion of a nuclear scenario in combination with renewable(s) suggests an even further fall in the carbon emission factor to 197 and 259 g CO_2e/kWh for the low and high growth scenarios, respectively, in the same year. Clearly, there is a large opportunity for energy policy to look at a growing share of non fossil fuel generation technology. On the contrary, the adverse effect on carbon emissions using pet coke in fluidized bed combustion plants would imply higher emissions (i.e. a carbon emissions factor at 852.7 g CO_2e/kWh) and this is taken into account in the coal dominance scenario. Clearly supporting the use of pet coke is not a suitable option for climate change mitigation.

11.2.3 The Significance of Carbon Emissions in the Steel Industry

A holistic assessment of the carbon emissions in the steel industry included the effect of carbon emission factors from electricity generation. With this notion, the contribution of electricity generation and uses was a central part in the model. Carbon emissions from electricity uses in the steel sector amounted to 4,676.6 thousand tonnes CO_2e after considering the carbon emission factor of the Mexican electricity grid in 2005 (i.e. 638.7 g CO_2e/kWh). If the carbon emission factor was lower as in the renewable and nuclear energy scenarios for 2030, the corresponding carbon emissions from electricity uses in the steel industry in 2005 would have been lower at 2,174.634 thousand tonnes and 1,442.434 thousand tonnes CO_2e, respectively. Thus different electricity futures have a potential dramatic effect on the industrial carbon emissions in the steel sector.

The use of other fuels generates also an important amount of carbon emissions in the steel industry. Major fuels are coking coal, coke, and natural gas. The carbon emissions from electricity uses represented 15% circa of the total overall emissions in the steel sector in 2005 thus suggesting an area of opportunity to reduce emissions in the electricity sector. The remaining 85% of carbon emissions is a major challenge and this needs to be addressed with specific strategies in regards to the technology, fuels and raw materials used in the steel sector.

Carbon emissions can also be reduced as a result of lowering electricity uses in steelmaking process and this was a central research concern in this thesis. The overall steel industry in Mexico showed a sustained reduction of electricity uses from 937.5 to 449.7 kWh/tonne of steel between 1990 and 2005. Using a CO_2 emission factor for the Mexican electricity grid in 2005 (i.e. 638.7 g CO_2e/kWh), it is noted that the effect of such a reduction of electricity intensity in the steel industry would reduce the carbon emissions from 598.8 to 287.2 kg CO_2e/tonne of steel. This demonstrates the critical importance of energy efficiency measures in the industry. There may have also been changes in the carbon emission factor of the electricity used in steel making, but the impact of these would have been less than the significance of the reduction in the actual demand for electricity.

The holistic approach of this thesis uncovers the potential effect of a combination of different strategies in energy industries (the petroleum and gas sectors), power plants and distributors, and steel facilities. Power plants can reduce the carbon emission factor as far as they include a higher share of non fossil fuel technology in the fuel mix and lower electricity loses. On the other hand, steel facilities can further reduce emissions while lowering the energy intensity of electricity requirements as was thoroughly documented in the case studies using a social science approach.

A straightforward conclusion from the social drivers and barriers is that the replacement of old steel capacity with new technologies would in itself imply a higher energy efficiency as the performance of the new technology would consume relatively less electricity in the case of electric arc furnaces. The quantification of carbon industrial emissions implies that new additional steel capacity could take place using Clean Development Mechanism (CDM) projects and in this respect it is suggested the use of a holistic methodology as it was done in this research. However further production of steels with electric arc furnaces has a limit as growth in steel production using direct reduction reactors and electric arc furnaces also puts a pressure on carbon emissions and this is addressed in the remainder of the conclusions.

11.2.4 Opportunities to Reduce Carbon Emissions in the Steel Industry

In the summary of findings of chapter 10 it was noted that producing steels with blast furnaces (BF) – basic oxygen converters (BOF) was more carbon intensive than with the use of direct reduction reactors (DRI) – electric arc furnaces (EAF). The arrangement of these two technological routes was based on the observation of the technology of Mexican steel plants. In the former route the carbon intensity amounted to 4.32 tonnes CO_2e/tonne of steel whereas in the latter one it amounted to 0.96 tonnes CO_2e/tonnes of steel, in 2005. It was also found that steel production with the use of DRI-EAF was the dominant process as 72.3% compared to 27.7% using the BF-BOF process in the same year. The combined effect of the carbon intensities of each steel production technique and a relative higher share of EAF steel resulted in an overall carbon intensity of the steel industry at 1.89 tonnes CO_2e/tonnes of steel and this was the observed value from the LCA.

As the majority of carbon emission (~85%) correspond to the use of raw materials, fossil fuels, and exhausted gas in the two main steel technological routes, four alternative scenarios were considered as whether carbon emissions could be reduced.

The most important conclusion is that growth in steel production puts an increasing pressure on carbon emissions whereas specific strategies only slightly counterbalance the effect of growth in steel production. Of the four considered scenarios, a 2.1% annual growth in steel production would result in 50,566.0 thousand tonnes CO_2e by 2030. Under this scenario the carbon intensity in the steel industry would fall from 1.89 to 1.79 tonnes CO2e/tonnes of steel in the period 2005-2030 and this scenario would be the most ideal.

The use of four combined strategies appears as desirable to reduce the effect of growth in steel production. The first strategy of slowing down the growth in physical steel production compares a 2.1% versus a 3.6% growth (table 11.2). Clearly, a 2.1% growth yields the lowest levels of carbon emissions at the end of the period. This amount of emissions can be referred as the baseline.

Scenario	Type of Strategy	2009	2030
		(thousand tones CO_2e)	
1)	2.1% growth in steel production	32,572.0	50,566.0
	3.6% growth in steel production	32,618.9	70,815.8
2)	*0.75% growth in BOF steel*	*18,608.3*	*21,763.5*
	6.58% growth in EAF steel	*14,081.5*	*53,656.7*
	Overall	32,689.8	75,420.2
3)*	The combined effect of changes in the emission factor of purchased electricity in a renewable energy policy** and:		
	Electricity intensity of the DRI-EAF reduces from 454.9 to 250 kWh/t steel	*3,260.2*	*1,241.6*
	Electricity intensity of BF-BOF reduces from 248.9 to 238.6 kWh/t steel	*587.4*	*390.3*
	Overall	3847.6	1631.9
* Only carbon emissions from electricity in scenario 3.			
** The carbon emission factor of purchased electricity in a Renewable scenario reduces from 556.3 to 385.4 g CO2e/kWh in the period 2009-2030.			

Table 11.2 – Alternative Potential Strategies of Carbon Emissions in the Steel Industry in Mexico, 2009-2030 (thousand tones CO_2e)

On the other hand, strategy 2 on an increasing share in the production of EAF steel would result into the highest level of carbon emissions by 2030. Strategy 3 pays attention on the carbon emissions from electricity uses only. This takes into account lowering the electricity intensity of both the BOF and EAF steel in combination with a reduction of the carbon emission factor of electricity under a renewable energy policy. If we take strategy 1 of a 2.1% growth in steel production as a baseline, the emissions from electricity uses in strategy 3 represent around 12% the overall total emissions of the baseline in 2009 in the steel industry. By the end of the period, the emissions from electricity uses using strategy 3 fall to around 3% the emissions of the baseline thus suggesting the potential of combining reductions in energy intensity in steelmaking with reductions in the carbon emission factor from electricity policy.

A fourth alternative strategy is use of combined heat and power (CHP) from exhausted gases. According to the summary of findings in chapter 10, carbon intensities of blast furnace and coke oven gases were found at 0.98 and 0.13 tonnes CO_2e/tonne of BOF steel. However this is not widely addressed in this thesis due to word length limitations and further research is needed. Hence mitigation of carbon industrial emissions needs to be seen from a holistic perspective with the consequential identification of an array of strategies as it was done in the research of this thesis.

Annex I – Technological Improvements on the Delivery of Sponge Iron from HYL-III Reactors to Melting Furnaces, company Centaury

Patent no.	Title	Issue Date	Inventors	Asignee name	U.S. patent class	Description
6,290,434	Expansion joint for high-pressure high-temperature pneumatic transport of DRI or other abbrasive particles	18-Sep-01	Celada-Gonzalez, Juan Flores-Verdugo, Marco Aurelio Lopez-Gomez, Ronald Victor Manuel Montemayor-Silva, Rolando Soriano-Gutierrez, Alberto Diego	Company A	406/197	conveyors: fluid current / process
5,447,550	Method and apparatus for the pneumatic transport of iron-bearing particles	05-Sep-95	Leal-Cantu, Nestor Trevin-Garza, Rogelio Davila-Chavez, Agustin Zazueta-Aispuro, Alberto	Company A	75/379	(*) Specialized metallurgical processes, compositions for use there in, consolidated metal powder compositions, and loose metal particulate mixtures / of feed gas
5,445,363	Apparatus for the pneumatic transport of large iron-bearing particles	29-Aug-95	Becerra-Novoa, Jorge Viramontes-Brown, Ricardo Flores-Verdugo, Marco Aurelio Garza-Ondarza, Jose J.	Company A	266/182	Metallurgical apparatus / by fluid current
5,296,015	Method for the pneumatic transport of large iron-bearing particles	22-Mar-94	Becerra-Novoa, Jorge Viramontes-Brown, Ricardo Flores-Verdugo, Marco Aurelio Garza-Ondarza, Jose J.	Company A	75/10.66	(*)/producing or treating iron (Fe) or iron alloy
5,218,617	Apparatus for feeding iron-bearing materials to metallurgical furnaces	08-Jun-93	Herrera-Garcia, Marco A. de la Garza-Villarreal, Rodolfo A.	Company A	75/10.66	(*)/producing or treating iron (Fe) or iron alloy
4,897,113	Direct reduction process in reactor with hot discharge	30-Jan-90	Becerra-Novoa, Jorge Lopez-Gomez, Ronald Victor Manuel Dominguez-Ahedo, Carlos Chapa-Martinez, Leobardo	Company A	75/436	(*)/ with consolidation (i.e. pelletizing, etc) of solid metallic iron (Fe) product after reduction
4,734,128	Direct reduction reactor with hot discharge	29-Mar-88	Becerra-Novoa, Jorge Lopez-Gomez, Ronald Victor Manuel Dominguez-Ahedo, Carlos Chapa-Martinez, Leobardo	Company A	75/436	(*)/ with consolidation (i.e. pelletizing, etc) of solid metallic iron (Fe) product after reduction
4,725,309	Method and apparatus for producing hot direct reduced iron	16-Feb-88	MacKay, Patrick W Lopez-Gomez, Ronald Victor Manuel Prieto-de-la-Fuente, Raul Flores-Verdugo, Marco Aurelio	Company A	75/490	(*)/ solid iron (Fe) produced with shaft furnace
4,451,925	Charging system for electric arc furnaces	29-May-84	Sandoval, Jorge	Company A	373/81	Industrial electric heating furnaces / top charging

Source: United States Patent and Trademark Office (USPTO), Advanced Patent Search, Guidance, Tools, and Manuals, 2009.

Annex II.a – Main Data Set Used in Chapter 8

This database can be downloaded at:

http://sie.energia.gob.mx/sie/bdiController

SENER, Sistema de Informacion Energetica, Mexico

Balance nacional de energía, 2005 (petajoules)

Item	Coal	Crude Oil	Condensates	Natural Gas	Nuclear	Hydro	Geothermal	Wind	Cane Waste	Firewood	Total Primary Energy
Production	216.00	6,702.65	183.67	1,896.44	117.88	278.43	73.60	0.05	103.78	247.22	9,819.71
From other sources	0.00	0.00	0.00	581.95	0.00	0.00	0.00	0.00	0.00	0.00	581.95
Residual gas from gas plants	0.00	0.00	0.00	417.39	0.00	0.00	0.00	0.00	0.00	0.00	417.39
Formation gas used by PEP	0.00	0.00	0.00	164.56	0.00	0.00	0.00	0.00	0.00	0.00	164.56
Imports	190.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	190.35
Strock Variation	-27.24	-4.52	-0.03	8.40	0.00	0.00	0.00	0.00	0.00	0.00	-23.39
Total Suppy	379.11	6,698.12	183.64	2,486.79	117.88	278.43	73.60	0.05	103.78	247.22	10,568.63
Exports	-0.10	-3,672.49	-3.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-3,675.64
Non-Use	0.00	-0.20	0.00	-78.64	0.00	0.00	0.00	0.00	-1.13	0.00	-79.98
Assemby line - net trade	0.00	-163.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-163.69
Gross Domestic Suppy	379.01	2,861.74	180.59	2,408.14	117.88	278.43	73.60	0.05	102.65	247.22	6,649.32
Total transformation	-370.23	-2,826.99	-180.67	-1,694.87	-117.88	-278.43	-73.60	-0.05	0.00	0.00	-5,542.73
Coking Plants	-42.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-42.77
Refineries and despuntadoras	0.00	-2,826.99	-44.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2,871.81
Gas plants and fraccionadoras	0.00	0.00	-135.85	-1,694.87	0.00	0.00	0.00	0.00	0.00	0.00	-1,830.72
Electricity Power Stations CFE y LFC	-327.45	0.00	0.00	0.00	-117.88	-278.43	-73.60	-0.05	0.00	0.00	-797.42
Electricity Power Stations IPP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Own Cosumption within Sector	0.00	0.00	0.00	-117.92	0.00	0.00	0.00	0.00	0.00	0.00	-117.92
Interproducts - Transference	0.00	0.00	0.00	-349.75	0.00	0.00	0.00	0.00	0.00	0.00	-349.75
Re-circulation	0.00	0.00	0.00	-245.61	0.00	0.00	0.00	0.00	0.00	0.00	-245.61
Statistical Difference	-3.87	-6.89	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-10.68
Losses (transp.,dist. and storage)	0.00	-27.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-27.86
Total Final Consuption (as pure fuel)	4.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	102.65	247.22	354.78
Non Energy Final Consumption	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.30	0.00	2.30
Petrochemicals Pemex	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other economic industries	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.30	0.00	2.30
Energy Final Consuption	4.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.35	247.22	352.48
Residential, commercial & public	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	247.22	247.22
Transport	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Agriculcuture, Farming & Fishing	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Industrial	4.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.35	0.00	105.27
Pemex Petrochemicals	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other Industry Activities	4.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.35	0.00	105.27
Secondary Energy Gross Production											

Annex II.a – Main Data Set Used in Chapter 8 (continuation)

This database can be downloaded at:

http://sie.energia.gob.mx/sie/bdiController

SENER, Sistema de Informacion Energetica, Mexico

Balance nacional de energía, 2005 (petajoules)

Item	Coke	Pet Coke	Liquified Petroleum Gas	Gasolines and Napthas	Kerosene	Diesel	Fuel Oil	Non Energetic Products	Dry Gas	Electricit y	Total Secondary Energy	TOTAL
Production	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9,819.71
From other sources	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	581.95
Residual gas from gas plants	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	417.39
Formation gas used by PEP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	164.56
Imports	10.35	64.08	100.23	339.28	0.00	42.30	97.03	0.00	321.94	0.31	975.51	1,165.86
Strock Variation	19.38	-0.27	-0.60	-3.79	1.39	-8.23	2.10	-0.21	0.74	0.00	10.51	-12.88
Total Suppy	29.73	63.81	99.62	335.49	1.39	34.07	99.13	-0.21	322.68	0.31	986.01	11,554.64
Exports	-0.04	-2.34	-2.44	-140.54	-13.25	-1.64	-210.86	-3.47	-8.85	-4.65	-388.07	-4,063.71
Non-Use	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-79.98
Assemby line - net trade	0.00	0.00	0.00	110.93	0.00	6.83	0.00	0.00	0.00	0.00	117.75	-45.94
Gross Domestic Suppy	29.69	61.47	97.19	305.87	-11.86	39.26	-111.73	-3.67	313.83	-4.33	715.70	7,365.01
Total transformation	39.57	46.72	340.48	936.72	122.63	616.44	349.94	186.71	596.72	788.30	4,024.21	-1,518.52
Coking Plants	39.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.57	-3.21
Refineries and despuntadoras	0.00	46.72	43.14	780.41	120.65	630.18	972.94	101.76	90.98	0.00	2,786.78	-85.04
Gas plants and fraccionadoras	0.00	0.00	297.34	156.31	1.98	0.00	1.55	84.96	1,137.74	0.00	1,679.87	-150.85
Electricity Power Stations CFE y LFC	0.00	0.00	0.00	0.00	0.00	-13.26	-624.55	0.00	-295.22	617.76	-315.27	-1,112.69
Electricity Power Stations IPP	0.00	0.00	0.00	0.00	0.00	-0.48	0.00	0.00	-336.78	170.53	-166.73	-166.73
Own Cosumption within Sector	-0.88	0.00	-6.04	-12.11	-0.01	-32.17	-88.15	0.00	-343.90	-40.10	-523.36	-641.28
Interproducts - Transference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	349.75	0.00	349.75	0.00
Re-circulation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-405.71	0.00	-405.71	-651.32
Statistical Difference	0.00	0.00	0.00	16.03	2.62	-3.81	-6.92	-1.38	0.00	1.97	8.51	-2.17
Losses (transp.,dist. and storage)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-134.71	-134.71	-162.56
Total Final Consuption (as pure fuel)	68.38	108.18	431.62	1,246.50	113.38	619.72	143.13	181.66	510.69	611.13	4,034.39	4,389.17
Non Energy Final Consumption	0.00	0.00	0.96	51.49	0.00	0.00	0.00	181.66	70.16	0.00	304.28	306.57
Petrochemicals Pemex	0.00	0.00	0.03	49.79	0.00	0.00	0.00	70.39	70.16	0.00	190.38	190.38
Other economic industries	0.00	0.00	0.93	1.70	0.00	0.00	0.00	111.27	0.00	0.00	113.90	116.19
Energy Final Consuption	68.38	108.18	430.66	1,195.01	113.38	619.72	143.13	0.00	440.52	611.13	3,730.11	4,082.59
Residential, commercial & public	0.00	0.00	329.63	0.00	1.48	3.46	0.00	0.00	37.31	223.09	594.97	842.18
Transport	0.00	0.00	58.19	1,195.01	111.83	490.37	4.37	0.00	0.68	3.91	1,864.36	1,864.36
Agriculcuture, Farming & Fishing	0.00	0.00	8.05	0.00	0.04	85.38	0.00	0.00	0.00	29.04	122.52	122.52
Industrial	68.38	108.18	34.79	0.00	0.03	40.51	138.76	0.00	402.54	355.08	1,148.27	1,253.54
Pemex Petrochemicals	0.00	0.00	0.00	0.00	0.00	0.32	5.10	0.00	22.22	0.00	27.63	27.63
Other Industry Activities	68.38	108.18	34.79	0.00	0.03	40.19	133.66	0.00	380.32	355.08	1,120.64	1,225.90
Secondary Energy Gross Production	39.57	46.72	340.48	936.72	122.63	630.18	974.49	186.71	1,228.72	788.30	5,294.50	5,294.50

Annex II.b – Main Data Set Used in Chapter 9

This database can be downloaded at:
http://www.energia.gob.mx/webSener/res/PE_y_DT/pe/EM_PC_2005.xls

EMISIONES SECTOR ELÉCTRICO 2005

No	CENTRAL	Company	Tecnología	Capacidad [MW]	Generación (GWh/Año)	Combustoleo (103 m3/Año)	Gas Natural (106 m3/Año)	Diesel (103 m3/Año)	Carbón (103 ton/Año)
1	Presidente Juárez (Tijuana)	CFE	V.	620.0	3027.97	0.0	623.31	0.00	0.0
2	Punta Prieta II	CFE	V.	112.5	633.89	190.41	0.0	0.24	0.0
3	Puerto Libertad	CFE	V.	632.0	3517.52	875.96	0.0	2.04	0.0
4	J. A. Pozos (Mazatlán II)	CFE	V.	616.0	3693.83	913.97	0.0	1.55	0.0
5	C. Rodríguez R. (Guaymas II)	CFE	V.	484.0	1357.56	364.73	0.0	0.66	0.0
6	J. D. Batiz (Topolobanpo)	CFE	V.	360.0	2093.77	514.05	0.0	0.28	0.0
7	Guaymas I	CFE	V.	70.0	14.92	5.52	0.0	0.03	0.0
8	Francisco Villa (Delicias)	CFE	V.	399.0	1479.25	377.23	0.0	0.40	0.0
9	Guadalupe Victoria (Lerdo)	CFE	V.	320.0	2305.17	572.81	0.0	0.35	0.0
10	B. Juárez (Samalayuca)	CFE	V.	316.0	1559.90	403.02	0.78	0.0	0.0
11	La Laguna	CFE	V.	39.0	144.20	0.00	58.96	0.0	0.0
12	Emilio Portes Gil (Río Bravo)	CFE	V.	375.0	1513.47	195.44	196.28	0.0	0.0
13	M. Alvarez M. (Manzanillo I)	CFE	V.	1200.0	5846.36	1428.39	0.0	1.27	0.0
14	M. Alvarez M. (Manzanillo II)	CFE	V.	700.0	4331.28	1019.91	0.0	0.51	0.0
15	San Luis Potosi (Villa De Reyes)	CFE	V.	700.0	3243.04	791.07	0.0	2.10	0.0
16	Francisco Pérez Ríos (Tula)	CFE	V.	1500.0	8741.96	1848.96	340.723	0.0	0.0
17	Salamanca	CFE	V.	866.0	2545.61	427.06	272.00	0.0	0.0
18	Adolfo López Mateos (Tuxpan)	CFE	V.	2100.0	12589.05	2930.24	0.0	1.79	0.0
19	Altamira	CFE	V.	800.0	3776.21	970.49	7.25	0.00	0.0
20	Poza Rica	CFE	V.	117.0	591.45	188.38	0.0	0.0	0.0
21	Mérida	CFE	V.	168.0	1016.84	293.27	1.69	0.0	0.0
22	Campeche II (Lerma)	CFE	V.	150.0	728.99	233.86	0.0	0.14	0.0
23	Felipe Carrillo Puerto (Valladolid)	CFE	V.	75.0	467.01	144.00	0.00	0.18	0.0
24	Nachi-cocóm	CFE	V.	49.0	264.18	90.28	0.0	4.2	0.0
25	Valle de Mexico V.	CFE	V.	228.0	1523.24	0.0	451.3	0.0	0.0
26	Presidente Juárez (Rosarito)	CFE	C.C.	496	682.66	53.18	150.65	0.08	0.0
27	Gómez Palacio	CFE	C.C.	200	146.18	0.0	55.09	0.0	0.0
28	B. Juárez (Samalayuca II)	CFE	C.C.	521.8	4393.62	0.0	918.33	0.57	0.0
29	Chihuahua II (El Encino)	CFE	C.C.	423.3	3053.22	0.0	637.44	0.04	0.0
30	Huinalá	CFE	C.C.	377.7	954.24	0.0	256.77	0.0	0.0
31	Huinalá II	CFE	C.C.	450.2	2806.31	0.0	583.48	0.0	0.0
32	Francisco Pérez Ríos (Tula)	CFE	C.C.	489	2961.27	0.0	705.85	0.0	0.0
33	El Sauz	CFE	C.C.	218	3193.34	0.0	634.70	10.41	0.0
34	Dos Bocas	CFE	C.C.	452	2664.57	0.0	789.13	0.0	0.0
35	Felipe Carrillo Puerto (Valladolid)	CFE	C.C.	220	1047.12	0.0	183.6	94.68	0.0
36	Valle de México	LFC	C.C.	88.00	3218.41	0.0	814.81	0.0	0.0

Annex II.b – Main Data Set Used in Chapter 9 (continuation)

No	CENTRAL	Company	Tecnología	Capacidad [MW]	Generación (GWh/Año)	Combustoleo (103 m3/Año)	Gas Natural (106 m3/Año)	Diesel (103 m3/Año)	Carbón (103 ton/Año)
37	Río Escondido	CFE	C.E.	1200	9357.26	0.0	0.0	8.28	5077.05
38	Carbón II	CFE	C.E.	1400	9023.02	0.0	0.0	28.04	4517.07
39	A. Olachea (San Carlos)	CFE	C.I.	104.12	585.56	110.4	0.0	7.04	0.0
40	Santa Rosalía	CFE	C.I.	10.60	13.51	0.0	0.0	4.50	0.0
41	Guerrero Negro	CFE	C.I.	11.25	46.16	0.00	0.0	3.65	0.0
42	Yécora	CFE	C.I.	1.10	5.55	0.0	0.0	0.53	0.0
43	Holbox	CFE	C.I.	2.57	5.39	0.0	0.0	0.59	0.0
44	Villa Constitución	CFE	C.I.	2.57	7.65	0.0	0.0	2.44	0.0
45	Plutarco E. Calles (Petacalco)	CFE	D.	2100	14275.11	8.91	0.0	7.3	5322.83
46	Mexicali	CFE	T.G.	62.00	3.68	0.0	0.0	2.12	0.0
47	Presidente Juárez (Tijuana)	CFE	T.G.	210.00	61.60	0.0	23.62	0.0	0.0
48	Ciprés	CFE	T.G.	54.86	1.17	0.0	0.0	0.77	0.0
49	Punta Prieta I (La Paz)	CFE	T.G.	43.00	21.14	0.0	0.0	11.81	0.0
50	Ciudad Constitución	CFE	T.G.	33.22	19.51	0.0	0.0	9.69	0.0
51	Los Cabos	CFE	T.G.	30.00	61.06	0.0	0.0	27.52	0.0
52	Caborca Industrial	CFE	T.G.	42.00	3.04	0.0	0.0	1.36	0.0
53	Culiacán	CFE	T.G.	30.00	4.36	0.0	0.0	1.74	0.0
54	Ciudad Obregón	CFE	T.G.	28.00	3.75	0.0	0.0	1.86	0.0
55	Hermosillo	CFE	T.G.	131.89	165.09	0.0	47.45	0.0	0.0
56	Parque Juárez	CFE	T.G.	87.00	7.97	0.0	0.0	4.31	0.0
57	Chihuahua I	CFE	T.G.	64.00	4.06	0.0	0.0	2.2	0.0
58	Chávez	CFE	T.G.	28.00	10.18	0.0	5.06	0.01	0.0
59	Parque Juárez (Industrial)	CFE	T.G.	18.00	1.30	0.0	0.0	0.87	0.0
60	Monclova	CFE	T.G.	48.00	0.77	0.0	0.4	0.0	0.0
61	Universidad (Monterrey)	CFE	T.G.	24.00	0.38	0.0	0.23	0.0	0.0
62	Leona (Monterrey)	CFE	T.G.	24.00	0.23	0.0	0.16	0.0	0.0
63	Esperanzas	CFE	T.G.	12.00	0.03	0.0	0.0	0.02	0.0
64	Fundidora (Monterrey)	CFE	T.G.	12.00	0.19	0.0	0.0	0.0	0.0
65	Las Cruces	CFE	T.G.	43.00	0.88	0.0	0.0	0.43	0.0
66	Cancún	CFE	T.G.	102.00	87.33	0.0	0.0	37.64	0.0
67	Nizuc	CFE	T.G.	88.00	88.38	0.0	0.0	33.30	0.0
68	Chankanaab	CFE	T.G.	51.50	17.67	0.0	0.0	8.27	0.0
69	Ciudad Del Carmen	CFE	T.G.	14.00	5.02	0.0	0.0	2.50	0.0
70	Xul-Há	CFE	T.G.	14.00	0.64	0.0	0.0	0.35	0.0
71	San Lorenzo	CFE	T.G.	266.00	214.03	0.00	70.95	0.00	0.00

CFE= Comisión Federal de Electricidad
LFC= Luz y Fuerza del Centro
PEE= Productor Independiente de Electricidad

V.=Vapor
C.C=Ciclo Combinado
C.E=Carboeléctrica

D. =Dual
C.I=Combustión Interna
T.G=Turbogas

Annex II.c – Complementary Data Set Used in Chapter 9
Fuel Consumption in Electricity Generation in Mexico, 2005

This dataset can be downloaded at:
http://www.inegi.org.mx/prod_serv/contenidos/espanol/biblioteca/Default.asp?accion=1&upc=702825190170
El Sector Energetico en Mexico, Edicion 2005, INEGI.
Units in Tera joules

	Conventional thermal	**Internal Combustion**	**Turbogas**	**Combined Cycle**	**Coal based electricity**	**Dual**	**Nuclear**	**Total**
Fuel oil	561,102.3	5,447.6	0.0	0.0	0.0	340.5	0.0	566,890.4
Diesel	476.4	793.9	6,351.4	4,287.2	1,429.1	277.9	0.0	13,615.7
Gas	58,127.8	0.0	10,283.1	195,578.0	0.0	0.0	0.0	263,988.9
Coal	0.0	0.0	0.0	0.0	174,610.8	96,878.6	0.0	271,489.4
Uranium							138,127.6	138,127.6
TOTAL	619,706.5	6,241.5	16,634.5	199,865.1	176,039.9	97,496.9	138,127.6	1,254,112.1

Annex II.d – Main Data Set Used in Chapter 10

This dataset can be downloaded at:
Source : INEGI http://dgcnesyp.inegi.gob.mx/
Source: SENER http://sie.energia.gob.mx/sie/bdiController

Fuels and Materials in Overall Steel Industry

Year	Coal to coking plants (TJ)	MW Coal (tonnes)	Coke (tonnes)	Pig Iron (tonnes)	Limestone (tonnes) (a)	Dolomite (tonnes) (a)	Iron Ore (tonnes)	Sinter Product (tonnes) (a)	Coke Oven Gas (cum) (b)	Blast Furnace Gas (cum) (a)	Petroleum coke (TJ)
1980	97,456.0	**3,048,458**	**3,045,946**	3,639,000	**1,133,844**	**413,414**	**5,247,804**	**1,270,929**	**1,533,144,040**	**5,641,499,977**	0.0
1981	85,698.0	3,036,479	2,973,748	3,767,034	**1,173,737**	**427,959**	5,292,609	**1,315,645**	**1,496,804,050**	**5,839,989,619**	0.0
1982	88,165.0	3,199,671	3,019,104	3,598,014	**1,121,073**	**408,757**	5,382,239	**1,256,614**	**1,519,633,504**	**5,577,959,851**	0.0
1983	75,044.0	3,578,198	2,996,126	3,536,607	**1,101,940**	**401,781**	5,306,343	**1,235,168**	**1,508,067,775**	**5,482,761,283**	0.0
1984	71,045.0	3,454,622	2,927,480	3,926,108	**1,223,301**	**446,031**	5,489,343	**1,371,202**	**1,473,515,550**	**6,086,600,217**	0.0
1985	74,777.0	3,422,196	2,901,310	3,594,935	**1,120,114**	**408,408**	5,161,144	**1,255,539**	**1,460,343,162**	**5,573,186,512**	0.0
1986	81,645.0	3,101,220	2,604,000	3,737,540	**1,164,547**	**424,608**	4,817,410	**1,305,344**	**1,310,695,374**	**5,794,265,409**	0.0
1987	68,981.0	3,025,892	2,340,265	3,711,735	**1,156,507**	**421,677**	4,965,133	**1,296,331**	**1,177,947,200**	**5,754,260,213**	0.0
1988	72,206.0	2,340,279	2,332,245	3,678,230	**1,146,067**	**417,870**	5,564,492	**1,284,630**	**1,173,910,419**	**5,702,317,796**	0.0
1989	64,029.0	2,760,772	2,260,480	3,229,866	**1,006,365**	**366,933**	5,373,051	**1,128,038**	**1,137,788,279**	**5,007,224,228**	0.0
1990	67,832.0	3,008,795	2,337,159	3,664,723	**1,141,859**	**416,336**	5,327,890	**1,279,912**	**1,176,383,828**	**5,681,378,049**	0.0
1991	62,203.0	2,206,731	2,107,738	2,962,265	**922,986**	**336,532**	4,976,087	**1,034,577**	**1,060,907,237**	**4,592,365,465**	0.0
1992	59,976.0	1,606,977	2,033,003	3,403,596	**1,060,496**	**386,670**	5,154,046	**1,188,713**	**1,023,290,179**	**5,276,555,855**	0.0
1993	57,283.0	2,555,507	1,941,832	3,422,953	**1,066,528**	**388,869**	5,596,952	**1,195,474**	**977,400,238**	**5,306,564,790**	0.0
1994	58,552.0	3,172,446	1,984,730	3,500,780	**1,090,777**	**397,711**	5,516,193	**1,222,655**	**998,992,484**	**5,427,219,096**	0.0
1995	63,285.0	2,469,709	2,147,602	4,141,783	**1,290,502**	**470,533**	5,625,111	**1,446,527**	**1,080,972,352**	**6,420,958,697**	0.0
1996	64,638.0	2,946,287	2,184,363	4,228,940	**1,317,658**	**480,435**	6,109,453	**1,476,966**	**1,099,475,606**	**6,556,077,195**	0.0
1997	63,040.0	2,339,983	2,139,376	4,449,591	**1,386,409**	**505,502**	6,279,783	**1,554,029**	**1,076,831,884**	**6,898,149,910**	0.0
1998	63,150.0	2,610,355	2,202,558	4,531,531	**1,411,940**	**514,811**	6,334,257	**1,582,647**	**1,108,633,864**	**7,025,180,553**	0.0
1999	63,866.0	2,520,131	2,227,531	4,807,642	**1,497,971**	**546,179**	6,885,217	**1,679,079**	**1,121,203,754**	**7,453,232,270**	0.0
2000	64,081.0	5,995,083	2,235,032	4,855,876	**1,513,000**	**551,659**	6,795,406	**1,695,925**	**1,124,979,302**	**7,528,008,887**	5,108.0
2001	59,220.0	4,920,544	2,065,483	4,372,540	**1,362,401**	**496,749**	5,269,820	**1,527,119**	**1,039,638,638**	**6,778,698,628**	2,132.0
2002	57,281.5	4,856,843	1,451,091	3,996,297	**1,245,171**	**454,005**	5,965,427	**1,395,715**	**730,391,037**	**6,195,413,419**	3,055.0
2003	57,216.8	5,186,151	1,462,106	4,183,296	**1,303,436**	**475,249**	6,759,198	**1,461,025**	**735,935,319**	**6,485,315,825**	0.0
2004	56,496.0	4,340,966	1,445,052	4,278,110	**1,332,979**	**486,021**	6,889,538	**1,494,139**	**727,351,371**	**6,632,304,882**	0.0
2005	57,400.7	3,160,724	1,491,847	4,047,122	1,261,007	459,779	7,012,306	1,413,466	750,905,131	6,274,206,834	0.0
2006	58,710.5	2,739,905	1,569,561	3,789,809	**1,180,833**	**430,547**	6,589,586	**1,323,599**	**790,021,636**	**5,875,297,440**	5,812.8
2007	59,014.9	**2,729,096**	**1,531,455**	**3,790,688**	**1,181,107**	**430,646**	**6,645,371**	**1,323,906**	**770,841,184**	**5,876,659,688**	6,012.9

Annex II.d – Main Data Set Used in Chapter 10 (continuation)

This dataset can be downloaded at:
Source : INEGI
Source: SENER

Fuels and Materials in Overall Steel Industry

Year	LPG (TJ)	Kerosene (TJ)	Diesel (TJ)	Fuel oil (TJ)	Dry gas (TJ)	Steel Scrap (tonnes)	Sponge Ironr or DRI (tonnes)	Basic Oxigen Furnace steel t	Electric Arc Furnace steel t	Open Hearth Furnace (OHF) t	TOTAL finished steel	Total electricity (GWh)
1980	0.0	0.0	7,138.0	9,246.0	66,872.0	**900,081**	1,636,000	2,688,000	3,118,000	1,350,000	7,156,000	4,282.5
1981	0.0	0.0	7,644.0	9,901.0	71,610.0	959,750	1,685,960	2,971,264	3,373,474	1,318,000	7,662,738	4,594.2
1982	0.0	0.0	7,039.0	9,117.0	65,938.0	1,236,888	1,505,055	2,904,925	3,071,100	1,080,000	7,056,025	4,230.3
1983	0.0	0.0	6,961.0	9,016.0	65,209.0	1,121,326	1,497,296	2,965,820	3,200,694	811,000	6,977,514	4,184.2
1984	0.0	0.0	7,541.0	9,768.0	70,648.0	1,603,623	1,447,623	3,421,687	3,205,700	932,000	7,559,387	4,538.1
1985	0.0	0.0	7,381.0	9,560.0	69,143.0	2,399,995	1,500,370	3,139,114	3,240,537	1,019,000	7,398,651	4,479.4
1986	0.0	0.0	7,207.0	9,335.0	67,517.0	1,156,084	1,420,344	3,463,482	2,907,579	854,000	7,225,061	3,799.7
1987	80.0	255.0	7,406.0	10,011.0	75,460.0	1,378,234	1,550,785	2,967,308	3,366,426	1,309,000	7,642,734	4,221.4
1988	2,088.0	16.0	1,607.0	24,441.0	95,759.0	1,479,328	1,686,041	3,285,739	3,564,145	929,000	7,778,884	7,229.7
1989	4,725.0	0.0	2,009.0	26,573.0	74,820.0	1,568,667	2,163,621	2,964,653	4,065,647	821,000	7,851,300	8,092.8
1990	1,257.0	0.0	780.0	26,414.0	80,280.0	1,751,408	2,525,196	3,529,733	4,491,093	713,393	8,734,219	8,188.1
1991	931.0	0.0	680.0	24,668.0	77,959.0	1,709,259	2,409,940	3,124,869	4,576,814	262,333	7,964,016	6,623.3
1992	338.0	0.0	879.0	13,969.0	76,602.0	1,830,226	2,320,860	3,744,384	4,715,045	0	8,459,429	6,661.7
1993	298.0	0.0	871.0	17,246.0	65,121.0	2,012,204	2,737,184	3,749,202	5,449,582	0	9,198,784	5,226.7
1994	334.0	0.0	974.0	19,235.0	66,507.0	2,718,345	3,216,383	3,834,294	6,425,815	0	10,260,109	5,829.2
1995	397.0	0.0	1,183.0	19,967.0	68,689.0	2,980,537	3,700,317	4,541,751	7,605,695	0	12,147,446	7,047.8
1996	426.0	0.0	1,245.0	23,250.0	106,788.7	3,491,887	3,794,429	4,730,674	8,441,158	0	13,171,832	7,472.2
1997	439.0	0.0	1,282.0	23,941.0	119,323.5	3,756,512	4,439,772	4,964,358	9,253,981	0	14,218,339	7,694.2
1998	439.0	0.0	1,282.0	23,933.0	116,298.6	3,376,408	5,584,032	4,959,683	9,222,002	0	14,181,685	7,691.4
1999	908.0	0.0	1,284.0	20,828.0	127,225.6	3,499,441	6,070,490	5,245,129	10,029,058	0	15,274,187	8,622.2
2000	7.0	0.0	1,041.0	16,535.0	155,678.3	3,800,836	5,588,852	5,236,369	10,394,943	0	15,631,312	9,326.7
2001	6.0	0.0	827.0	13,143.0	117,028.0	4,015,453	3,672,347	4,771,431	8,528,576	0	13,300,007	7,413.1
2002	5.0	0.0	723.0	10,523.0	108,959.8	3,319,853	4,740,530	4,116,541	9,893,875	0	14,010,416	6,693.9
2003	5.0	0.0	736.0	10,712.1	114,598.1	4,036,732	5,473,338	4,590,942	10,567,826	0	15,158,768	6,814.4
2004	5.4	0.0	787.6	11,462.6	122,305.6	4,280,656	6,344,713	4,762,148	11,974,889	0	16,737,037	7,291.8
2005	5.4	0.0	790.8	11,510.1	122,812.3	4,232,225	5,973,217	4,504,541	11,777,758	0	16,282,299	7,322.0
2006	6.5	0.0	1,029.4	6,538.5	123,702.5	4,604,849	6,166,968	4,187,613	12,259,326	0	16,446,939	7,404.9
2007	7.1	0.0	1,105.1	7,691.5	128,929.1	**4,891,138**	**6,482,375**	**4,243,247**	**12,883,090**	0	17,126,336	7,657.6

Observations on Annex II.d:

Values in standard font are observed; values in blue bold font are simulated (i.e. extrapolated to compound annual growth rates for the period 1981-2006)
a) Assume that these materials in 2005 are proportional to pig iron production in a BF and that this proportion keeps constant along the period.
b) Amount of COG in 2005 is proportional to coke production in the previous years.
Primary sources of information are obtained from three different sources:

Data from INEGI:	Aggregated Plant Data (only 2005):	Data from Energy Balance Tables (SENER):
1) MW Coal	1) Limestone	1) Coal to coking plants
2) Coke	2) Dolomite	2) Petroleum coke
3) Pig Iron	3) Sinter Product	3) LPG
4) Iron Ore		4) Diesel
5) Steel scrap		5) Fuel oil
6) Sponge iron		6) Dry gas
7) BOF steel		
8) EAF steel		
9) OHF steel		

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