Sustainability Assessment of Electricity Options for Mexico: Current Situation and Future Scenarios

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Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BAU	Business as Usual
BWR	Boiling Water Rector
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CFE	Federal Electricity Commission
CHP	Combined Heat and Power
CML	Leiden Institute of Environmental Sciences
EIA	Energy Information Administration
EP	Eutrophication Potential
EPR	European Pressurised Reactor
EREC	European Renewable Energy Council
ESP	Electrostatic precipitator
FAETP	Freshwater Toxicity Potential
FGD	Flue Gas Desulphurisation
GHG	Greenhouse Gases
GT	Gas Turbine
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IAE	AInternational Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
INEGI	National Institute of Statistics and Geography of Mexico
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MAVT	Multi-Attribute Value Theory

MAETP	Marine Toxicity Potential
MCDA	Multi-Criteria Decision Analysis
MIT	Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NEB	National Energy Balance
NEEDS	New Energy Externalities Developments for Sustainability
NMVOC	Non-Methane Volatile Organic Compounds
NREL	National Renewable Energy Laboratory
ODP	Ozone Depletion Potential
OECD	Organisation for Economic Co-Operation and Development
PEMEX	Petroleum Mexican Company
PM	Particulate Matter
POCP	Photochemical Oxidation Potential
PWR	Pressurised Water Reactor
SCR	Selective catalytic reduction
SENER	Ministry of Energy of Mexico
SMART	Simple Multi-Attribute Rating Technique
ST	Steam Turbine
TETP	Terrestrial Toxicity Potential
UNFCCC	United Nations Framework Convention on Climate Change
WNC	World Nuclear Association

Sustainability Assessment of Electricity Options For Mexico: Current Situation and Future Scenarios

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Submitted for the degree of Doctor of Philosophy

Abstract

The aim of this research has been to identify the most sustainable options for electricity production in Mexico with an outlook to 2050. An integrated methodology for sustainability assessment of different electricity technologies and scenarios has been developed, taking into account environmental, economic and social aspects. The environmental impacts have been estimated using life cycle assessment; the economic costs considered include total capital and annualised costs while social aspects include security and diversity of energy supply, public acceptability, health and safety impacts and intergenerational issues. To help identify the most sustainable options, multi-criteria decision analysis has been used.

The methodology has been applied to Mexican conditions for the assessment of both current and future electricity production. The results for the current situation show that on a life cycle basis 129 million tonnes of CO_2 eq. are emitted annually from 225 TWh of electricity generated in Mexico. Heavy fuel oil, gas and coal power plants contribute together to 87% of CO_2 eq. emissions. Total annualised costs are estimated at US$ 22.4 billion/yr with the fuel costs contributing 54%, mainly due to the operation of gas and heavy fuel oil power plants.

A range of future scenarios up to 2050 has been developed in an attempt to identify the most sustainable options. The development of the scenarios has been driven and informed by the national greenhouse gas emission reduction target of 50% by 2050 on the 2000 levels, translating to an 85% reduction from the power sector. The results show that the business as usual (BAU) scenario (with the highest contribution from fossil fuels) is the least sustainable option with the CO_2 eq. emissions increasing by almost 300% for a projected electricity demand of 813 TWh in 2050.

Overall, the most sustainable scenarios are those with higher penetration of renewable energies (wind, solar and hydro) and nuclear power, as in Green, A-3 and C-3. For example, compared to the BAU scenarios, the CO_2 eq. emissions reduce by 84%, 89% and 89%, respectively. Although renewable energy based scenarios require high capital costs, the total annualised costs even out over time due to lower fuel costs. The lowest annualised costs are for C-3 and A-3 scenarios, representing a 40% reduction on BAU which is by far the most expensive option.

With respect to social issues, the BAU scenario is also the least preferred option with the highest risks related to security and diversity of supply, health and safety and climate change. The most sustainable options are scenarios A-3 and Green, with social barriers related to public acceptability, reliability of supply and availability of energy resource. Most critical aspects for scenario C-3 are health and safety risks, and intergenerational issues related to nuclear power. In the case of the energy policy driver focusing on climate change mitigation and annualised costs, scenarios A-3 and C-3 are the most sustainable options.. Therefore, the Mexican Government should aim to strengthen the current low carbon energy policies as well as put measures in place to encourage reducing the electricity demand.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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1.Introduction

Energy security and mitigation of climate change are key energy drivers for sustainable development (IEA/OECD, 2008). The increasing global energy demand, as a consequence of population and economic growth, has raised concerns in terms of security of energy supply due to a high dependence on fossil fuels and a depletion of fossil fuel reserves. Currently, ~80% of global energy demand is met by fossil fuels, mainly oil, gas and coal. If business as usual continues, the increasing CO_2 emissions could raise global average temperatures by 6°C, which would have critical impacts on the environment and consequently on all aspects of life (IPCC, 2007). It has been estimated that global CO_2 emissions should decrease by 50% - 80% by 2050 compared to 2000 levels to limit the global average temperature increase between 2.0 and 2.4°C (IPCC, 2007).

Like other countries, Mexico is also concerned about security of energy supply and the increasing greenhouse gas (GHG) emissions. Mexico's long-term target is to reduce the GHG emissions by 50% by 2050 relative to the emissions in 2000 (PECC, 2009). If achieved, Mexico would contribute to the stabilization of CO_2 concentrations in the atmosphere below 450 ppm.

The electricity sector is one of the significant contributors to GHG emissions in Mexico. In 2006, it emitted around 27% of the total energy-related GHG emissions (PECC, 2009). If business as usual continues, the sector would contribute up to 42% of national CO_2 emissions by 2050 (Greenpeace and EREC, 2008). Therefore, to achieve the 50% reduction of GHG emissions by 2050, the GHG emissions from electricity generation should be cut by 85% on year 2000, emitting only 16.2 Mt CO_2 eq. by 2050 (PECC, 2009). This is a very challenging target and will require significant reductions in the short and medium terms, particularly as the electricity demand is projected to grow (Greenpeace and EREC, 2008).

Both the energy supply and demand will play a crucial role in meeting GHG reduction targets (Krewitt et al., 2007, 2009). From the energy supply point of view, decarbonisation of the power sector will require a more diverse energy mix based on low-carbon technologies (renewable energies, nuclear power and carbon capture and storage) as well as energy efficiency improvements for all available power plant technologies (IEA/OECD, 2008). However, currently, it is not clear which options are most sustainable for future electricity supply in Mexico. Therefore, the aim of this research has been to identify the most sustainable options and scenarios for electricity production in Mexico with an outlook to 2050 by considering environmental, economic and social aspects.

The specific objectives have been:

- to develop an integrated methodology which would enable identification of most sustainable electricity options and scenarios for Mexico;
- to develop a life-cycle model of current electricity sector in Mexico (as a base case scenario) and to evaluate environmental and economical aspects;
- to identify low carbon technologies for electricity production in Mexico for the future; these include renewable energies, improved fossil fuels-based power plants with and without carbon capture and storage, and nuclear power;
- to develop future scenarios for electricity production in Mexico with an outlook to 2050 and to evaluate these considering environmental, economical and social aspects; and
- to identify the most sustainable future scenarios for Mexico through a multi-criteria assessment (MCDA) considering different sustainability indicators.

As far as the author is aware, this is the first study of its kind for Mexico. The main novelty of the work includes:

- an integrated methodology for sustainability assessment of electricity options – although the methodology has been applied to Mexican conditions, it is generic enough to be applicable to other countries;

- first ever life cycle assessment of the current electricity sector in Mexico (as published in Santoyo-Castelazo et al., 2011);
- scenario development to reduce GHG emissions from the Mexican power sector by 2050 for different reduction targets;
- life cycle environmental and socio-economic evaluation of different scenarios; and
- MCDA to help identify most sustainable electricity options for the future.

The dissertation is structured in the following way. Chapter 2 presents an overview of the Mexican energy sector, describing availability of energy resources, energy supply and demand, and energy consumption sectors. The current electricity sector is also described in this chapter, with information related to electricity generation by type of fuel and technology, as well as operating parameters of power plant technologies used in Mexico. An overview of sustainability aspects of power generation technologies is presented in Chapter 3. The proposed methodology for sustainability assessment of electricity scenarios is described in Chapter 4. Chapter 5 discusses the LCA and economic results of the current electricity sector. Future scenarios for electricity production in Mexico in 2050 are described in Chapter 6. Chapters 7 and 8 discuss the LCA results and socio-economic assessment of future scenarios. The MCDA of future scenarios using selected sustainability indicators is described in Chapter 9. Finally, the findings and the conclusions from this research are given in Chapter 10 along with a number of policy recommendations and suggestions for future work.

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2.Overview of the Mexican Energy Sector

In 2009, Mexico was the sixth-largest oil producer in the world. However, oil production in the country is beginning to decrease and the oil reserves are continuously declining. Consequently, Mexico is currently becoming more dependent on imports of gasoline, natural gas and other high-value secondary energy sources, while exporting significant amounts of crude oil (PEMEX, 2007; EIA, 2010). In addition, no significant increase has been observed in the use of renewable energies even though there is a large potential for the development of wind, solar, geothermal and hydro energy. At the same time, the oil sector is a crucial component of Mexico's economy, representing approximately one-third of government revenues (Huacuz, 2005; EIA, 2010). Therefore, sustainable energy options for Mexico must be identified, requiring a comprehensive analysis of the current energy situation. This chapter presents the current energy options in Mexico, in terms of the availability of energy resources, energy supply, demand, and consumption patterns. Given that the focus of this work is on electricity, it also gives an overview of the Mexican power sector and related information regarding current installed capacity and electricity generation, power plant technologies, and transmission and distribution of electricity in Mexico.

2.1 Background

Mexico is located in the northern part of the American Continent, together with Canada and United States (U.S.). It is adjacent in its northern part with the U.S. and south eastern part with Guatemala and Belize (Figure 2-1). The total Mexican surface area is ~1,964,375 km² (IAEA, 2005). Mexico has 32 states (indicated in the red capital letters in Figure 2-1) and its capital is Mexico City. Figure 2-1 also shows the state boundaries together with their main cities and roads.

Figure 2-1 Geographical location of Mexico together with its main states and cities (EIA, 2007).

Mexico is a developing country rich in natural energy resources including crude oil, natural gas, coal and renewable energy sources such as hydro, geothermal, wind, solar and others (e.g. Foster et al., 1998; Iglesias and Torres, 2003; Sheinbaum and Masera, 2004; Bertani, 2005; IAEA, 2005; Lund et al., 2005; Manzini, 2006; Islas et al., 2007; Ruiz et al., 2008).

In 2008, the National Institute of Statistics and Geography of Mexico (INEGI,) reported a population of ~107 million for Mexico (INEGI, 2008). During the last 50 years, the population growth has put significant economic, social and environmental pressures on the country (Medina-Ross et al., 2005).

According to the World Bank, Mexico's Gross Domestic Product (GDP) was estimated at US $874.9 billion in nominal exchange rates, and US $1.540 trillion in purchasing power parity (PPP). In 2009, Mexico was ranked as the 14th largest economy in the world in nominal terms, and 11th in PPP terms (Word bank, 2010a; 2010b).

The oil production is a crucial sector for Mexico’s economy representing over 15 percent of the country’s export earnings and more importantly for about one-third of total government revenues (EIA, 2010; Posma and Jonca, 2007; Reyes-Loya and Blanco, 2008). For the last 40 years (1968-2008), fossil fuels have been the primary energy source in the country (Figure 2-2). In this context, the term “fossil fuels” comprises crude oil, natural gas, coal and condensate resources. Crude oil and gas resources are by far the most important energy sources of the country (Nava et al., 2006; Kuntsi-Reunanen, 2007; SENER, 2009). On the other hand, “the term alternative sources” in Figure 2-2, include renewable energies (e.g. hydro, geothermal and biomass) and nuclear power.

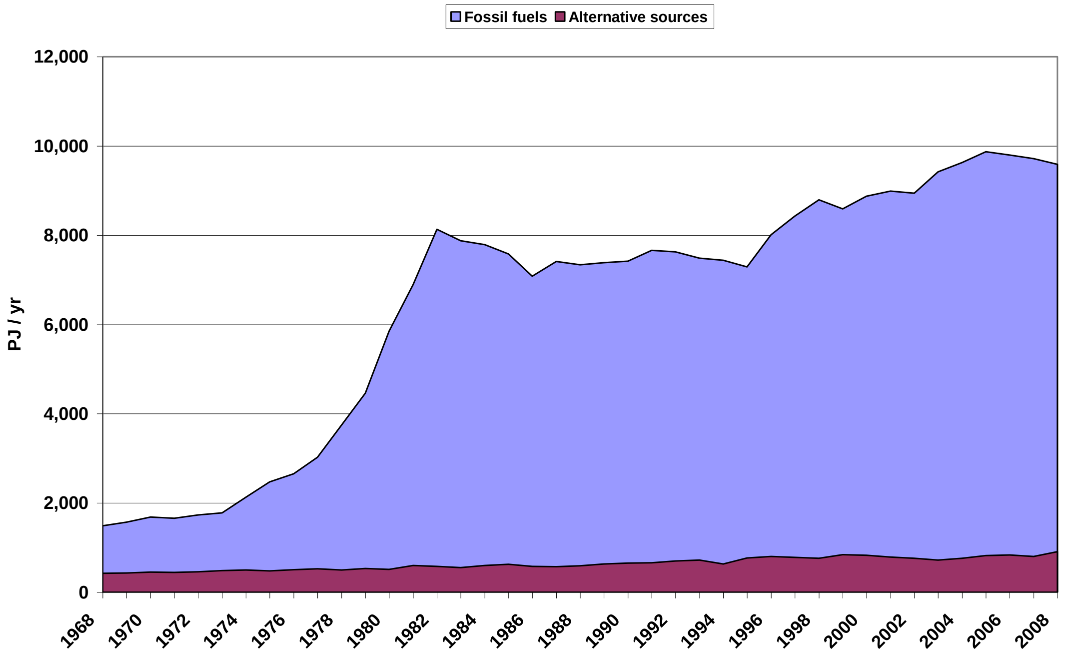

Figure 2-2 Primary energy production in Mexico from 1968 to 2008 (SENER, 2008a).

In 2009, Mexico was ranked sixth and 16th in the world for crude oil and natural gas production, respectively (EIA, 2010). The Petroleum Company of Mexico (PEMEX; Petróleos Mexicanos) is the state-owned company which is responsible for the oil production management in the country, and it is one of the largest oil companies in the world (EIA, 2010; Medina-Ross et al., 2005).

The high dependence on fossil fuels and the lack of a sustainable energy planning are serious concerns in Mexico (Bauer and Quintanilla, 2000; Aguayo and Gallagher, 2005; Bazán-Perkins and Fernández-Zayas, 2008). Although Mexico is recognised as one of the world's largest crude oil exporters, it is also a net importer of refined oil products (EIA, 2010; Bauer et al., 2003).

In 2009, Mexico imported 519,000 barrels per day (bbl/d) of refined petroleum products while exporting 1.23 million bbl/d of crude oil (EIA, 2010). Currently, the most critical aspect is the Mexico's proven oil reserves. These reserves have recently declined and many analysts believe that Mexican oil production has peaked, and thus the country's production will continue to decline in the coming years (e.g. Shields, 2003; Bazán-Perkins and Fernández-Zayas, 2008; Posma and Jonca, 2007; Reyes-Loya and Blanco, 2008; EIA, 2010). According to PEMEX (2008) and SENER (2009), Mexico's proven oil and gas reserves/production ratio will be insufficient to satisfy the national energy demand for more than nine years.

2.2 Energy reserves and production

2.2.1 Crude oil

According to the Energy Information Administration (EIA), Mexico had 10.4 billion barrels of proven oil reserves as of January 2010. Most reserves consist of heavy crude oil varieties. The largest concentration of remaining reserves has been detected offshore in the southern part of the country, especially in the Campeche basin (see Figure 2-1). There are also sizable reserves in Mexico's onshore basins in the northern parts of the country (Figure 2-1; EIA, 2010). Most of Mexico’s oil production takes place in the Gulf of Campeche, located off the south-eastern coast of the country in the Gulf of Mexico (see Figure 2-1). This area accounted for 80% of Mexico’s total crude oil production (EIA, 2010; Villasenor et al., 2003). Other important production sites are concentrated onshore basins in the northern and southern parts of the country (EIA, 2010).

There are currently six refineries in Mexico, all operated by PEMEX, with a total refining capacity of 1.68 million bbl/d (EIA, 2007; Marín-Sánchez, and Rodríguez-Toral, 2007). These refineries are: (i) Salamanca and Tula (located in the central area of the country, in Guanajuato and Hidalgo states, respectively); (ii) Cadereyta and Madero (located in the northeast part, in Nuevo Leon and Tamaulipas states, respectively); (iii) Minatitlán (located in the south part of the Gulf of Mexico, in Veracruz province); and (iv) Salina Cruz (located in the south pacific part of the country, in Oaxaca state (for the location of these refineries, see Figure 2-3).

Number	Refinery	Capacity	Area
1	Cadereyta	275	Región norte
2	Cd. Madero	190	Regiones del centro y Golfo
3	Minatitlán	185	Penisnusla de Yucatán y sureste de México
4	Salamanca	245	Regiones Centroy Occidente. Lubricantes a todo el país
5	Salina Cruz	330	Costa del Pacífico (combustibles)
6	Tula	315	Ciudad de México (combustibles)

Figure 2-3 Location of the main refineries in Mexico (GTEAN, 2006).

Atmospheric distillation accounts for the highest capacity process followed by vacuum distillation, reforming, catalytic and thermal cracking, hydrodesulphurization, visbreaking and natural gas liquids fractionating (IAEA, 2005). PEMEX also controls 50% of the 334,000-bbl/d capacity of Deer Park refinery in Texas (EIA, 2007).

PEMEX operates an extensive pipeline network in Mexico that connects major production centres with domestic refineries and export terminals. This network consists of over 453 pipelines spanning 4667 km, with the largest concentration of pipelines in the southern part of the country. There are no international pipeline connections so that most of exports leave from the country via tanker using three export terminals located in the southern part of the country: Cayo Arcas, Dos Bocas, and Coatzacoalcos (EIA, 2010).

Many analysts believe that Mexican oil production has peaked, and that it will decline in the coming years (e.g. Shields, 2003; Bazán-Perkins and Fernández-Zayas, 2008; Posma and Jonca, 2007; Reyes-Loya and Blanco, 2008; EIA, 2010). This decline is mainly driven by the production falling recorded at the super-giant Cantarell oil field, which is located in the Gulf of Campeche (see Figure 2-1). In 2006, 1.8 million bbl/d of crude oil were extracted from Cantarell which represented 55% of the national total production (EIA, 2007; Posma and Jonca, 2007; Reyes-Loya and Blanco, 2008), while in 2009, Cantarell’s production fell to 630,000 bbl/d (EIA, 2010).

According to internal reports and based on previous annual productions, Mexico’s oil proven reserves/production ratio has decreased from 13 years in 2002 to nine years in 2008 (PEMEX, 2008). Analysts believe that PEMEX does not have sufficient funds available for exploration and investment to reverse the decline, owing to the larger amount of its revenues that the company transfers to the federal government (Shields, 2003; EIA, 2007; Reyes-Loya and Blanco, 2008). In 2008, the Mexican federal government proposed a new legislation to reform the country’s oil sector, to increase current oil production. Among the most important changes, it is the fiscal reorganization of PEMEX to facilitate further technological investments for exploration and extraction of hydrocarbons (Posma and Jonca, 2007; SENER, 2008b; EIA, 2010).

2.2.2 Natural gas

According to EIA (2010), Mexico had 373.8 billion m^3 of proven natural gas reserves as of January 2010. The largest share of proven reserves is stored in the southern region of the country. However, the northern region is likely to be the most promising site for increasing the natural gas reserves, since it contains almost ten times as much probable and possible natural gas reserves as the southern region.

Mexico's natural gas production is spread throughout the country. Onshore fields in the northern part of the country represent 38% of Mexico's natural gas production, while onshore fields in the south contribute 21%, and offshore fields in the Gulf of Campeche represent the remainder. In 2008, Mexico produced 52.1 billion m^3 of natural gas, while consuming 66.8 billion m^3, with imports coming mainly via pipeline from the U.S. (EIA, 2010).

PEMEX operates over 9,173 km of natural gas pipelines in Mexico. The company has twelve natural gas processing centres with a liquids extraction capacity of 167 million m^3 per day (EIA, 2010). The Mexican gas processing system includes sweetening, cryogenic process, condensates sweetening, sulphur recuperation, fractionating and absorption plants (IAEA, 2005). PEMEX also operates most of the country's natural gas distribution network, which supplies processed natural gas to consumption centres. The natural gas pipeline network includes ten active import connections with the U.S. (EIA, 2010).

2.2.3 Coal

The coal reserves in Mexico are estimated to be ~663 million of tonnes (IAEA, 2005), which are distributed in four coal basins located in the states of Coahuila, Nuevo Leon, Oaxaca and Sonora (see Figure 2-1). Most of the thermal coal reserves are stored in the basin Villa de Fuentes-Río Escondido, Coahuila. This coal basin is located in the northeast region of Coahuila state, and it has been exploited through several opencast mines and underground mines. The proven reserves of coal have been quantified in 65 million tonnes of opencast mines, and 470 million tonnes of underground mines. The coal of this basin is characterised as bituminous coal (IAEA, 2005).

In Mexico, there are currently four coal plants which together provide a total installed capacity of 3.5 million tonnes (of coal (SENER, 2006a).

2.3 Alternative energy sources: current status and the potential

2.3.1 Current status

Hydroelectric and geothermal power are well established renewable energy technologies in Mexico, which in 2006 together represented 16.5% of total national electricity generation (Public sector; SENER, 2006a). The hydropower installed capacity is 10.9 GW of which approximately 300 MW corresponds to small hydro-plants (such as run-of-river). In terms of geothermal power, Mexico has an installed capacity of 960 MW, representing about the tenth of the worldwide current capacity (SENER-GTZ, 2009). In 2006, wind power produced 45 GWh/yr with an installed capacity of 23 MW (Public sector; SENER, 2006a).

In terms of biomass energy, wood and cane bagasse are by far the most used energy resources in Mexico, together representing about 344 PJ/yr of the total primary energy supply (SENER, 2006a). Wood is mainly applied for cooking and heating in rural households and in small cities contributing 29% of energy consumption in the residential sector in Mexico (SENER, 2006a). On the other hand, sugar cane bagasse is mainly applied for self-supply of heat and power in sugar cane mills in Mexico (SENER-GTZ, 2009).

In addition to renewable energies, nuclear power contributes 4.8% of total electricity production (Public sector; SENER, 2006a) with an installed capacity of 1,365 MW (CFE, 2010).

2.3.2 Energy potential

Biomass

The potential of biomass energy in Mexico is estimated between 3,000 and 4,500 PJ/year (Masera et al., 2006; Islas et al., 2007), and it is classified into i) wood fuels (from natural forests or plantations, forestry and the wood industry by-products), ii) agro-fuels and iii) biogas from landfills.

According to SENER-GTZ (2009), this potential would be enough to sustain the following energy activities:

- to meet energy needs of the population for cooking and heating through improved stoves, instead of open fires;
- to produce charcoal for domestic use, small business and to substitute coke in the steel industry;
- to generate approximately 50,000 GWh of electricity per year (e.g. small wood-fired power plants);
- to produce bioethanol and biodiesel, to meet 10% and 5% of the current demand for gasoline and diesel, respectively.

All these options, with exception of the production of biofuels, are considered economically feasible in Mexico (SENER-GTZ, 2009).

Hydropower

Excluding projects already in operation or in the planning stage, The Federal Electricity Commission (CFE) has identified a potential of 39 GW for large hydropower projects (CFE, 2000). Even though the technical, economical, environmental and social feasibility of this potential has not yet been defined, it can be assumed that at least 25% of this potential would be feasible to implement (SENER-GTZ, 2009).

A preliminary estimation indicates a potential of around 3 GW for small hydro-plants in Mexico, which would be economically feasible (Mulás et al., 2005; SENER-GTZ, 2009). According to SENER-GTZ (2009), there is also an unquantified existing potential for micro-hydro energy for supplying electricity to isolated communities (e.g. water pumping).

Geothermal energy

In terms of power generation, a potential of 12 GW for high enthalpy geothermal reservoirs has been estimated in Mexico (Alonso, 1985; SENER-GTZ, 2009). According to CFE, approximately 2,400 MW of this potential is economically feasible, depending on the development of technology for the exploitation of these reservoirs, (Greenpeace and EREC, 2008). On the other hand, Mercado et al. (1985) has estimated a potential of 45 GW for low enthalpy geothermal applications (e.g. heating for residential and industrial sectors).

Solar power

For solar thermal power plants, the average solar insolation in Mexico is 5 kWh/day/m², and in some cases 6 kWh/day/m² can be reached in certain northern regions of the country (Mulás et al., 2005). Assuming an efficiency of 15%, 25 km^2 in Chihuahua State or in the Sonora desert would be sufficient to supply all current electricity demand in the country (SENER-GTZ, 2009). However, the economic and financial feasibility of solar thermal power is still limited due to the high investment costs.

Nevertheless, Mexico is currently building a new integrated combined cycle solar system (ISCCS) with a thermoelectric solar field of 30 MW using solar parabolic trough technology (Cancino-Solorzano, 2010). This project, known as “Solar Thermal Project Agua Prieta II”, will be located in the State of Sonora (SENER-GTZ, 2009).

Photovoltaic (PV) systems are one of the most suitable power generation options for communities isolated from the electrical grid. In Mexico, almost all of the PV systems are located in rural communities with an estimated installed capacity of 18.5 MW, generating an average of 0.03 TJ/year (SENER-GTZ, 2009).

In addition, solar energy has been used for other thermal applications such as water heating. In Mexico, the demand for fluids heating in all sectors has been estimated in 230 PJ/year (SENER-GTZ, 2009). Assuming that half of this demand could be met with solar energy, the potential for solar collectors would be 35 million m² (PROCALSOL, 2007). In 2007, Mexico had an installed capacity of one million m² of solar water heaters (Weiss et al., 2009).

Wind power

It has been estimated that Mexico's wind power potential (onshore and offshore) exceeds 40 GW (Greenpeace & EREC, 2008). The states of Oaxaca, Yucatan and Baja California, have been identified as the regions with the greatest potential (NREL, 2003, 2009; Greenpeace & EREC, 2008).

Ocean energy

In Mexico, there are no current power plants or projects under development utilising ocean energy (Cancino-Solórzano et al., 2010). According to Alcocer and Hiriart (2008), there is a great potential to produce electricity from tidal energy in the region of the Peninsula of Baja California in Mexico. The potential of other forms of ocean energy, such as wave power, has not been evaluated yet within the country (Greenpeace-EREC, 2008; SENER-GTZ, 2009).

The renewable energy potential data from all available sources in Mexico presented in this section has been used further in Chapter 6.

Nuclear energy

Around 2,000 tonnes of confirmed uranium reserves are available in Mexico. However, at present, there are no plans for the mining of the Mexican uranium reserves due to high production costs (IAEA, 2010).

In Mexico, there is one nuclear power plant in operation producing 10,866 GWh/yr with an effective power capacity of 1365 MW (SENER, 2006b). The uranium used in the nuclear power plant of Laguna Verde is actually imported. It is bought, either as hexafluoride or as concentrate that is converted to hexafluoride, from Comurhex in France. Enrichment and fuel fabrication are carried out in U.S. by the U.S. Department of Energy and General Electric, respectively (IAEA, 2010).

2.4 National energy balance

The Mexican Ministry of Energy (SENER, Secretaría de Energía) is the government institution responsible for the management of the energy sector and its resources. Current information related to the Mexican Energy Sector is reported by SENER in the National Energy Balance (SENER, 2006a). This energy balance reports production data and statistics of the main energy activities, such as energy production (primary and secondary resources), energy export and import, gross domestic energy supply, and the national energy demand and consumption. A diagram showing the structure of the national energy balance of Mexico is presented in Figure 2-4.

Before describing the national energy balance it is important to note the difference between the terms “primary” and “secondary” energy. The former is defined as energy which has been extracted directly from natural resources; examples of these are: oil, coal and gas, uranium and all forms of renewable energy such as hydro and geothermal energy (IEA/OECD, 2005). On the other hand, secondary energy refers to energy produced from the transformation or processing of primary energy; an example is electricity generation from the combustion of natural gas or transformation from hydro energy. Other examples of secondary energy are the production of oil products such as gasoline from crude oil refining and the production of coke from coal.

As shown in Figure 2-4, the first stage of the national energy balance is the production of primary energy, followed by its processing into secondary energy and the consumption of primary and secondary energy by end-use sector. The energy mix for electricity production presented in Figure 2-4 has been used further in Chapter 5.

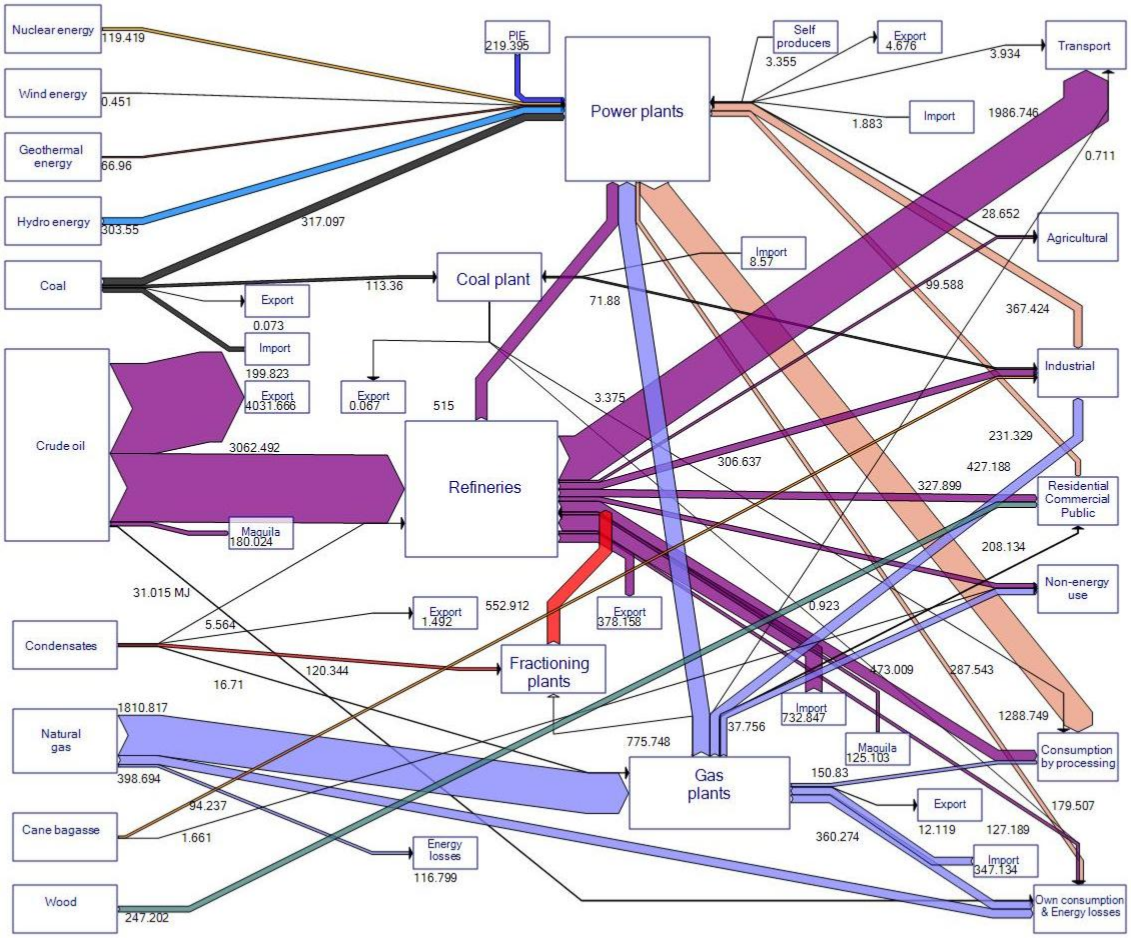

Figure 2-4 National energy balance for Mexico for year 2006 presented in PJ units (SENER, 2006a)

2.4.1 Primary energy

In 2006, the total primary energy production was quantified as 10,619 PJ, of which 9,784 PJ were generated by fossil fuels, 715 PJ by renewable energy sources, and the remaining 119 PJ by nuclear fuel. The total primary energy by source is represented in Figure 2-5.

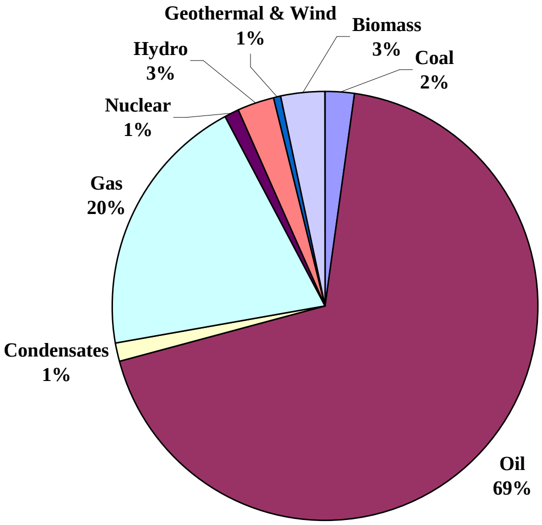

Figure 2-5 Primary energy production for Mexico in 2006 (SENER, 2006a).

From Figure 2-5, it can be seen that crude oil was by far the main primary source (7304 PJ) followed by natural gas (2108 PJ), hydro energy (303 PJ), biomass (344 PJ) and coal (230 PJ). From the production of renewable energies, besides hydro and biomass, geothermal energy had a significant contribution to the total production (67 PJ). Even though wind energy production was about 0.4 PJ in 2006, representing just 0.004% of the total, in the last ten years (1997-2006) its contribution has increased on average by 27% annually.

As mentioned in section 2.3.1, in 2006 biomass energy production was mainly dominated by wood, followed by cane bagasse (247 PJ and 97 PJ, respectively). These resources are directly consumed as end-use energy in the residential and industrial sectors, mainly as a source of heating and on a smaller scale to produce electricity (SENER-GTZ, 2009).

In 2006, crude oil exports accounted for 4211 PJ, representing 40% of total primary energy production. According to SENER (2006a), 80% of crude oil exports were to U.S., 10% to Europe, 6% to Central and South America, 2% to Canada, and the remaining 2% to other regions of Asia.

Regarding the energy imports, in 2006 only 200 PJ of coal were imported. Energy losses from primary energy production accounted for 118 PJ, mainly due to gas flaring and venting during extraction of oil and gas (SENER, 2006a). In 2006, SENER reported a total primary energy supply (TPES) of 7071 PJ, from which crude oil and natural gas represented ~82% of TPES (see Table 2-1).

Table 2-1 Primary energy supply for Mexico in 2006 (SENER, 2006a).

Energy	PJ	%
Coal	380	5.4
Oil	3108	43.9
Condensates	140	2.0
Gas	2611	36.9
Nuclear	119	1.7
Hydro	304	4.3
Geothermal	67	0.9
Wind	0.45	0.006
Cane bagasse	96	1.4
Wood	247	3.5
Total	7071	100.0

The primary energy supply has two main destinations (Figure 2-4): (1) the energy sent to the processing centres (83% of TPES), and (2) the energy used by end-use sectors, as energy resources and raw materials (5% of TPES). The remainder corresponds mainly to the energy sector own use, energy distribution losses, energy recirculation and transfers (SENER, 2006a).

2.4.2 Secondary energy

In 2006, SENER reported a total secondary energy production of 5,237 PJ, from which 1,338 PJ corresponded to natural gas, 949 PJ to petrol and naphtha, 810 PJ to electricity, 767 PJ to heavy fuel oil, 650 PJ to diesel, 332 PJ to liquefied petroleum gas (LPG), 175 PJ to non-energy products (used as raw material), 124 PJ kerosene, and 92 PJ to coke (from oil and coal) (SENER, 2006a). Figure 2-6 shows the secondary energy production mix.

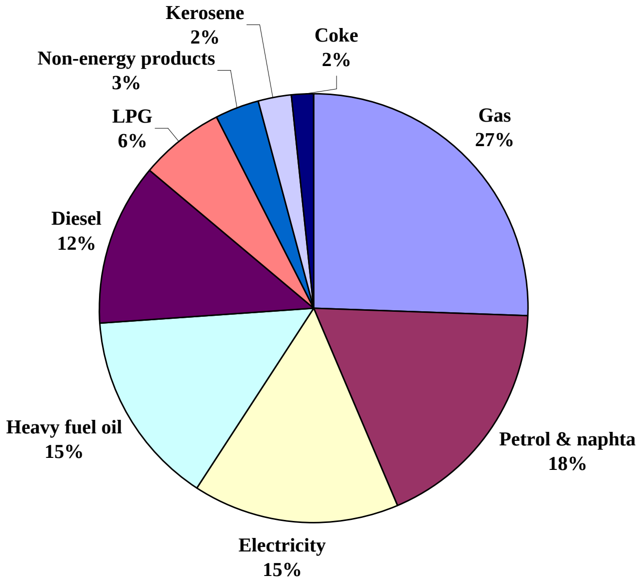

Figure 2-6 Secondary energy production for Mexico in 2006 (SENER, 2006a).

According to SENER (2006a), total secondary energy imports accounts for 1,215 PJ of which petrol had the largest contribution (505 PJ) followed by gas (347 PJ). In 2006, SENER reported 395 PJ of secondary energy exports, which mainly corresponded to heavy fuel oil (196 PJ).

Table 2-2 Secondary energy imports and exports for Mexico in 2006 (SENER, 2006a).

Energy	Imports (PJ)	Exports (PJ)
Coke from coal	9	0.1
Coke from oil	88	3
LPG	111	3
Petrol and naphta	505	154
Kerosene	0.3	12
Diesel	82	5
Heavy fue oil	71	196
Non-energy products	--	4
Gas	347	12
Electricity	2	5
Total	**1215**	**395**

Energy losses during energy processing, the sector's own secondary energy use, together with the transport and distribution energy losses, accounted for 2,740 PJ (SENER, 2006a). Table 2-3 shows the gross domestic energy supply (GDES), which considers the secondary energy resources and primary energy available in Mexico for final consumption.

Table 2-3 Gross domestic energy supply for Mexico in 2006 (SENER, 2006a)

Product	PJ	%
Petrol & naphtha	1328	29.4
Diesel	665	14.7
Electricity	631	14.0
Gas	544	12.0
LPG	420	9.3
Wood	246	5.4
Coke from oil	123	2.7
Kerosene	119	2.6
Heavy fuel oil	114	2.5
Cane bagasse	95	2.1
Coke from coal	72	1.6
Coal	4	0.1
Non-energy products	159	3.5
Total	**4520**	**100.0**

2.4.3 Energy consumption

In 2006, the total energy consumption was quantified as 4,520 PJ (primary and secondary energy) (SENER, 2006a). This consumption is classified as i) final energy use, representing 94% of total and ii) non-energy use, with the remainder of 6% (SENER, 2006a).

The final energy use is distributed to four end-use sectors: i) transport, ii) industrial, iii) the aggregated residential (including residential households, commercial and public subsectors) and iv) agriculture (see Figure 2-7). The non-energy consumption consists of gas, ethane, propane, butane and petrol being used as raw materials by PEMEX and other industries (SENER, 2006a).

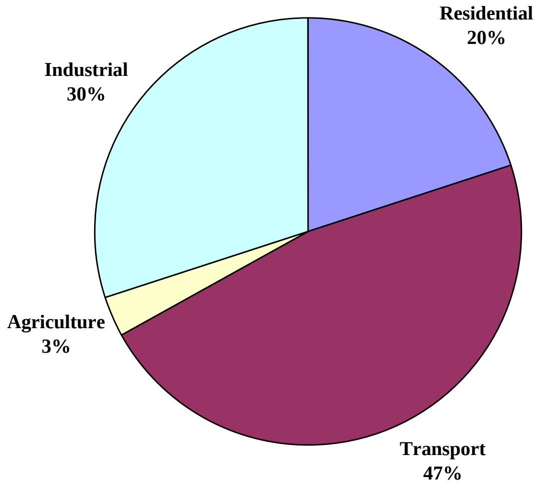

Figure 2-7 Final energy consumption by end-use sectors for Mexico in 2006 (SENER, 2006a).

The transport sector was the highest energy consumer accounting for 1,991 PJ, followed by industrial sector 1,273 PJ, the aggregated residential sector 844 PJ and the agriculture sector 128 PJ (SENER, 2006a).

From the energy resources consumed by transport sector, petrol accounts for 1,278 PJ, diesel 532 PJ, kerosene 116, LPG 56 PJ, heavy fuel oil 3 PJ, electricity 4 PJ, and gas 0.7 PJ (see Figure 2-8). "Other" in Fig. 2.8 corresponds to heavy fuel oil, electricity and gas.

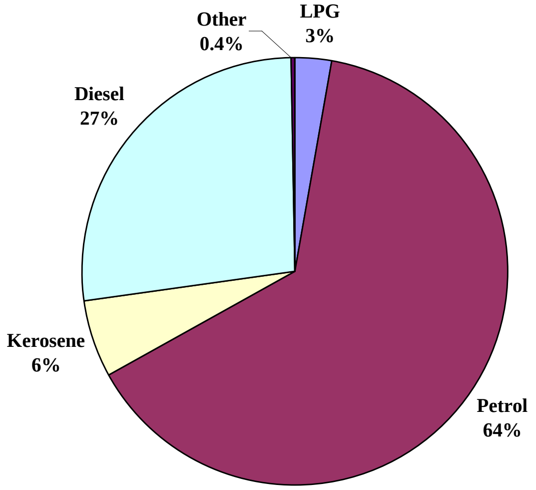

Figure 2-8 Fuel consumption by transport sector of Mexico in 2006 (SENER, 2006a).

According to SENER (2006a), the industry sector is divided mainly into 16 sub-sectors: PEMEX petrochemicals, iron and steel, chemicals, sugar, cement, paper and cellulose, glass, fertilizers, malt and beer, mining, bottled soft drinks, construction, automotive, rubber, aluminium, tobacco.

In 2006, the industrial sector energy consumption was as follows: natural gas 427 PJ, electricity 367 PJ, coke 195 PJ, cane bagasse 94 PJ, heavy fuel oil 111 PJ, diesel 39 PJ, LPG 34 PJ, coal 6 PJ and kerosene 0.04 PJ (see Figure 2-9). “Other” in Figure 2-9 corresponds to coal and kerosene.

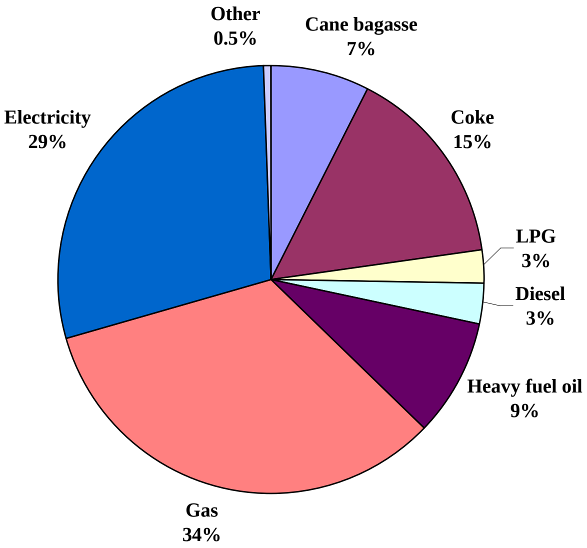

Figure 2-9 Fuel consumption by industry sector of Mexico in 2006 (SENER, 2006a).

The aggregated residential sector energy consumption accounted for 844 PJ, of which 83% corresponded to the residential households subsector, commercial 14% and 3% to public services (SENER, 2006a). From the fuel consumption point of view, LPG represented 322 PJ, wood 247 PJ, electricity 231 PJ, natural gas 38 PJ, diesel 4 PJ and kerosene 1.8 PJ (see Figure 2-10). “Other” in Figure 2-10 corresponds to diesel and kerosene.

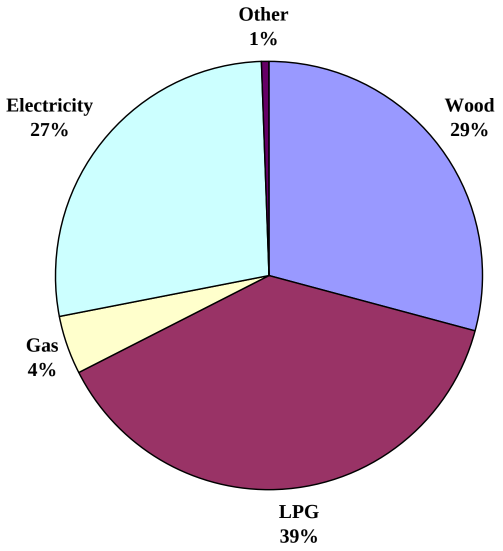

Figure 2-10 Fuel consumption by the aggregated residential sector of Mexico in 2006 (SENER, 2006a)

The energy consumed by the aggregated residential sector is classified into different end uses such as: cooking, water heating, lighting, refrigeration, electric domestic appliances and air conditioning. The energy consumption of the public sector is mainly represented by the electricity consumption for lighting and water pumping.

According to SENER (2006a), the energy resources used in agricultural sector are diesel accounting for 92 PJ, electricity 29 PJ, LPG 8 PJ, and a small contribution from kerosene 0.05 PJ (see Figure 2-11).

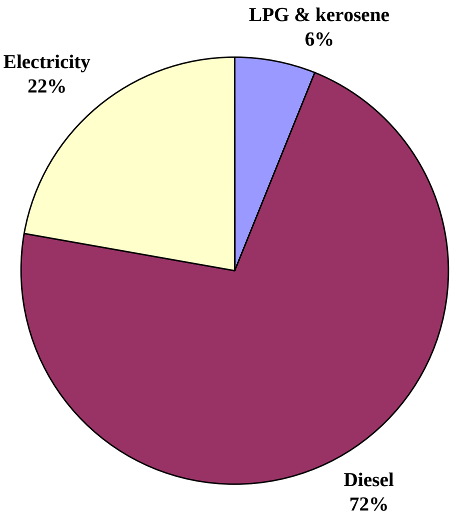

Figure 2-11 Fuel consumption by agricultural sector of Mexico in 2006 (SENER, 2006a).

Production and consumption of electricity is an important energy activity in all end-use sectors in Mexico (as shown in Figures 2-9-2-11). It contributes to a number of services (e.g. lighting, heating and cooling) but also negative impacts to the environment and human health in Mexico (López et al., 2005; Santoyo-Castelazo et al., 2011). For this reason, it is important to assess the sustainability aspects of electricity production in Mexico along its life cycle. The next section gives an overview of the Mexican power sector. Information from the Mexican energy balance (electricity production mix; Figure 2-4) and renewable energy potential (section 2.3.2) have been used for the life cycle modelling of current and future scenarios for electricity generation in Mexico. These will be discussed further in Chapters 5 and 6.

2.5 The Mexican Power Sector

In 2006, the base year considered in this work, fossil fuels contributed 79% of the total electricity generation (mainly from steam turbine and combined cycle power plant technologies). Other sources include hydro (13.5%), nuclear (4.8%), geothermal (3%) and wind power (0.02%; SENER, 2006a). The electricity mix by fuel type is shown in Figure 2-12.

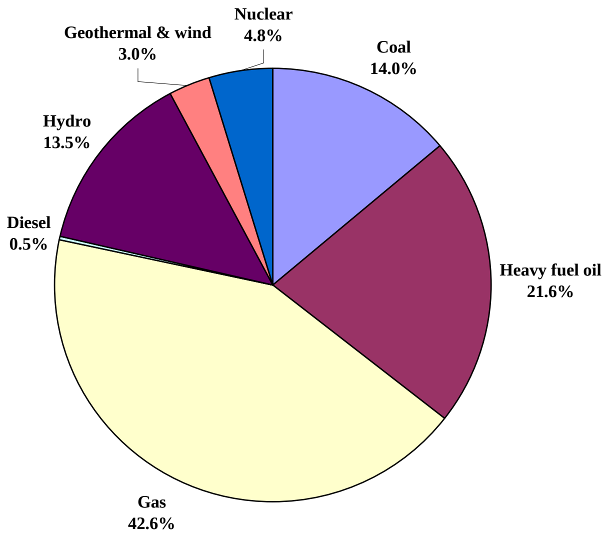

Figure 2-12 Contribution of different fuels to the electricity mix in Mexico (SENER, 2006a).

The electricity in Mexico is provided by the National Electric System (SEN, Sistema Eléctrico Nacional), consisting of both public and private producers. In 2006, the total installed capacity was 56 337 MW, of which 48 790 MW was in the public sector and 7 569 MW in the private sector (SENER, 2006b).

The public sector integrates the Federal Electricity Commission (CFE, Comisión Federal de Electricidad) and the Independent Energy Producers. CFE owns 69% of the total SEN-installed capacity (see Figure 2-13). The Independent Energy Producers (PIE, Productores de Energía Independientes) deliver their energy to CFE, which is responsible for the electricity transmission and distribution throughout the country. CFE currently supplies electricity to 95% of the nation. The remainder corresponds to rural populations living in remote and hard-to-access places with no access to the grid (Huacuz, 2005).

On the other hand, the private sector brings together the modalities of cogeneration, self-production, own-consumption and electricity export. Of these, self-producers contribute the highest percentage of 7% (Figure 2-13).

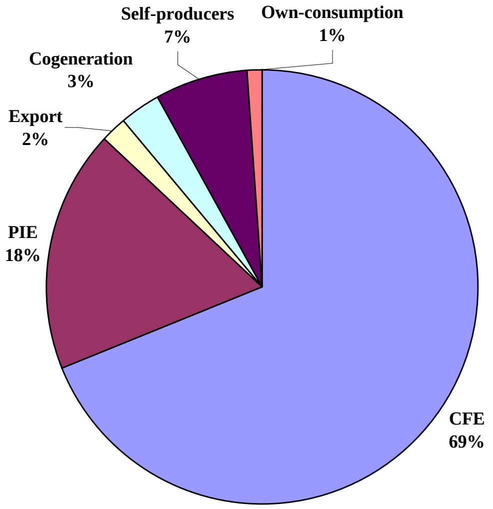

Figure 2-13 SEN installed effective capacity (SENER, 2006b)

In 2006, the total electricity generation (public and private sectors) accounted for 256,422 GWh, of which ~88% corresponded to the public sector (225,079 GWh), 6% to self-production, 3% from cogeneration, 2.7% to export and 0.5% of total was for own-consumption (SENER, 2006b).

In the same year, the public sector had an installed capacity of ~48,790 MW (SENER, 2006b; CFE, 2007). Table 2-4 lists the different types of technologies deployed in the Mexican electricity sector.

Table 2-4 Energy technologies used for electricity generation in Mexico in 2006 (SENER, 2006a; 2006b)

Power plant technology	Total capacity (MW)	Capacity factor (%)	Electrical efficiency (%)	Generation (GWh)
Coal-fired steam turbine (CST)	2600	79	35.8	17 931
Dual steam turbine (DST)[a]	2100	75	35.8[d]	13 875
Fuel oil & gas steam turbine (OGST)[b]	12 895	46	34.9[e]	51 931
Gas combined cycle (CC)	15 590	67	44.5[f]	91 064
Gas turbine (GT)	2509	7	44.5[g]	1523
Diesel combustion engine (CE)	182	54	37.5	854
Hydroelectric dam (HD)	10 566	33	35.9	30 305
Geothermal steam turbine (GST)	960	79	35.9	6685
Wind turbine (WT)[c]	23	23	35.9	45
Nuclear (Boiling Water Reactor)	1365	91	32.8	10 866
Total	**48 790**			**225 079**

[a] DST operates as a coal-fired steam turbine power plant but it can use either coal or heavy fuel oil. In 2006, the mixture was 99.5% coal and 0.5% heavy fuel oil (SENER, 2006b).
[b] Approx. 94% of total OGST power generation is from heavy fuel oil and the remainder from gas.
[c] SENER (2006b) reported a generated capacity value of 2 MW. This value is incorrect as it does not match the electricity generation of 45 GWh/yr. Therefore, a correction has been made in this work by using 22.5 MW. This value was estimated assuming an operating time of 2000 hours per year.
[d] Refers only to the electricity production from coal (the efficiency for a mix coal-heavy fuel oil has not been available)
[e] Refers only to the electricity production from heavy fuel oil (the efficiency for the gas steam turbine power plants has not been available)
[f] Assumed that all gas power is from the combined cycle power plants.
[g] Assumes the same efficiency as for the gas combined cycle power plants.
[h] The capacity factor of a power plant is the ratio of the actual electricity output over a period of time divided by the amount of electricity produced if it had run at full power over that period (Chatzimouratidis and Pilavachi, 2009).

Figure 2-14 shows how the electricity mix in Mexico changed over time, from 1996 – 2006. The contribution of natural gas increased from 12.1% in 1996 to 42.6% in 2006, representing an average annual growth rate of 17.9%. At the same time, the contribution of heavy fuel oil decreased from 46.1% to 21.6%, equivalent to an average annual decrease of 3.6%. This is mainly due to the introduction of the combined-cycle (CC) natural gas power plants and the refurbishing of oil steam turbine (ST) power plants to replace heavy fuel oil. In 2006, the CC and ST power plants accounted for about 78% of the total electricity generated. The contribution of other sources remained more or less the same over the period. To date, the electricity mix has remained more or less the same as in 2006 and a similar trend is expected over the next few years (SENER, 2006b).

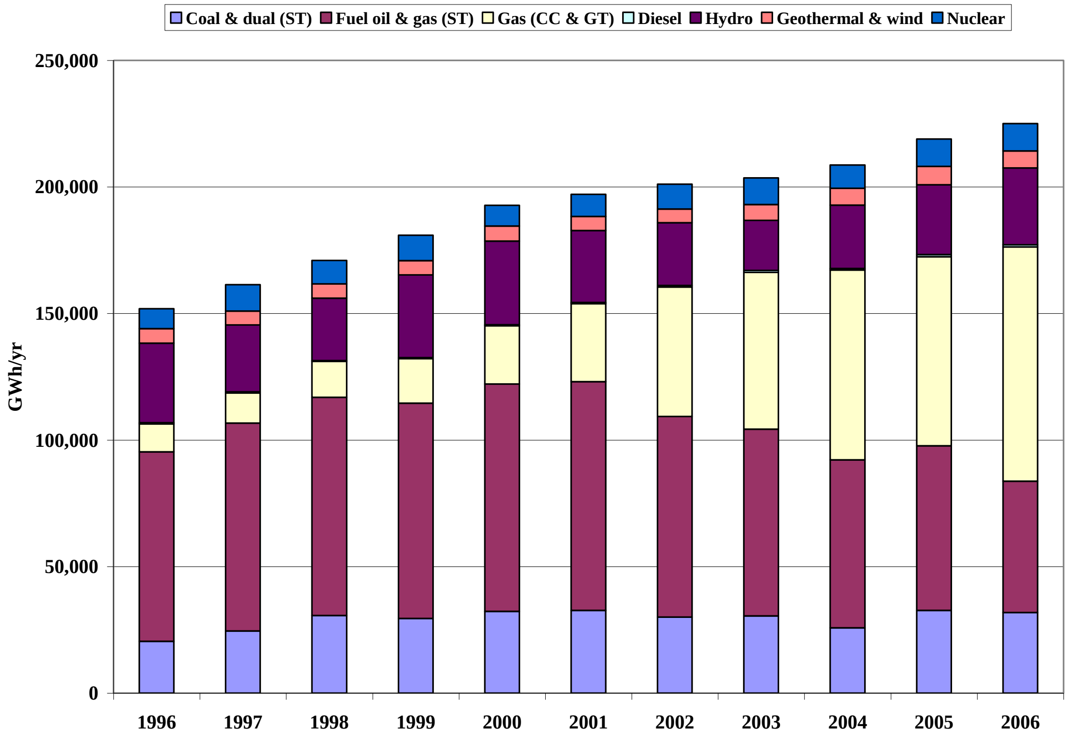

Figure 2-14 Electricity generated by the Mexican power sector (1996-2006); SENER, 2006b

2.5.1 Transmission and distribution

CFE is the only company responsible for distributing the electricity in Mexico (CFE, 2007). The transmission and distribution lines are classified into high, medium and low voltage conduction lines (CFE, 2007). In 2007, the transmission lines network reached 48,566 km; while the length of sub-transmission, and distribution lines accounted for 47,141 km and 619,705 km, respectively (SENER, 2006b).

2.6 Summary

The energy sector is an important sector for sustainable development, as it provides primary services (e.g., transport, heating, cooling, cooking), and it is an essential factor for economic growth and social well being.

The Mexican energy sector is strongly based on fossil fuels (~91% of total primary energy production), which mainly contributes to environmental pollution as well as energy security issues. Even though Mexico is one of the most important world oil exporters, it still depends on imports of high-value added fuels such as petrol and natural gas. This energy dependence is mainly due to the insufficient national refining capacity along with the growing country's energy demand.

Even though Mexican fossil fuel reserves are estimated to last no more than nine years, electricity generation in Mexico is mainly based on the use of natural gas, heavy fuel oil and coal. In 2006, these resources together with coal represented 79% of total electricity generation. Moreover, to meet the electricity demand of the country, the Mexican government has projected to increase the installed capacity of power plants based on a gas combined cycle technology. According to SENER, this technology will represent ~54% of total generation by 2016. This fact will lead to a major dependence on natural gas, which opens questions about security of future supply due to the price volatility and availability of natural gas.

In addition, the production and use of fossil fuels have negative environmental effects at the local, regional and national levels; for example, combustion of fossil fuels and wood leads to indoor and outdoor pollution and it generates considerable amounts of GHG emissions.

In spite of the abundance of renewable energy resources, renewable energy installations are minimal. Opportunities to use renewable sources as part of the Mexican energy mix are many, and could bring environmental, economic, and social benefits. These aspects have been assessed in this work.

To secure a more sustainable energy supply for the country, it is essential to consider alternative cleaner energy sources, both for electricity generation and for energy end-uses (in residential, transport and industrial sectors). Prior to that, it is important to first examine the country's current energy technology status, and then to carry out a feasibility study for the application of cleaner and more efficient energy technologies. The next chapter gives an overview of the sustainability aspects of current and future technologies for power generation.

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3. Life cycle sustainability aspects of electricity generation by different technologies: An overview

There are a number of technologies for power generation that are well established and widely used, including coal, gas and nuclear as well as mature renewable technologies such as hydro and geothermal power. Other technologies, such as wind, biomass and solar power are developing fast and becoming more economically competitive; thus their application is increasing worldwide. Other emerging technologies such as marine and carbon capture and storage are quite promising but still in development. This chapter provides an overview of all main available and future power generation technologies and discusses their main life cycle environmental, economic and social aspects as an introduction to the work carried out within this research. The information provided here is then used as an input for the sustainability assessment of different electricity options discussed in the subsequent chapters.

3.1 Introduction

The power sector is one of the most significant contributors to greenhouse gas (GHG) emissions globally and is therefore in focus for GHG reductions. For example, in 2007, it contributed to 41% of energy-related global CO_2 emissions with total emissions of ~10 Gt; this is projected to increase up to more than 20 Gt by 2050 if business as usual continues (IEA/OECD, 2008a, 2010a). To reverse this trend and meet the global targets for the reduction of GHG emissions, a decarbonisation of the power sector will be required. From the energy-supply point of view, this can be achieved in various ways, including the use of more diverse low-carbon energy technologies (e.g., renewable energies and nuclear power), major energy efficiency improvements and the use of Carbon Capture and Storage (CCS). However, in the short to medium term, the existing technologies are still going to play a significant role in providing electricity.

This chapter examines major power-generating technologies, outlining their main sustainability aspects along their life cycle. The chapter starts with the discussion of fossil fuel-based power plants and their possible retrofit with CCS, followed by nuclear power and renewable energy technologies. For each technology, first their life cycle is described, followed by a brief overview of the environmental, economic and social sustainability issues associated with their life cycles.

Note that the costs discussed as part of the economic sustainability comprise the capital costs expressed as ‘overnight’ costs, and levelised costs of generating electricity (LCOE). The former refer to the costs of building a power plant overnight, without incurring any additional costs of borrowing. The latter are based on a 10% discount rate (IEA/NEA, 2010), and they comprise capital costs, fuel costs (where applicable) and operating and maintenance costs (O&M). For the methodology for estimation of the overnight and levelised costs, see Chapter 4. All the costs are reported in US$ 2008, and have been sourced primarily from IEA/NEA (2005; 2010).

3.2 Electricity from coal

3.2.1 The life cycle

The life cycle of electricity generation from coal comprises the following stages: coal mining and transport, electricity generation and distribution (Figure 3.1). Construction and decommissioning of the power plant are also part of the electricity generation life cycle – typically, construction of a coal-power station takes up to 4 years and the plant can operate for up to 40 years (IEA/NEA, 2010). Currently, coal provides 8,216 TWh per year worldwide providing 42% of global electricity generation (IEA/OECD, 2009). The estimated global coal reserves are 990 billion tonnes, potentially providing 150 years of electricity supply, assuming current consumption (IE/OECD, 2009, 2010b).

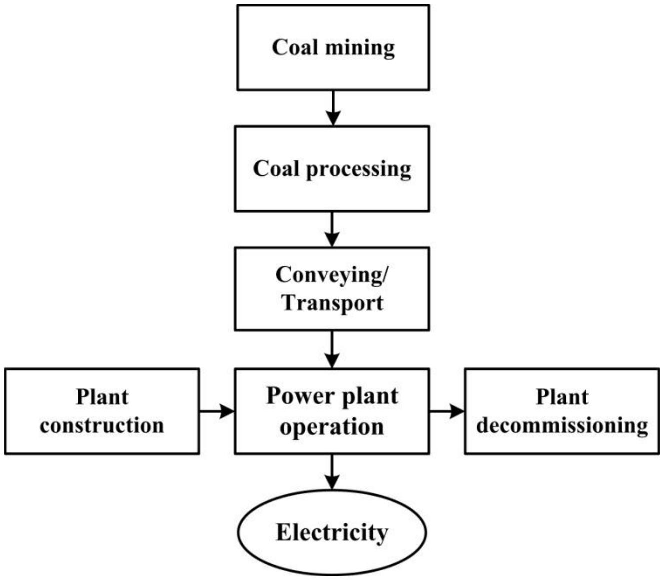

Figure 3-1 The life cycle of coal-based electricity (modified from Odeh & Cockerill, 2008)

Coal is classified as bituminous (or hard coal with higher heating value), sub-bituminous, and lignite (or brown coal with lower heating value) (IEA/OECD, 2005). After extraction from an open cast or underground mine, it is usually cleaned and crushed and then subsequently conveyed or transported to the power plant where it is combusted to generate electricity.

Different technologies are used for electricity generation from coal, including pulverised coal and integrated gasification combined cycle (IGCC)[1]. Pulverised-coal power plants are most common globally, accounting for 97% of the world's coal-fired capacity (Bauer et al., 2008, IEA/OECD, 2008a). Their efficiency depends on different factors,

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[1] An IGCC power plant consists of a gasification unit and a gas-fired combined-cycle unit. In the gasification unit, syngas (a mixture of hydrogen and carbon monoxide) is produced from the coal (or other solid or liquid fuel). This high temperature syngas is firstly cleaned then fired in a gas turbine. A power generator coupled to the gas turbine generates electricity. The high temperature exhaust of the gas turbine produces super-heated steam to drive a steam turbine and produce electricity in a connected second generator (MIT, 2007; Bauer et al., 2008).

including the quality of coal and type of operation. Older large subcritical[2] plants operate with electrical efficiency of 35-36% while for new units (with conventional environmental controls) the efficiency is closer to 39% (IEA/OECD, 2008a). Supercritical[3] steam-cycle plants are becoming more widely spread in many countries, especially in Europe, China and Japan, due to higher operating efficiencies, ranging from 42% to 45%. There are also ultra-supercritical[4] plants in operation in Japan, Denmark and Germany, with expected efficiencies in the range of 50% to 55% by 2020 (IEA/OECD, 2008a). By using the heat output from coal-based electricity generation in combined heat and power systems (CHP)[5], 75-80% of the fuel source can be converted into useful energy for heating or industrial applications. The most modern CHP plants reach efficiencies of 90% or more (IEA/OECD, 2008a, 2008b).

IGCC is an emerging clean-coal technology which can use different carbonaceous feedstock, including coal, oil coke, residual oil, biomass and municipal solid waste. There are currently seventeen IGCC plants operating in the world, totalling 4000 MW, of which only five use coal, with efficiencies ranging between 40-43% (IEA/OECD, 2008a). Other promising technologies such as the fluidised bed combustion (FBC) and pressurised pulverised coal combustion (PPCC), are still in development or at a demonstration stage, but expected to become commercially available in the short to medium term (Bauer et al., 2008).

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[2] Subcritical, supercritical and ultra-supercritical are engineering terms relating to boiler temperature and pressure conditions in the pulverized coal (PC) combustion process (IEA/OECD, 2010b). Subcritical operation refers to steam pressure and temperature below 22.0 MPa and about 550 °C, respectively (MIT, 2007).

[3] Current state-of-the-art supercritical PC generation involves an operating steam cycle of 24.3 MPa and 565 °C (MIT, 2007).

[4] Operating steam cycle conditions above 565 °C are referred to as ultra-supercritical. Current research and development is targeting steam cycle operating conditions of 36.5 to 38.5 MPa and temperatures of 700-720 °C (MIT, 2007).

[5] CHP is the simultaneous utilisation of useful heat and power from a single fuel source (IEA/OECD, 2008a, 200b).

3.2.2 Environmental impacts of electricity from coal

Environmental impacts are generated throughout the life cycle of electricity from coal, but most impacts arise during operation of the power plant. For example, global warming potential (GWP)[6] due to the emissions of GHG from operation ranges between 800 and 1000 g CO_2-eq./kWh, whereas life cycle emissions are between 950 and 1300 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007) (see Figure 3-2). Coal mining and transport contribute on average 7% to the life cycle GWP while the GHG emissions from construction, decommissioning and waste disposal are negligible (Dones et al., 2004). For advanced and future coal power plant technologies life cycle GHG emissions are expected to range between 750 and 850 gCO_2-eq./kW h (Weisser, 2007).

Abiotic depletion potential (ADP) from coal ranges from 5-10 g Sb-eq./kWh because of coal production (see Figure 3-3). Another significant environmental impact of electricity from coal is acidification potential (AP) due to the emissions of acid gases such as SO_2 and NO_x, ranging from 0.7-11 g SO_2-eq./kWh (Figure 3-4). Eutrophication potential (EP) from emissions of NOx, N_2O and NH_3 (0.1-0.6 g PO_4-eq./kWh) because of coal combustion (Figure 3-5).

Other impacts include freshwater aquatic ecotoxicity potential (FAETP) (5-111 g dichlorobenzene-eq./kWh), human toxicity potential (HTP) (58-286 g DCB-eq./kWh), marine aquatic ecotoxicity potential (MAETP) (365-1913 kg DCB-eq./kWh), and terrestrial ecotoxicity potential (TETP) (0.61-2.17 g DCB-eq./kWh) due to emissions of toxic compounds (heavy metals and chemicals) from life cycle of electricity from coal (mostly fuel combustion) (Figure 3-6 and Figure 3-9, respectively).

Ozone depletion potential ranges from 2.7×10^{-6} to 9.1×10^{-6} g R-11-eq./kWh due to NMVOC emissions from coal transportation. Summer smog or photochemical oxidant creation potential (POCP) can also be significant, mainly from the emissions of NO_x and NMVOC, during coal combustion. POCP typically ranges from 0.08-0.56 g ethene-

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[6] GWP and other environmental impacts discussed in this chapter are defined in Appendix 1.

eq./kWh. An overview of the values found in literature for ODP and POCP is given in Figure 3-10 and Figure 3-11).

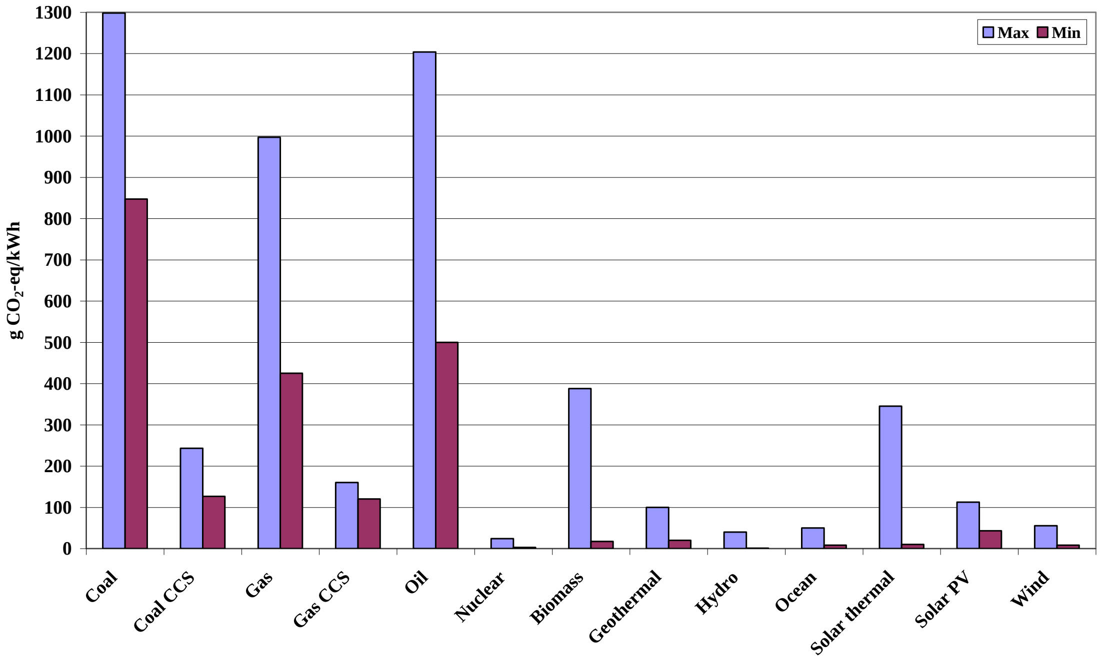

Figure 3-2 GWP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Weisser, 2007; Bauer et al., 2008), coal with CCS (Bauer et al., 2008; Koornneef et al., 2008; Singh et al., 2011), gas with CCS (Bauer et al., 2008; Singh et al., 2011), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007; Weisser, 2007), geothermal (Clark & Sullivan, 2010; Frick et al., 2007, 2010), ocean - wave (Carbon Trust, 2006; Sørensen & Naef, 2008), and solar thermal (Cavallaro and Ciraolo, 2006; Lechon et al., 2008; Viebahn et al., 2008)).

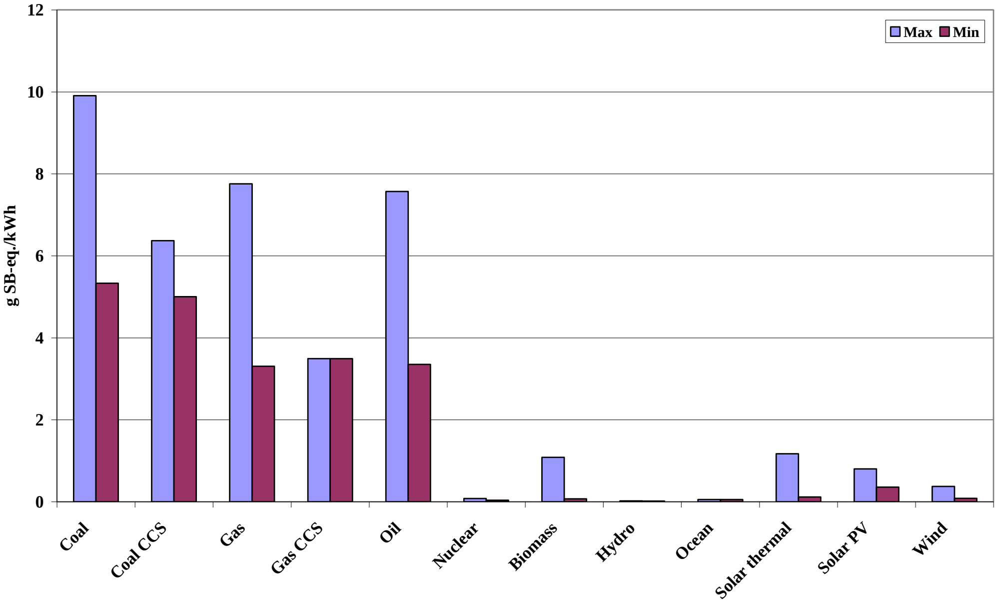

Figure 3-3 ADP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), ocean - wave (Sørensen & Naef, 2008), and solar thermal (Viebahn et al., 2008)).

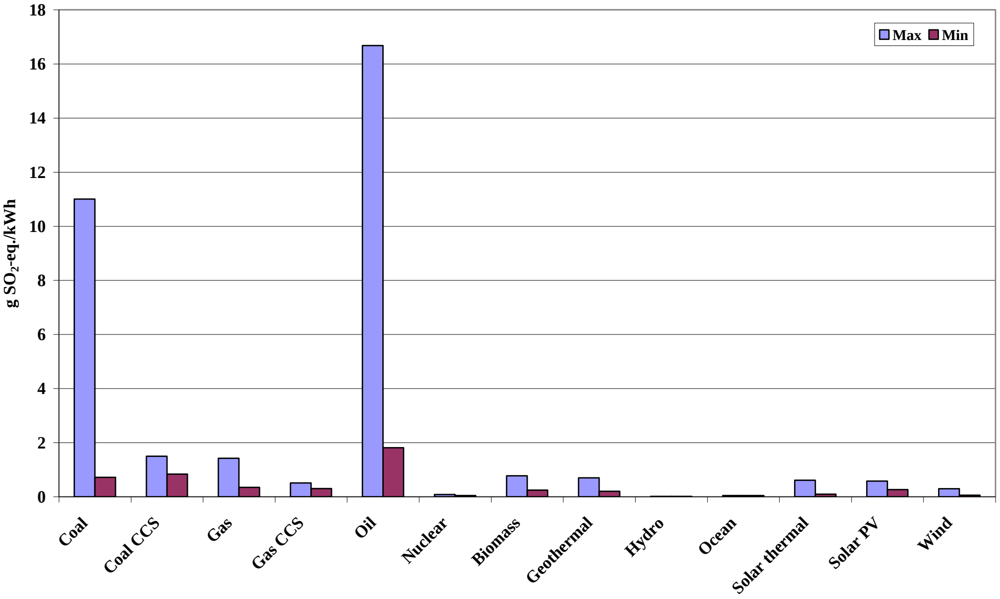

Figure 3-4 Range of AP values from power generation technologies; Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008; Singh et al., 2011), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), geothermal (Frick et al., 2007), ocean (Sørensen & Naef, 2008), and solar CSP (Lechon et al., 2008; Viebahn et al., 2008).

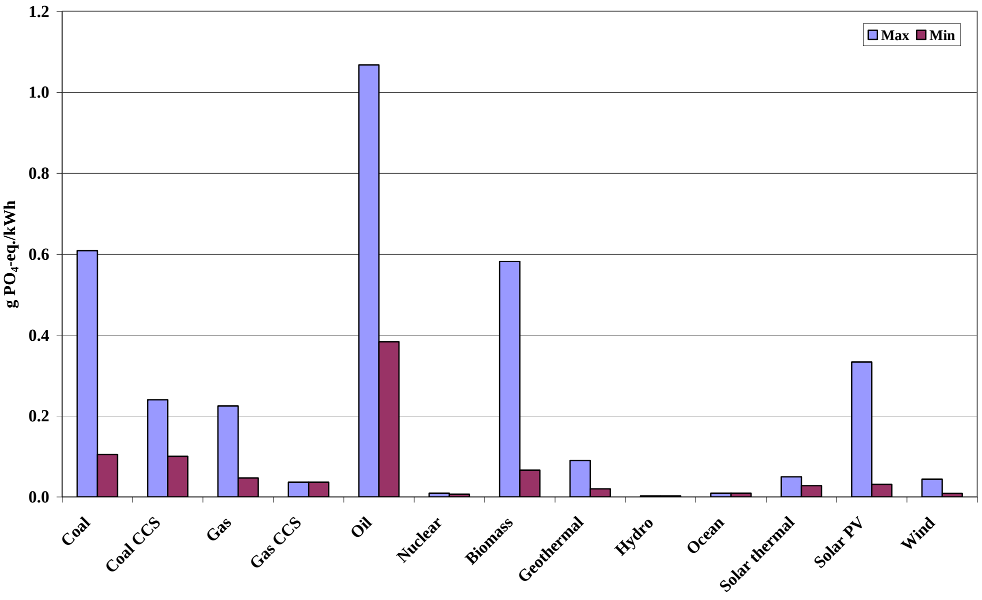

Figure 3-5 Range of EP values from power generation technologies; Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), geothermal (Frick et al., 2007), ocean (Sørensen & Naef, 2008), and solar CSP (Lechon et al., 2008; Viebahn et al., 2008).

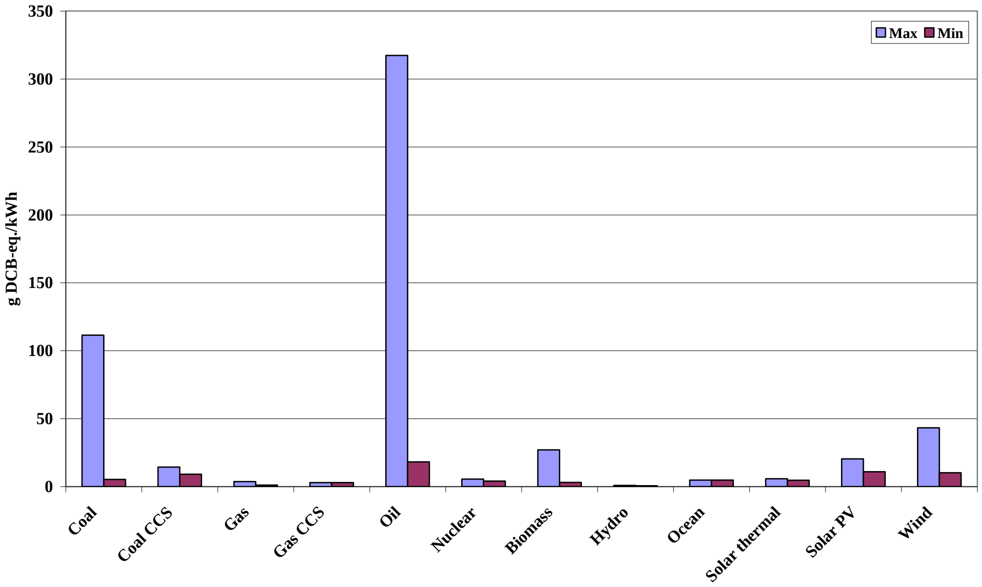

Figure 3-6 FAETP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), ocean - wave (Sørensen & Naef, 2008), and solar thermal (Viebahn et al., 2008)).

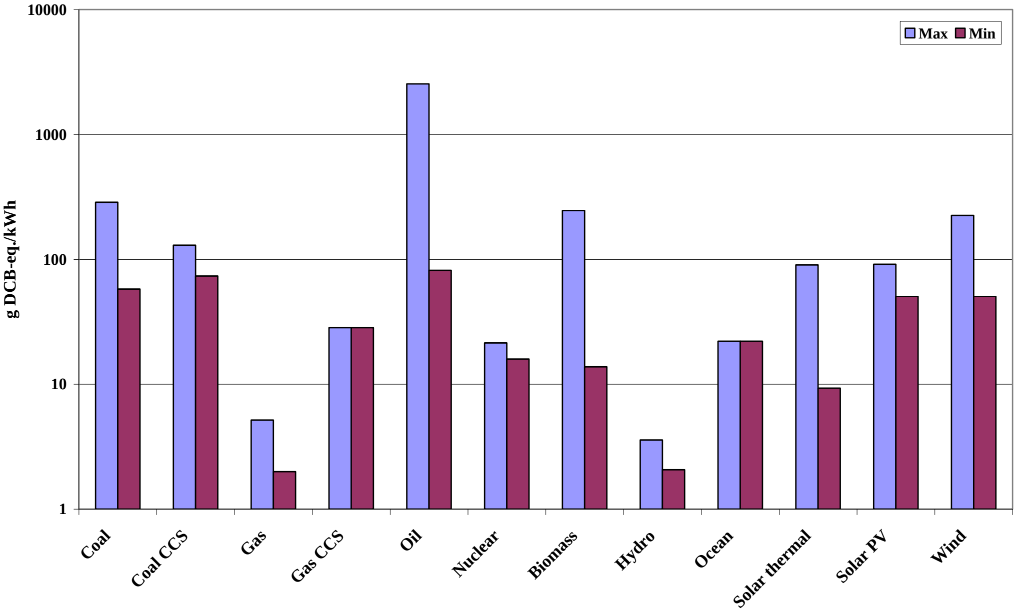

Figure 3-7 Range of HTP values from power generation technologies; Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), geothermal (Frick et al., 2007), ocean (Sørensen & Naef, 2008), and solar CSP (Lechon et al., 2008; Viebahn et al., 2008).

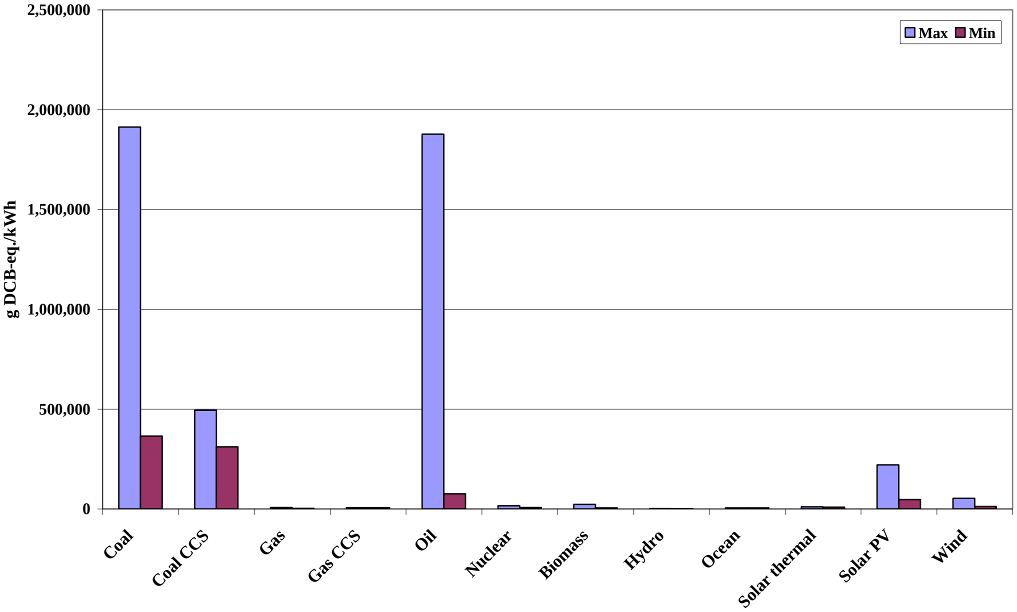

Figure 3-8 MAETP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), ocean - wave (Sørensen & Naef, 2008), and solar thermal (Viebahn et al., 2008)).

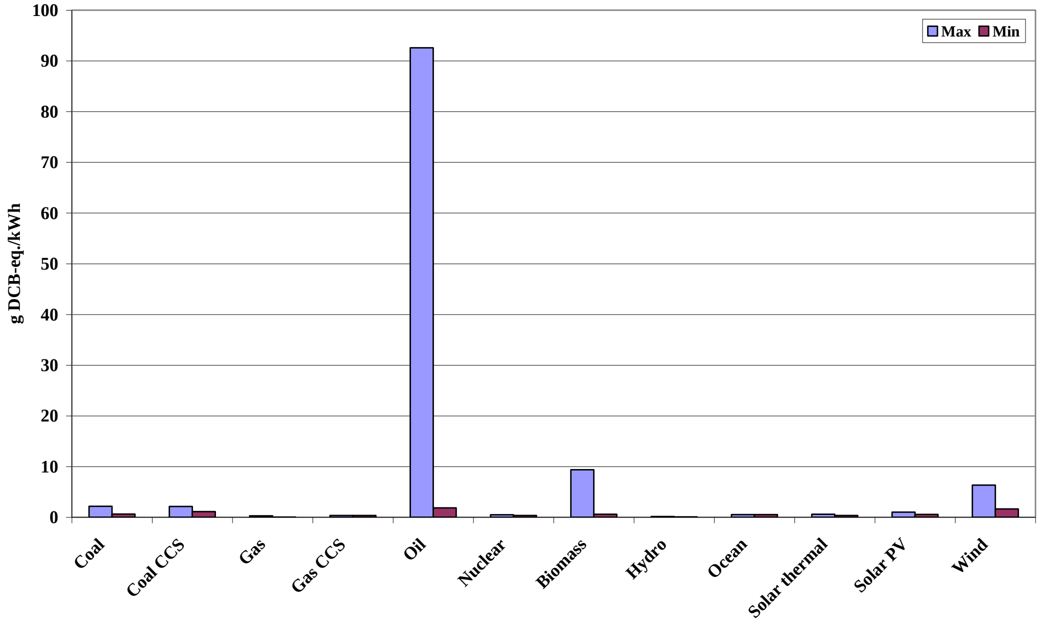

Figure 3-9 TETP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), ocean - wave (Sørensen & Naef, 2008), and solar thermal (Viebahn et al., 2008)).

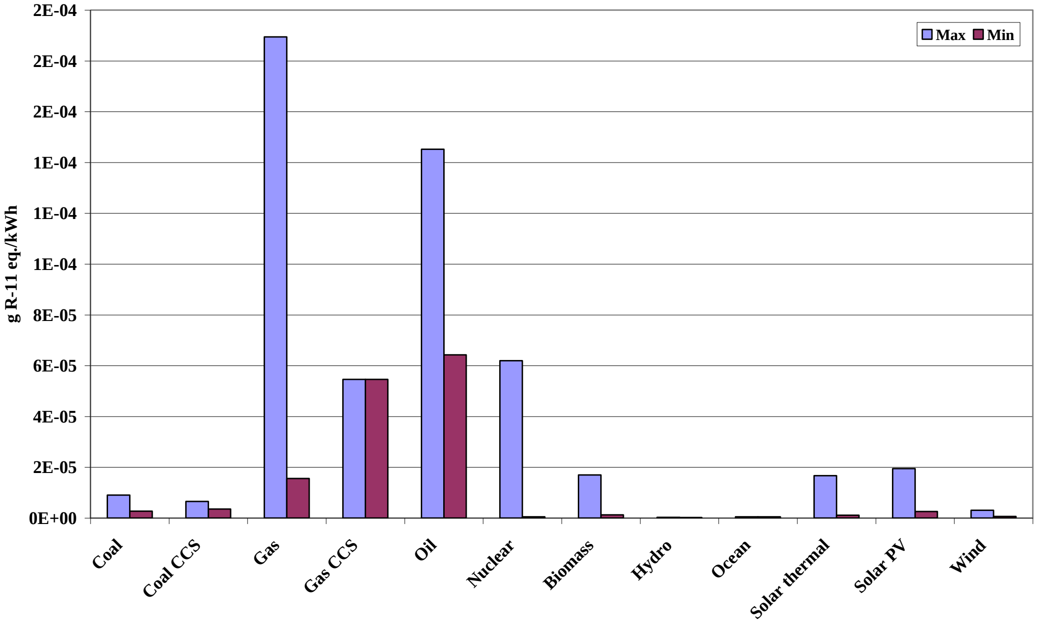

Figure 3-10 ODP values from different electricity-generating technologies (Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), ocean - wave (Sørensen & Naef, 2008), and solar thermal (Viebahn et al., 2008)).

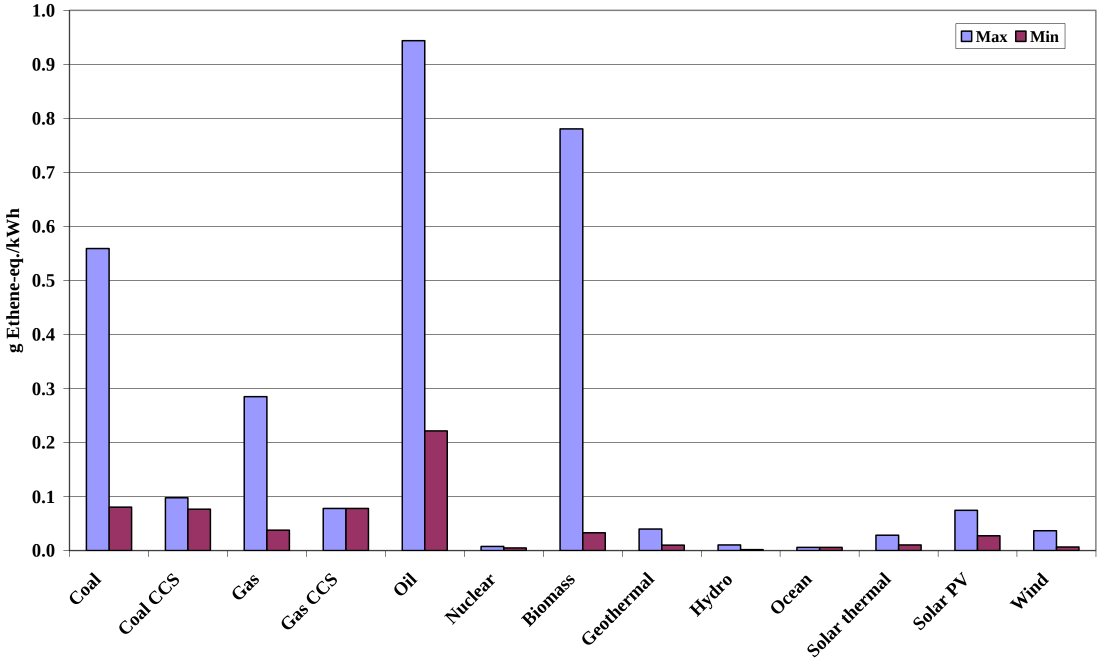

Figure 3-11 Range of POCP values from power generation technologies; Sources: coal (Dones et al., 2007; Bauer et al., 2008), coal and gas with CCS (Bauer et al., 2008), gas, oil, nuclear, biomass, hydro, solar PV and wind (Dones et al., 2007), geothermal (Frick et al., 2007), ocean (Sørensen & Naef, 2008), and solar CSP (Lechon et al., 2008; Viebahn et al., 2008).

3.2.3 Economic costs and social aspects of electricity from coal

According to IEA/NEA (2010), overnight investment costs for coal power plants range between 602 and 4671 US$/kW. The LCOE range between 33 and 114 US$/MWh (see Figures 3.12 and 3.13). At 10% discount rate, investment costs contribute around 50%, fuel 35% and O&M 15% of the total costs (IEA/NEA, 2005).

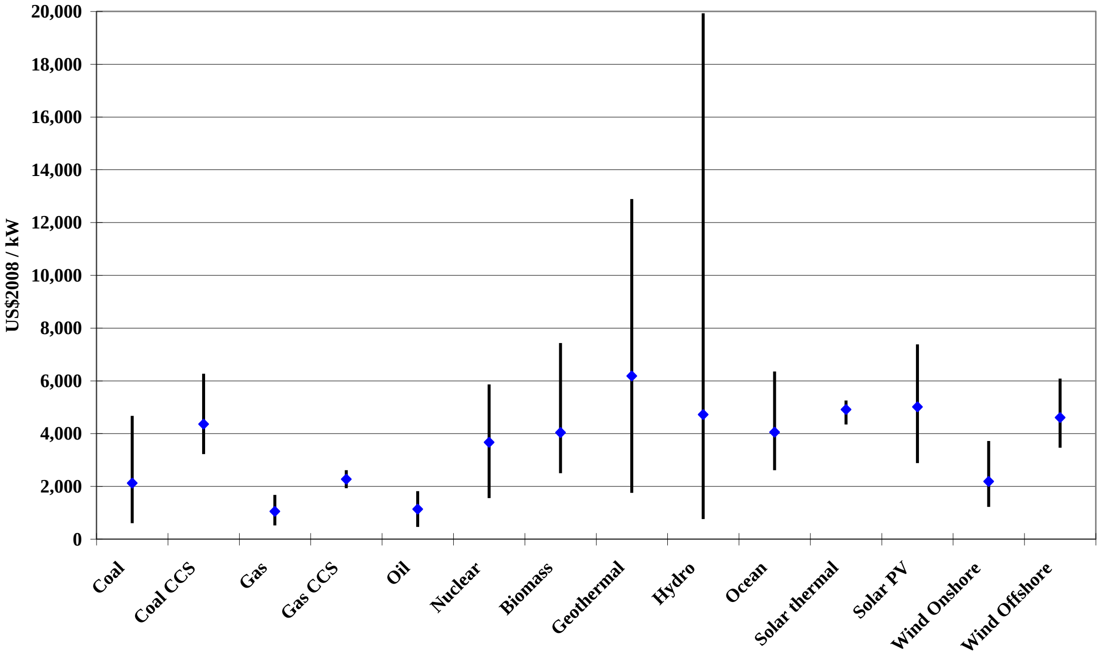

Figure 3-12 Range and mean values of overnight capital costs for different electricity-generating options (IEA/NEA, 2010).

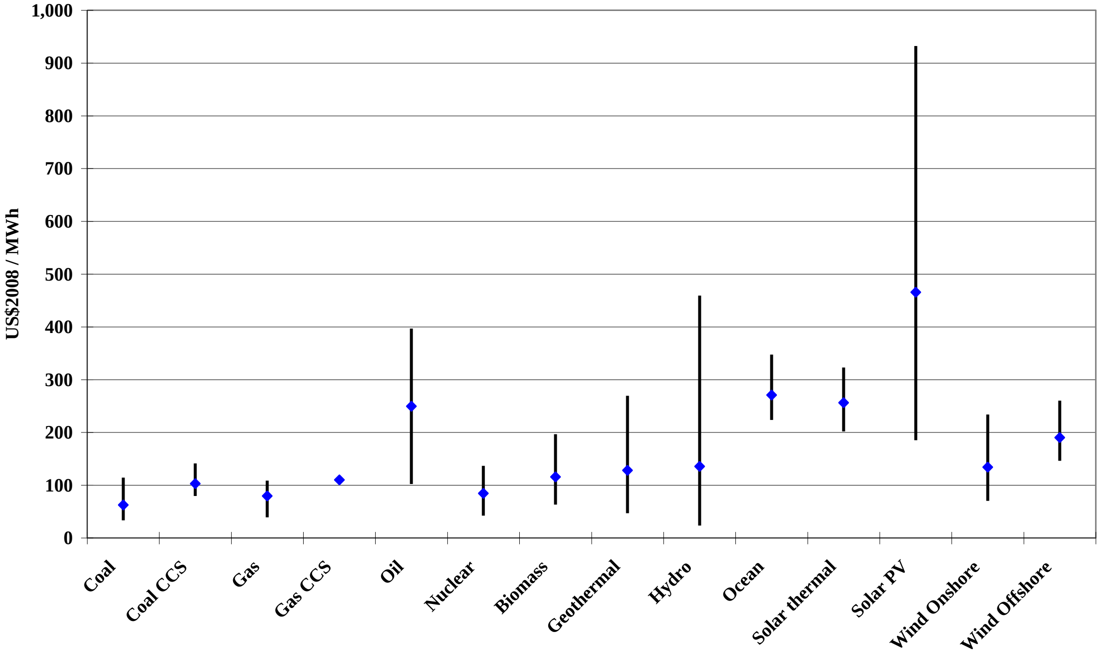

Figure 3-13 Range and mean values of levelised costs for different electricity-generating options (IEA/NEA, 2010).

Coal-fired power plants are also associated with significant social impacts, such as human health impacts, safety risks and waste generation along its life cycle (Rashad & Hammad, 2000; Boyle, 2003).

Major concerns for human health from exposure to emissions of SO_2, NO_X and particulate matter from coal combustion are: effects on breathing, respiratory illness, damage to lung tissue, cancer, aggravation of existing cardiovascular disease and premature death (Rashad & Hammad, 2000; Gagnon et al., 2002; Boyle, 2003; EPA, 2011).

Safety risks are mainly related to occupational accidents and public hazards (injuries, fatalities and health impacts on miners and public). The total number of fatalities per TWh of electricity from coal ranges from 2-38 for occupational hazards and from 18-61 for public hazards. Non-fatal hazards per TWh are 552 (occupational) and 17,678 (public) (see Table 3.1; Boyle, 2003).

Table 3-1 Occupational hazards of electricity production by fuel (including entire fuel cycle); number of deaths and diseases per TWh (after Boyle, 2003)

Fuel	**Occupational hazards**		**Public hazards (off-site)**	
	Fatal	Non-fatal	Fatal	Non-fatal
Coal	2-38	552	18-61	17678
Oil	2-12	263	18-53	17520
Gas	1-9	131	2-4	131
Nuclear	1-8	131	0.1-2	140

3.3 Electricity from natural gas

3.3.1 The life cycle

Currently, gas produces 4,126 TWh per year contributing 21% of global electricity generation (IEA/OECD, 2009). Proven gas reserves are more than 180 trillion m^3

potentially providing 60 years of gas supply at current consumption rates (IEA/OECD, 2009).

As shown in Figure 3-14, the life cycle of gas-based power generation comprises:

- gas extraction, processing and distribution;
- electricity production and power distribution; and
- power plant construction and decommissioning.

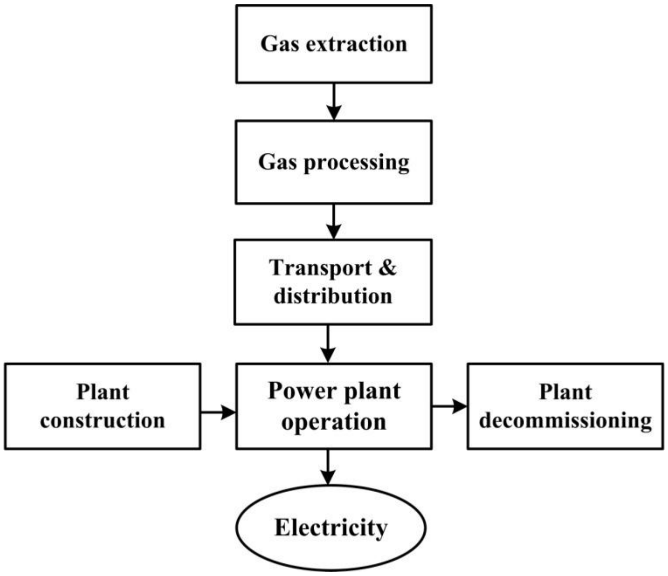

Figure 3-14 The life cycle of gas-based electricity (modified from Dones et al., 2007)

Gas can be extracted from onshore and offshore reservoirs on its own (as non-associated gas) or together with crude oil (associated gas). Energy use for the production of gas can vary according to the gas field conditions, fuels and technology used for extraction. For example, energy use per 1 Nm^3 of gas produced can range between 0.17 and 0.5 MJ for Norwegian and Russian conditions, respectively (Dones et al., 2007). A purification process is then used to eliminate water and oil, higher hydrocarbons, and sulphur from natural gas.

Purified gas is then normally distributed by pipelines and compressors, and depending on the final point of use, can involve very long distances. Usually, the compressors are driven by gas turbines fed with a share of the gas transported; this typically consumes 1.8% of gas per 1000 km in Europe and of 2.7% per 1000 km for Russia (Dones et al., 2007).

Electricity from natural gas is today mainly generated by steam turbines (ST)[7], gas turbines (GT)[8], or combined cycle gas-turbine (CCGT)[9]. Conventional ST plants have an operating efficiency similar to that of coal-fired power plants (33%-35%) and GT power plants operate with efficiencies around 38%, expected to increase up to 46% for future, improved plants (Bauer et al., 2008; IEA/OECD, 2008a).

CCGT is currently the most advanced power generation technology. It is mainly used in Europe, but its application is growing rapidly worldwide, due to its higher operating efficiency (55%-58.5%), lower investment costs, and its overall environmental impacts reduction per unit of electricity produced (Bauer et al., 2008; IEA/OECD, 2008a). The CCGT efficiencies are expected to reach up to 65% in the future (Bauer et al., 2008).

Combined heat and power (CHP) systems using natural gas are also used, especially for industrial applications and in some countries for district heating. Some CHP plants can reach the overall efficiency of 90% or more (IPCC, 2007; IEA/OECD, 2008a).

Construction of a gas power plant takes 2 years with an expected life time of around 30 years (IEA/NEA, 2010), after which they are decommissioned.

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[7] ST power plant consists of a steam generation unit where fossil fuels (e.g. gas, coal or heavy fuel oil) are burned in a boiler to heat water and produce steam, which then turns a turbine to generate electricity (Masters, 2004).

[8] In a GT based power plant, hot gases from fossil fuels combustion (particularly natural gas) are used directly to turn the turbine (instead of producing steam) and generate electricity (Masters, 2004).

[9] CCGT power plant consists of both a gas turbine and a steam generator cycle. The hot gases released from burning natural gas are used to turn a turbine and generate electricity. The waste heat from the gas-turbine process is directed towards producing steam, which is then used to generate electricity.

3.3.2 Environmental impacts of electricity from natural gas

As shown in Figure 3-2, the GWP of current gas power plants ranges between 425 and 997 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007). The majority of this (360 to 575 g CO_2-eq./kWh) is due to the GHG emitted during the operation of power plants (Weisser, 2007). Upstream GHG emissions (from the production and transport of gas) are also significant due to gas leakage (emissions of, CH_4), ranging from 60 to 130 g CO_2-eq./kWh. No significant GHG emissions arise during the construction and decommissioning of a power plant. Advanced and future gas-fired power plants are estimated to emit just under 400 g CO_2-eq./kWh over the full life cycle (Weisser, 2007).

ADP from gas ranges from 3-8 g Sb-eq./kWh because of gas production. Emissions to AP mostly due to NO_x emissions from gas combustion, ranging from 0.35-1.42 g SO_2-eq./kWh (Figure 3-4). EP of electricity from gas ranges from 0.05-0.22 g PO_4-eq./kWh because of NOx emissions mostly from gas combustion (see Figure 3-5).

Other impacts of the life cycle of electricity from gas include FAETP: 1-4 g dichlorobenzene-eq./kWh, HTP: 2-5 g DCB-eq./kWh, MAETP: 3-7 kg DCB-eq./kWh, and TETP: 0.05-0.27 g DCB-eq./kWh (Figure 3-6 to Figure 3-9 , respectively). ODP ranges from 1.6×10^{-5} to 1.9×10^{-4} g R-11-eq./kWh due to NMVOC emissions from gas supply (see Figure 3-10). POCP of electricity from gas ranges from 0.04-0.28 g ethene-eq./kWh mainly from the emissions of NO_x and NMVOC (see Figure 3-11).

3.3.3 Economic costs and social aspects of electricity from natural gas

In most cases, the overnight construction costs for gas power plants range between 520 and 1678 US$/kW (see Figure 3-12). Levelised costs in Figure 3-13 range from 39 to 108 US$/MWh (IEA/NEA, 2010). At 10% discount rate, fuel costs are the major contributor, representing 73% of total LCOE costs, while investment and O&M costs contribute around 20% and 7%, respectively (IEA/NEA, 2005).

Social aspects associated with the life cycle of electricity from gas are mainly related to health and safety risks from gas production and transportation (e.g. CH_4 leakage, explosions and gas rig accidents, etc.) and NO_x emissions from gas combustion (Rashad & Hammad, 2000; Boyle, 2003). The total number of fatalities per TWh of electricity from gas ranges from 1-9 for occupational hazards and from 2-4 for public hazards. Non-fatal hazards (occupational and public) per TWh of electricity output are approximately 262 (see Table 3.1; Boyle, 2003).

3.4 Electricity from oil

3.4.1 The life cycle

In the last years, global electricity generation from oil has decreased from 11% in 1990 (1,132 TWh) to 6% in 2007 (1,117 TWh) because of fast depletion of reserves and fluctuation in oil prices (Bauer et al., 2008; IEA/OECD, 2009). World proven oil reserves are estimated at 1,383 thousand million barrels potentially providing 46 years of oil supply at current consumption rates (BP, 2011).

The life cycle of electricity from oil comprises extraction of crude oil, its transport, refining and regional distribution, and electricity production at the power plant (Hondo, 2005; Dones et al., 2007). This is illustrated in Figure 3-15, also showing construction and decommissioning of power plants as part of the life cycle.

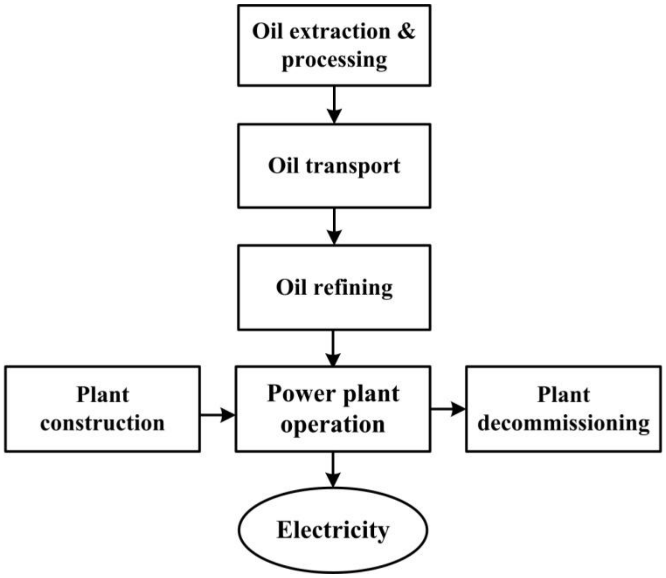

Figure 3-15 The life cycle of electricity from oil (modified from Dones et al., 2007)

Extraction of crude oil can take place from onshore or offshore oil reservoirs. The extracted crude is transported via pipelines or tankers to oil refineries to produce a range of products including petrol, light and heavy fuel oil and diesel. Heavy fuel oil and diesel are used for power generation using steam turbine (ST) and combustion engine (CE)[10], respectively. The average electrical efficiency of oil-based steam turbine power plants in Europe is about 38% (Dones et al., 2007) and 32-38% for diesel-based power plants (Öko Institute, 2005).

Due to energy security (depletion of oil resources and variability of price), as well as climate change targets, the number of oil-based power generation has been considerably reduced around the world, especially in Europe (Bhattacharyya, 2009). However, electricity generation from oil is still significant in some countries, including Japan, Saudi Arabia, United States, Mexico and China (IEA/OECD, 2008c). In the last years, oil power plants have been mainly replaced by gas CCGT power plants. This trend is expected to continue for the future (IEA/OECD, 2008a; Bauer et al., 2008).

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[10] These power plants are fitted with internal combustion engines where gas expansion is used to obtain mechanical power, which is then transformed into electrical power in the generator (Masters, 2004).

3.4.2 Environmental impacts of electricity from oil

Life cycle GHG emissions from oil-based power plants range between 500 and 1204 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007; (see Figure 3-2), with most of the emissions arising from the operation of the power plant (Weisser, 2007). Significant upstream emissions arise in oil production (mainly from gas flaring and venting), oil transport and refining, ranging from 40 to 110 g CO_2-eq./kWh (Weisser, 2007). Similar to coal and gas power plants, GHG emissions from construction and decommissioning of oil power plants are negligible.

ADP of electricity from oil ranges from 3-8 g Sb-eq./kWh because of oil production. Emissions to AP are significant mainly due to SO_2 and NO_x emissions from oil combustion ranging from 2-7 g SO_2-eq./kWh (see Figure 3-4). EP of electricity from oil ranges from 0.05-0.22 g PO_4-eq./kWh because of NO_x emissions from oil combustion (see Figure 3-5).

Impacts from oil combustion, mostly due emissions of heavy metals include, FAETP: 18-317 g dichlorobenzene-eq./kWh, HTP: 82-2536 g DCB-eq./kWh, MAETP: 75-1877 kg DCB-eq./kWh, and TETP: 2-93 g DCB-eq./kWh, mostly from heavy metals (Figures 3.6-3.9, respectively). ODP ranges from 6.4×10^{-5} to 1.5×10^{-4} g R-11-eq./kWh due to NMVOC emissions from oil supply (see Figure 3-10). POCP of electricity from oil ranges from 0.2-0.9 g ethene-eq./kWh mainly from the emissions of SO_x, NO_x and NMVOC (see Figure 3-11).

3.4.3 Economic costs and social aspects of electricity from oil

Current overnight capital costs of heavy fuel oil[11] steam turbine power plants in Mexico are 1817 US$/kW (IEA/NEA, 2010). This estimation is based on an 83 MW power plant with a load factor of 85%, and a levelised cost of 102 US$/MWh. The overnight capital

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[11] Only costs available for heavy fuel oil-based power in IEA/NEA (2010).

costs of a much larger diesel-based[12] GT power plant (1050 MW) with the same load factor in South Africa, for example, are 461 US$/kW, and a LCOE are 397 US$/MWh (IEA/NEA, 2010). The levelised costs in Europe for oil and diesel power plants range from 131-144 and 138-172 US$/MWh, respectively (del Rio, 2011).

Social impacts of electricity from oil are also related to human health and safety aspects. As mentioned previously for coal, emissions of SO_2, NO_x and particulate matter from oil combustion have significant negative impacts on human health (EPA, 2011).

Similar to gas power plants, the main social impacts from electricity from oil are safety concerns associated with the extraction, transportation and storage of oil due to the risks of explosions and fires, and oil leakages (Rashad & Hammad, 2000). The most recent example is the oil disaster caused by British Petroleum (BP) in the Gulf of Mexico (BP, 2010). The total number of fatalities per TWh of electricity from oil ranges from 2-53 for occupational and public hazards. Non-fatal hazards per TWh of electricity produced are 263 (occupational) and 17,520 (public) (see Table 3.1; Boyle, 2003).

3.5 Carbon capture and storage (CCS)

Carbon capture and storage (CCS) involves CO_2 capture from flue gas and its subsequent storage in suitable geological structures, for example, depleted oil and gas fields and aquifers (IPCC, 2005; Pehnt and Henkel, 2009). It is an attractive option as it has a potential to reduce GHG emissions from fossil fuels on average by 85% (IPCC, 2005). CCS has been used in the chemical processing and oil and gas industries for decades, but it has not yet been commercially incorporated into large-scale power plants (IEA/OECD, 2008a; IEA/NEA, 2010). These developments are currently under way (Koornneef et al., 2008; Pires et al., 2011). First full-scale integrated CCS installations are expected by 2020 (Bauer et al., 2008). Currently, there are at least six large-scale (over 0.5 Mt injected CO_2 per year) CCS demonstration projects in operation around the

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[12] Only costs available for diesel-based power in IEA/NEA (2010).

world: Sleipner and Snohvit in Norway, Karlshamn in Sweden, Maasvlakte in the Netherlands, Weyburn in Canada-United States), In Salah in Algeria (IEA/OECD, 2008a; E.ON, 2011). Five additional CCS demonstration projects are under construction (E.ON, 2011).

The potential for CCS deployment is still limited because of significant technical, economical and political barriers that can delay the deployment of new technologies (Stangeland, 2007; IEA/OECD, 2008a; Pires et al., 2011). These include (IEA/OECD, 2008a):

- legal guidelines regarding the injection of CO_2 and long-term liabilities must be established;
- economic incentives for CCS need to be developed and agreed on;
- RD&D must be accelerated with the objective of improving reliability and reducing costs;
- Public awareness: education and outreach to all stakeholders are crucial.

CCS will initially be applied to fossil-fuel power plants; if successful, it is also possible that it will be used with biomass plants. Figure 3-16 shows a schematic diagram of a possible future integrated CCS system.

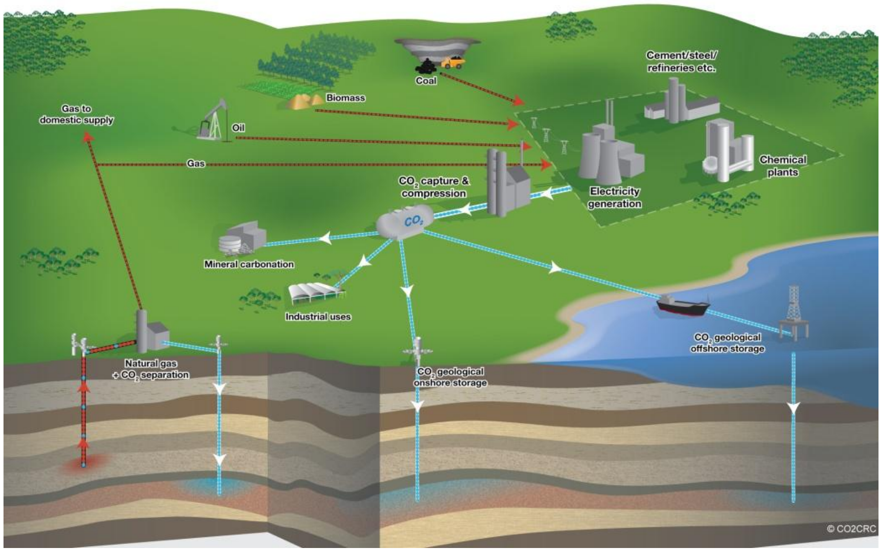

Figure 3-16 Schematic diagram of possible CCS systems (CO2CRC, 2010)

3.5.1 The life cycle

As shown in Figure 3-1 the CCS life cycle involves the following main stages (IPCC, 2005; Pires et al., 2011; Stangeland, 2007):

- CO_2 capture from the flue gas;
- transportation to a storage site; and
- underground injection and storage.

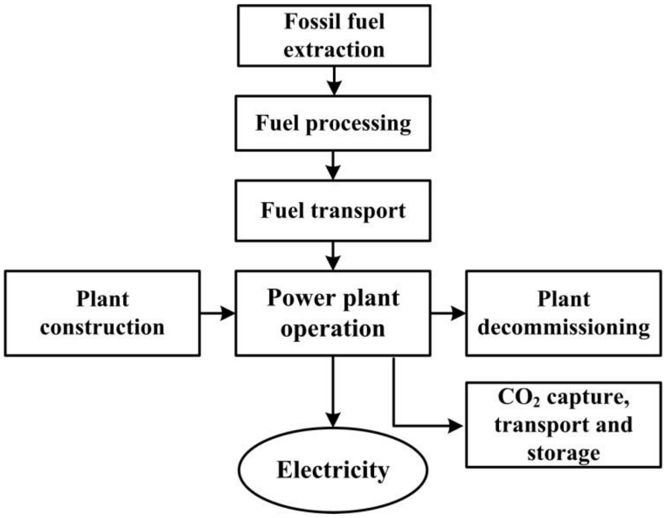

Figure 3-17 The life cycle of electricity from fossil fuels with CCS

Three types of CO_2 capture processes can be used (IPCC, 2005; IEA/OECD, 2008a; Pehnt and Henkel, 2009):

i. post-combustion: separating the CO_2 in the flue gas from other components, mainly N_2 and water vapour; the amine-based absorption systems, already widely applied in the chemical industry, are used for these purposes (Abu-Zahra et al., 2007, Koornneef et al., 2008, Pires et al., 2011);
ii. pre-combustion: converting the fuel for the power plant into CO_2 and a carbon-free combustible, e.g. hydrogen, and then separating CO_2 from the hydrogen; and
iii. oxyfuel-combustion: combusting the fuel in pure O_2, resulting in a flue gas mixture of concentrated CO_2 and water vapour. Cooling the flue gas enables the CO_2 to be separated from the steam.

The compressed CO_2 can be transported by pipelines or shipped to the injection site; the former is more cost-effective, especially for distances shorter than 1000 km (IEA/OECD, 2008a). There are some examples of existing CO_2 pipelines around the world with a proven safety track record, including in the United States, where a network of CO_2 pipelines has been operational for more than two decades, (IEA/OECD, 2008a).

Carbon storage involves injecting CO_2 in a supercritical state via wellbores into suitable geological strata such as deep saline formations, depleted oil and gas reservoirs, and non-mineable coal seams on land or under the sea floor (at depths generally exceeding 700 metres) (Bauer et al., 2008; IEA/OECD, 2008a). Other methods, such as storage in ocean waters and mineral carbonation are still in the research phase and will require a considerable amount of testing and assessment of environmental risks (IPCC, 2005; IEA/OECD, 2008a).

3.5.2 Environmental impacts of CCS

Although as mentioned previously CCS can reduce the emissions of GHG from fossil power plants on average by 85%, the life cycle of CCS itself is associated with emissions of GHG. This is due to the use of energy and materials to run the system as well as the efficiency penalty on the power plants, which can be reduced by 16-38% (Weisser, 2007; Dones et al., 2004).

The IPCC (2005) estimates that direct CO_2 emissions for pulverised coal power plants with CCS lie in the range of 92–145 g CO_2/kWh, 65–152 g CO_2/kWh for coal IGCC, and 40–66 g CO_2/kWh for gas CCGT. This is equivalent to a CO_2 emission reduction per kWh in the range of 80–90% depending on technology and fuel type. Consequently, CCS decreases the net efficiency of a power plant and increases the fuel consumption per kWh delivered to the grid (Weisser, 2007). Dones et al. (2004) estimate that for gas CCGT fuel consumption increases by 16–28%, for pulverised coal by 22–38% and coal IGCC by 16–21%.

Another study (Koornneef et al., 2008) reports the life cycle GHG emissions of 243 g CO_2-eq./kWh for a 89% capture of CO_2. The direct emissions represent 44%, coal supply chain 41%, and the remainder due to construction of infrastructure. These results are based on an ultra-supercritical pulverized coal power plant with post-combustion CCS using mono-ethanolamine (MEA) for CO_2 absorption.

These results are congruent with that reported by Bauer et al. (2008) and Singh et al. (2011), who found that the life cycle GHG emissions for coal power plants with CCS range between 126 and 223 g CO_2-eq./kWh. These results refer to a range of coal technologies (e.g. IGCC, and supercritical power plants) and CCS methods (post-combustion, and oxy-fuel capture) as well as different CO_2 geological storage options (aquifer and depleted gas reservoir). The authors also found that the life cycle GHG emissions for gas CCS are between 120 and 160 g CO_2-eq./kWh.

Other potential environmental consequences associated with CCS include:

- leakage of CO_2 within the CCS systems with a potential to cause further climate change due to the concentrated CO_2 streams;
- potential seismic activity due to structural changes caused by underground CO_2 storage; and
- environmental impacts associated with the CCS supply chain (Figures 3.2-3.11)

The latter are discussed below. Only impacts from coal and gas CCS are discussed here due to data availability.

ADP for coal CCS ranges from 5-6 g Sb-eq./kWh because of coal production (see Figure 3-3). AP and EP are between 0.8-1.5 g SO_2-eq./kWh (Figure 3-4) and 0.1-0.2 g PO_4-eq./kWh (see Figure 3-5), respectively, due to coal supply and coal combustion. Other impacts of electricity from coal with CCS comprise FAETP: 9-14 g DCB-eq./kWh, HTP: 73-130 g DCB-eq./kWh, MAETP: 311-494 g DCB-eq./kWh, TETP: 1.1-2.1 g DCB-eq./kWh (Figures 3.6-3.9). ODP ranges from 3.5×10^{-6} to 6.6×10^{-6} g R-11-eq./kWh and POCP from 0.08-0.1 g ethene-eq./kWh.

ADP for gas CCS is 3 g Sb-eq./kWh because of gas production (see Figure 3-3). AP ranges from 0.3-0.5 g SO_2-eq./kWh (Figure 3-4) and EP 0.04 g PO_4-eq./kWh (see Figure 3-5). Other impacts of electricity from gas with CCS are FAETP: 3 g DCB-eq./kWh, HTP: 28 g DCB-eq./kWh, MAETP: 6 g DCB-eq./kWh, TETP: 0.3 g DCB-eq./kWh (Figures 3.6-3.9). ODP and POCP are 5.5×10^{-5} g R-11-eq./kWh and 0.08 g ethene-eq./kWh, respectively.

3.5.3 Economic costs and social aspects of CCS

The overnight capital cost estimates for coal CCS range from 3223 to 6268 US$/kW, with levelised costs from 79 to 141 US$/MWh (see Figures 3.18 and 3.19). This compares with 602-4671 US$/kW and 33-114 US$/MWh, respectively, for coal without CCS, representing an increase of 105% and 66%. For gas power plants with CCS, the overnight capital costs are between 1928 and 2611 US$/kW, with levelised costs from 103 to 117 US$/MWh (IEA/NEA, 2010). This increases the costs of electricity from natural gas without CCS by 115% and 39%, respectively.

It is still unclear what social consequences CCS could have, but these include public acceptability and safety aspects related to the long-term storage and potential leaks of CO_2 as well as potential seismic activities, as mentioned above. These concerns could be one of the greatest barriers for implementation of CCS (Pires et al., 2011).

3.6 Nuclear power plants

3.6.1 The life cycle

At present, nuclear energy produces 2,719 TWh per year representing 14% of global electricity generation (IEA/OECD, 2009). Global estimates of recoverable uranium resources are 5.4 million tonnes which are potentially enough to last 80 years at current consumption rates (WNA, 2010a).

As can be seen in Figure 3-18, the life cycle of nuclear power comprises mining and milling of uranium, production of nuclear fuel, electricity generation at the power plant, radioactive waste disposal as well as plant construction and decommissioning (Weisser, 2007). Reprocessing of spent fuel for mixed-oxide (MOX) fuel fabrication can also be part of the nuclear life cycle (Dones et al., 2005; Hondo, 2005).

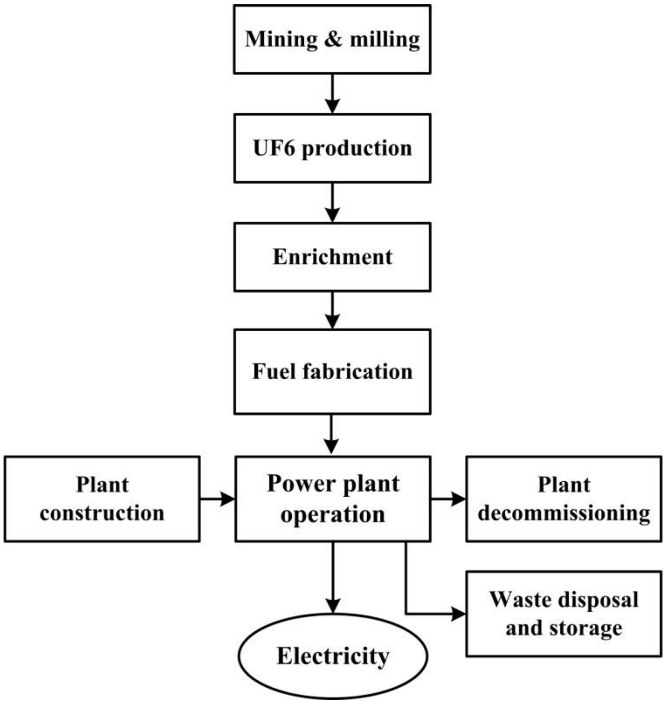

Figure 3-18 The life cycle of a nuclear electricity (Dones et al., 2005)

The uranium ore can be mined in underground or open-pit mines, or by in-situ leaching. The ore is then milled to extract uranium dioxide (UO_2). This is followed by conversion of UO_2 to uranium hexafluoride (UF_6) and the subsequent enrichment of the fissile uranium isotope U-235. The enriched UF_6 is then converted back to UO_2 and manufactured into fuel assemblies for use in nuclear reactors (Azapagic and Perdan, 2011). The time the fuel spends in the core depends on the type of reactor but typically the fuel is replaced at intervals of 12-24 months (WNA, 2010b). Construction of a nuclear power plant takes around 7 years (IEA/NEA, 2010). Nuclear power plants in Europe operate with an average net efficiency of 33 % and a lifetime of 40 years. Load factors range between 72-89 % (Dones et al., 2007).

The spent fuel has to be stored over a long period of time to allow for the decay of radioactive substances; it can also be reprocessed for further use as fuel in nuclear reactors (Azapagic and Perdan, 2011). In addition to spent fuel, radioactive waste is generated during mining and fuel preparation, but the level of radioactivity is significantly lower compared to the spent nuclear fuel.

There are a number of different nuclear reactor types, but the most widely used are boiling water reactors (BWR) and pressurised water reactors (PWR), also referred to as Generation II reactors. The next, Generation III reactors incorporate various design improvements to the existing nuclear reactors. They include the Advanced BWR (ABWR), three of which are already in operation in Japan, and the new European Pressurised Water Reactor (EPR) in operation in France (Greenpeace and EREC, 2008). Generation III reactors were designed according to the following drivers (Lecointe et al., 2007; Greenpeace and EREC, 2008):

- to reduce capital cost and construction time;
- to improve safety levels, in particular reducing the probability of a severe accident;
- to extend the operating life, typically to 60 years;
- to reduce the environmental implications; and
- to increase the burn-up to reduce fuel use and nuclear waste.

Generation IV reactors are currently being developed with the aim of commercialisation in 20-30 years. According to Lior (2010), these new nuclear reactors would have the following main attributes: electricity price competitive with natural gas, capital cost of 1000 US$/kW, construction time of 3-4 years, improved safety, and proliferation-resistance.

3.6.2 Environmental impacts of nuclear electricity

The life cycle GHG emissions for nuclear power range between 2.8 and 24 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007). Unlike fossil fuel-based power plants, the majority of the GHG emissions arise in the upstream stages with values ranging from 1.5 to 20 g CO_2-eq./kWh. The difference in the upstream emissions is mainly due to the type of enrichment process. Downstream emissions, such as during decommissioning and waste management, range from 0.46 to 1.4 g CO_2-eq./kWh (Weisser et al., 2007).

ADP from nuclear ranges from 0.04-0.08 g Sb-eq./kWh because of uranium production. AP ranges from 0.04-0.08 g SO_2-eq./kWh (Figure 3-4) and EP is 0.01 g PO_4-eq./kWh (see Figure 3-5) mostly due to of uranium supply.

Other impacts of electricity from nuclear include FAETP: 4-5 g dichlorobenzene-eq./kWh, HTP: 16-21 g DCB-eq./kWh, MAETP: 7-16 kg DCB-eq./kWh, and TETP: 0.4-0.5 g DCB-eq./kWh (Figures 3.6-3.9, respectively). ODP ranges from 5.2×10^{-7} to 6.2×10^{-5} g R-11-eq./kWh due to NMVOC emissions from uranium supply (see Figure 3-10). POCP ranges from 0.005-0.008 g ethene-eq./kWh due emissions of NMVOC, SO_2 and NO_x also from uranium supply (see Figure 3-11).

3.6.3 Economic costs and social aspects of nuclear electricity

According to the IEA/NEA (2010), current overnight capital costs for nuclear power plants are between 1556 and 5863 US$/kW with LCOE ranging from 42 to 136 US$/MWh (see Figures 3-12 and 3-13). At a 10% discount rate, the share of capital investment in total LCOE is around 70%, while O&M and fuel cycle costs account for 20% and 10% of the total, respectively (IEA/NEA, 2005).

Even though nuclear power has become a viable solution to global warming due to its considerable lower GHG emission per kWh, there are a number of social sustainability issues that need to be dealt with (Rashad & Hammad, 2000; Lior, 2010; Azapagic and

Perdan, 2011). Some of the most important social aspects are related to health and safety, public acceptability and intergenerational issues involving:

- the risk of proliferation of hazardous nuclear material, which has become a much more serious problem in the past decade;
- safety aspects related to possible nuclear accidents (such as the latest in Fukushima);
- long-term management of radioactive waste; and
- public perception of nuclear power, associated with the above issues.

3.7 Electricity from biomass

3.7.1 The life cycle

Electricity from biomass is becoming an increasingly important energy option worldwide, mainly because of the climate change drivers. Currently, biomass energy produces 259 TWh per year worldwide with an installed capacity of 46 GW (IEA/OECD, 2009). Biomass energy could potentially provide 3%-4% of global electricity production in 2050 (IEA/OECD, 2008a).

Biomass used for electricity generation includes wood (e.g. forestry or wood chips from industry), dedicated energy crops (e.g. poplar), agricultural residues (e.g. sugar cane bagasse) and municipal waste residues (e.g. producing biogas) (Islas et al., 2007; Jungbluth et al., 2007; Evans et al., 2010). Wooded biomass is currently used most widely (Dones et al., 2007; Jungbluth et al., 2007; Bauer, 2008; Jeswani et al., 2011) so that the life cycle of wood-based power generation is described here (Figure 3-19).

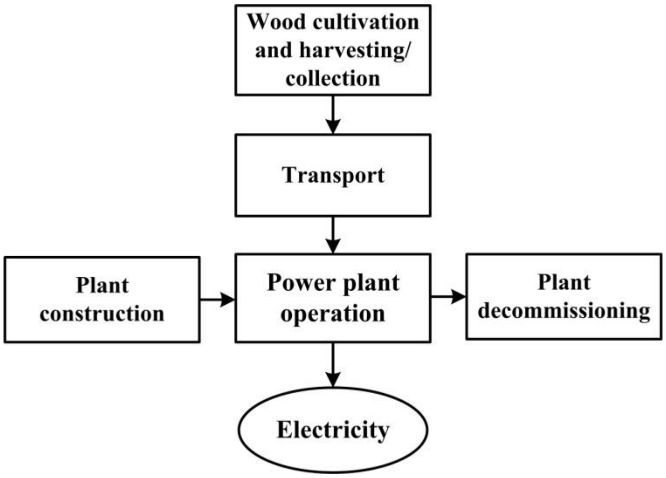

Figure 3-19 The life cycle of electricity from wooded biomass (modified from Bauer, 2008)

Depending on the source of biomass (energy crop or forestry waste), the wood biomass is either cultivated and harvested or collected and transported to the point of use. Some processing may be required before use, including drying. Biomass can either be co-fired with coal in large power stations or burned on its own, in small- to medium-size combined heat and power (CHP) units (POST, 2006; Jeswani et al., 2011). The efficiency of biomass systems for electricity generation ranges from 20%-40%, in CHP systems from 60%-90% and co-firing with coal from 30%-40% (IEA/OECD, 2008a).

3.7.2 Environmental impacts of electricity from biomass

The life cycle GHG emissions from biomass systems depend on the type of the fuel cycle, fuel properties and thermal conversion efficiency. The life cycle GHG emissions from wood-based electricity range between 35 and 99 g CO_2-eq./kWh. By comparison, the emissions from other biomass options such as sugar cane, and sweet sorghum bagasse, and biogas) range from 17 to 388 g CO_2-eq./kWh (Dones et al., 2007; Jungbluth et al., 2007). Since CO_2 released during biomass combustion is biogenic, this stage is considered carbon neutral, so that the life cycle GHG emissions are from the upstream stages (fuel production and transport). The GHG emissions from plant construction and decommissioning are negligible.

ADP of electricity from biomass ranges from 0.1-1.1 g Sb-eq./kWh. AP ranges from 0.2-0.8 g SO_2-eq./kWh (Figure 3-4) and EP is 0.07-0.6 g PO_4-eq./kWh (see Figure 3-5) mostly due to fuel supply and operation of power plant. Other impacts include FAETP: 3-27 g dichlorobenzene-eq./kWh, HTP: 14-245 g DCB-eq./kWh, MAETP: 5-23 kg DCB-eq./kWh, and TETP: 0.6-9.4 g DCB-eq./kWh (from Figure 3-6 to Figure 3-9, respectively). ODP ranges from 1.3×10^{-6} to 1.7×10^{-5} g R-11-eq./kWh (see Figure 3-10 Figure 3-10) and POCP from 0.03-0.8 g ethene-eq./kWh (see Figure 3-11).

3.7.3 Economic costs and social aspects of electricity from biomass

Average overnight capital costs for biomass-based (e.g. wood combustion, biogas) power generation range between 2500 and 7431 US$/kW, with LCOE ranging from 63 to 197 US$/MWh (IEA/NEA, 2010; see Figures 3-12 and 3-13). These costs are still not competitive compared to the fossil fuel options.

Furthermore, various social issues such as competition for agricultural land, water and food production may affect the public acceptability and limit future use of biomass for electricity generation (Boyle 2003; Evans et al., 2010; Lior, 2010).

3.8 Electricity from geothermal energy

Geothermal energy is heat derived from deep underneath the Earth’s crust. The use of geothermal heat depends on the type of heat source and consequently its temperature (Espinoza-Ojeda et al., 2011). These can vary from hydrothermal sources to dry rock or magma. High-temperature geothermal resources can be used for electricity generation, as well as in CHP systems while lower-temperature sources can be used directly for district or industrial heat and for ground-source heat pumps (Boyle, 1996; Holland et al., 1999; IEA/OECD, 2008a).

The capacity of geothermal power has grown at a broadly constant rate of about 200 MW/yr from 1980 to 2005 (IEA/OECD, 2008a). In 2007, the total worldwide capacity reached around 10 GW, generating 56 TWh/yr. Several countries with a high geothermal energy potential, such as Indonesia, Mexico (Santoyo and Torres-Alvarado, 2010), New Zealand, Nicaragua and the United States, are now accelerating development. The economic potential of geothermal power for 2050 is estimated between 70 GW and 140 GW, potentially providing 1%-3% of global electricity production in 2050 (Bertani, 2003; IEA/OECD, 2008a).

3.8.1 The life cycle of geothermal electricity

The life cycle of geothermal power comprises drilling and exploration of a well, and construction, operation and decommissioning of the geothermal power plant (see Figure 3-20).

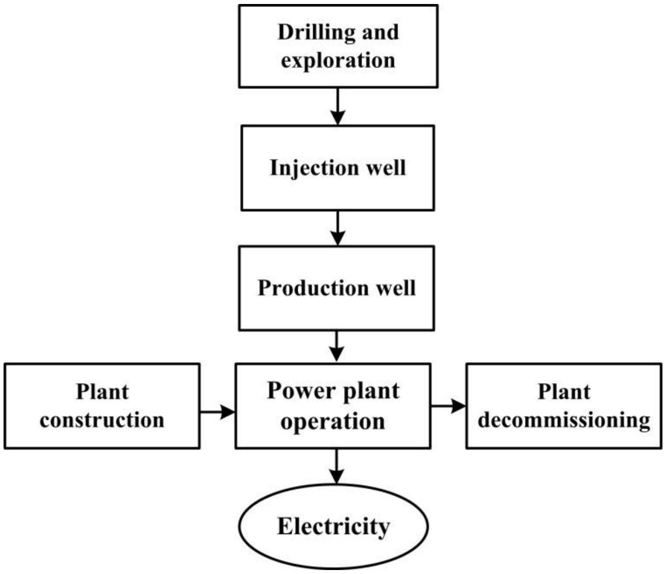

Figure 3-20 The life cycle of electricity from geothermal energy (modified from Clark and Sullivan, 2010)

Drilling and exploration of geothermal wells are based on the approach used in the oil and gas industry (Santoyo, 1997). The depth of commercial geothermal wells can reach up to 3000 m (Lior, 2010). The heat extracted from the wells is used on the power plant to produce electricity. There are three main types of geothermal power systems: dry steam, flash steam, and binary cycle (Boyle, 1996; EGEC, 2007; Santoyo and Barragán-Reyes, 2010).

Dry steam power plants use direct steam from a geothermal source, which is piped from production wells to the plant, then directed towards a steam turbine to produce electricity. Conventional dry steam turbines require fluids of at least 250 °C, which makes these systems less commonly available (EGEC, 2007; Santoyo and Torres-Alvarado, 2010).

Flash steam plants, by far the most common and commercial systems, operate with geothermal fluids above 180 °C. In these systems, the hot pressurised fluid goes up the well until its pressure decreases to the stage it vaporises, leading to a two phase water-steam mixture. The steam, separated from the water, is piped to the plant to drive a steam turbine to generate electricity. The separated left over brine, together with the condensed steam, is piped back into the source reservoir (EGEC, 2007; Santoyo and Torres-Alvarado, 2010).

Binary plants, based on a thermodynamic Rankine cycle, operate with geothermal fluids between 100 and 180 °C. In these plants, the heat is recovered from the geothermal fluid, via a heat exchanger, to vaporize a low boiling point organic fluid which is used to drive a steam turbine to produce electricity. The heat depleted geothermal brine is pumped back into the source reservoir (EGEC, 2007; Santoyo and Torres-Alvarado, 2010).

Over the life time of the power plant (up to 30 years), drilling of additional production and injection wells may be required for the operation of the power plant (Hondo, 2005). The power plant capacity can be very flexible and it depends mainly on the geothermal resource available and the number of production and injection wells required for its operation. For example, a 50 MW flash power plant requires 21 geothermal wells (15 production and six injection wells), while a 10 MW binary system requires only four wells (3 production and 1 injection well) (Clark and Sullivan, 2010).

3.8.2 Environmental impacts of geothermal electricity

The life cycle GHG emissions vary depending on the geothermal resource and technology used. For example, the GHG emissions for a 50 MW flash type power plant are around 100 g CO_2-eq./kWh, arising mainly from the operation of the power plant (Clark and Sullivan, 2010). For a 2 MW binary system, the emissions are between 40-60 g CO_2-eq./kWh and are mostly from power plant infrastructure (Frick et al., 2010).

Emissions of SO_2 and NO_x from geothermal power are of concern contributing to AP (0.2-0.7 g SO_2-eq./kWh), EP (0.02-0.09 g PO_4-eq./kWh) and POCP (0.01-0.04 g ethene-eq./kWh (Figures 3-4, 3-5 and 3-11).

Some geothermal aquifers can produce moderately to highly saline fluids that are corrosive and present a potential pollution hazard, particularly to freshwater drainage systems and groundwater (IEA/OECD, 2008a).

Other impacts are not discussed here due to lack of data.

3.8.3 Economic costs and social aspects of geothermal electricity

Exploration, well drilling and plant construction make up a large share of the overall costs of geothermal electricity. Drilling costs can account for as much as one-third to one-half of the total cost of a geothermal project (IEA/OECD, 2008a). Capital costs are closely related to the characteristics of the geothermal reservoir, and typically vary from 1752 US$/kW to 12887 US$/kW (see Figure 3-12). Levelised costs range between 47 and 269 US$/MWh (IEA/NEA, 2010; Figure 3-13).

Significant socio-economic concerns associated with geothermal energy include those to do with site preparation, such as noise pollution during the drilling of wells, odour from wastes, and social acceptance from local communities (EGEC, 2007; IEA/OECD, 2008a; Evans et al., 2009).

On the other hand, geothermal power has some advantages compared to some other technologies. For example, it requires less land than other renewables, such as wind and solar (Evans et al., 2009). Also, there is far less potential of drilling accidents with geothermal energy (e.g. fire accidents, oil spills), when compared to oil and gas production (Boyle, 1996).

3.9 Hydro electricity

Due to hydropower design flexibility, there are several types of hydropower plants and they can be classified into three main groups (Boyle; 1996; IEA/OECD, 2008a):

i. large power plants with, a dam used as a reservoir;
ii. small power plants, normally designed as run-of-the-river systems which use the river flow to generate electricity; and
iii. pumped storage systems, consisting of two or more reservoirs at different heights where water is pumped from the low to the high reservoir and then released, using its energy to generate electricity .

Currently, hydropower generates 3,078 TWh per year contributing 16% of global production (IEA/OECD, 2009). The world's technically feasible large hydropower generating potential has been estimated at 4.5 times its current production potentially providing 9%-13% of global production in 2050 (IEA/OECD, 2008a). Most of this potential is located in developing regions such as Africa, Asia and Latin America.

The global potential of small hydropower is estimated between 150 GW to 200 GW, but only 5% of this potential has been exploited (IEA/OECD, 2008a). Small hydro is often used in self-standing applications to replace diesel generators or other small-scale power plants or to provide electricity to rural populations.

3.9.1 The life cycle of hydro electricity

The life cycle of hydro power comprises construction of infrastructure, electricity production and decommissioning of the power plant. Figure 3-21 shows a schematic overview of the most common hydro power plants (dam-reservoir and run-of-the-river).

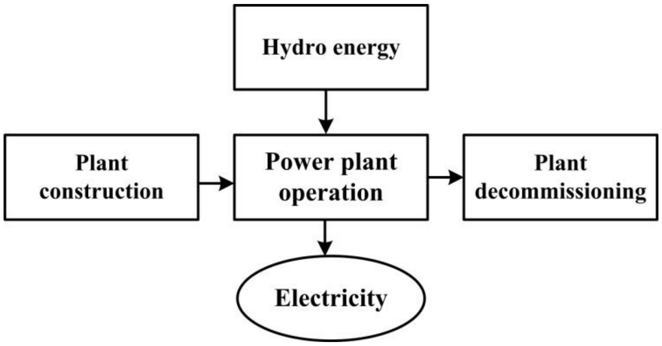

Figure 3-21 The life cycle of a hydro power plant (modified from Dones et al., 2007)

The expected electricity production of the power plant over its life time (80 years) primarily depends on the power plant capacity and the capacity factor. In turn, the latter depends on the climate and hydrological conditions of the site (IEA/NEA, 2010). Hydropower's average capacity factor is 38% (IEA/OECD, 2009).

3.9.2 Environmental impacts of hydro electricity

The life cycle GHG emissions of hydro electricity depend on the type of plant, reservoir size as well as the amount of flooded vegetation cover, soil type, water depth, and climate. Typically, they range between 1 and 40 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007). However, these values vary significantly for different types of plants; for example, the GHG emissions from pumped storage can be significantly higher than the values quoted here when the electricity mix used to pump water is generated from fossil fuels.

For dam-reservoir and run-off-the-river plants, most of the GHG emissions arise during the production and construction of the hydroelectric power plant (especially for large reservoir dams). Additionally, plants using large reservoirs can emit significant quantities of direct GHG emissions due to flooding of biomass and soil. For example, flooded biomass decays aerobically producing CO_2 and anaerobically producing both CO_2 and CH_4 (Gagnon et al., 2002; Denholm & Kulcinski, 2004; Weisser, 2007). These emissions can range from 6-30 g CO_2-eq./kWh (Dones et al., 2007).

Other impacts from the life cycle of hydropower are minimal compared to the other technologies (see Figures 3.3 to 3.11). They are mainly due to the construction of the power plant (Dones et al., 2007) and are as follows: ADP 0.02 g Sb-eq./kWh, AP from 0.0.1-0.02 g SO_2-eq./kWh (Figure 3-4), EP 0.002-0.003 g PO_4-eq./kWh (see Figure 3-5), FAETP 0.6-0.8 g DCB-eq./kWh, HTP 2-4 g DCB-eq./kWh, MAETP 1 kg DCB-eq./kWh, and TETP 0.08-0.13 g DCB-eq./kWh (Figures 3.6-3.9, respectively), ODP from 2.2×10^{-7} to 2.5×10^{-7} g R-11-eq./kWh (see Figure 3-10) and POCP 0.002-0.1 g ethene-eq./kWh (see Figure 3-11).

3.9.3 Economic costs and social aspects of hydro electricity

While hydro-power systems have many advantages over other technologies, including no or low direct GHG emissions, built-in energy storage, and fast response for fluctuations in electricity demand, they also have significant socio-economic aspects which need to be addressed.

From the economic perspective, the capital costs of hydro-power plants can range widely, depending on the type, capacity and the hydrological resource available. For example, the overnight capital costs of a large hydro with a capacity of 6277 MW in China are around 757 US$/kW while that of a small hydro of 10 MW in Czech Republic are around 19930 US$/kW. Similarly, the LCOE range from 23 to 459 US$/MWh, respectively (IEA/NEA, 2010).

Social aspects of hydro electricity are mainly associated with lack of public acceptability because of the transformation of land use in the project area (e.g. downstream effects on agriculture, inundate valuable ecosystems) and displacement of people living in the reservoir area (Boyle, 2003; Evans et al., 2009).

However, hydro dams may also benefit communities due to improved flood control, and access to irrigation (Evans et al. 2009).

3.10 Electricity from ocean energy

Energy from oceans can be converted to electricity by utilising (Sørensen & Naef, 2008):

- wave energy, based on surface and sub-surface motion of the waves;
- hydro-kinetic energy of ocean currents and tides;
- ocean thermal energy which uses the temperature differential between cold water from the deep ocean and warm surface water; and
- osmotic energy of pressure differential between salt and fresh water.

Currently, mainly wave and tidal are being developed and are at a relatively early stage of development (IEA, 2008). Wave power converters can be made up from smaller generator units of 100 – 500 kW to interconnected modules that can supply a larger turbine generator unit of 2 – 20 MW. There is no commercially leading technology on wave power conversion at present. The largest grid-connected system installed so far is the 2.25 MW Pelamis, operating off the coast of Portugal. Most development work has been carried out in the UK (Greenpeace and EREC, 2008).

Tidal current systems are also under development. However, their use will be limited to locations with strong currents and sufficient flow. New projects with tidal current turbines comprised of modules of 2 - 3 MW have been planned in the United Kingdom, Canada and the United States (IEA/OECD, 2008a).

Furthermore, tidal barrage projects (based on the rise and fall of the tides) have been built in France, Canada and Russia, with an additional project under construction in

Korea. Several factors, like high cost projections coupled with environmental objections (e.g. effects on estuarial habitats), have limited the technology's further expansion (Greenpeace and EREC, 2008).

3.10.1 The life cycle of electricity from ocean energy

The life cycle of electricity from ocean energy comprises manufacture of materials and components of a power plant and construction, operation and disposal of the power plant (Sørensen and Naef, 2008). As an example, Figure 3-22 shows the life cycle of electricity from wave energy.

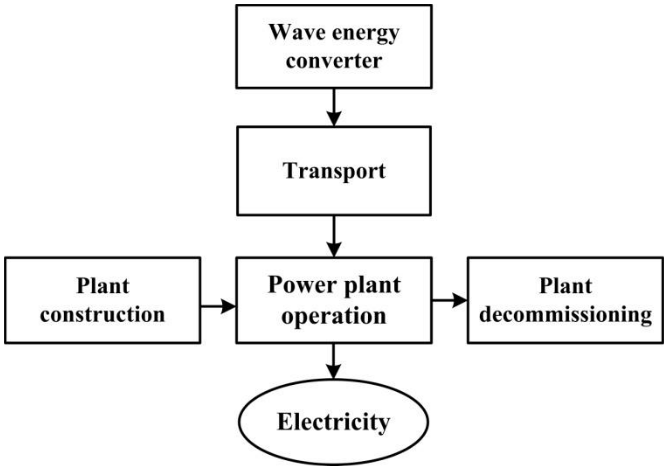

Figure 3-22 The life cycle of electricity from wave energy (modified from Sørensen and Naef, 2008)

3.10.2 Environmental impacts of electricity from ocean energy

Given that technologies for electricity from ocean energy are still under development, there are only a few studies of their environmental impacts and mainly for wave energy. The life cycle GHG emissions estimates for the latter range between 8 and 50 g CO_2-eq./kWh (Carbon Trust, 2006; Sørensen and Naef, 2008); see Figure 3-2.

The life cycle impacts from ocean energy are as follows: ADP 0.05 g Sb-eq./kWh (Figure 3-3), AP 0.04 g SO_2-eq./kWh (Figure 3-4), EP 0.01 g PO_4-eq./kWh (see Figure

3-5), FAETP 5 g DCB-eq./kWh, HTP 22 g DCB-eq./kWh, MAETP 6 kg DCB-eq./kWh, and TETP 0.5 g DCB-eq./kWh (Figures 3.6-3.9, respectively), ODP 5×10^{-7} g R-11-eq./kWh (see Figure 3-10) and POCP 0.01 g ethene-eq./kWh (see Figure 3-11). The majority of these impacts are because of construction of infrastructure (Sørensen and Naef, 2008).

3.10.3 Economic costs and social aspects of electricity from ocean energy

Similar to the environmental impact studies, estimates of economic costs are also scant and uncertain. Current estimates for overnight capital costs for wave power plants range from 3186 - 6354 US$/kW (IEA/NEA, 2010). Capital costs for one tidal power system has been estimated at 2611 US$/kW. The LCEO for different types of ocean energy range from 224 to 347 US$/MWh (IEA/NEA, 2010).

From the social point of view, visual intrusion and destruction of wildlife habitat are some of the main concerns associated with public acceptability of ocean-based power systems (Boyle, 2003; Greenpeace and EREC, 2008).

3.11 Electricity from solar thermal power plants

Solar thermal power generation systems capture energy from solar radiation and transform it into heat which is then used to generate electricity in steam turbines (Viebahn et al., 2010).

Three main types of solar thermal power plants have been developed and commercialised so far (Viebahn et al., 2008; 2010):

- parabolic and Fresnel troughs;
- central receivers (also known as power tower or solar tower); and
- dish–Stirling systems.

Parabolic troughs, using thermo-oil or direct steam, operate with steam temperatures up to 400 and 500 ˚C, respectively and use a steam turbine with an efficiency of 14.7% to generate electricity. Central receivers can operate a combination of a gas and steam turbine due to high temperatures (above 1000 ˚C), resulting in high conversion efficiency of 15.5%. Dish systems either use a Stirling engine at the focus of each dish or an array of dishes to transfer heat to a single central power generating block. Dish systems will most likely be used as decentralised applications (Viebahn et al., 2010).

There are also the hybrid operation systems, which are based on thermodynamic cycles of solar energy combined with fossil fuels or even biomass (Lechón et al., 2008; Viebahn et al., 2010). For example, hybrid solar thermal power plants installed in Spain, central tower and parabolic through technologies, produce up to 15% of their total electricity with gas combustion (Lechón et al., 2008).

Energy storage would increase the potential of solar thermal power; however, storage systems are still in development (Beaudin et al., 2010), including those based on concrete and molten salts (Viebahn et al., 2010).

3.11.1 The life cycle of solar thermal electricity

The life cycle of electricity from solar thermal power plants comprises the manufacturing of materials and components of the power plant, construction operation and decommissioning of the power plant (Ardente et al., 2005; Cavallaro & Ciraolo, 2006; Lechón et al., 2008). Figure 3-23 shows the life cycle of a typical solar thermal power system.

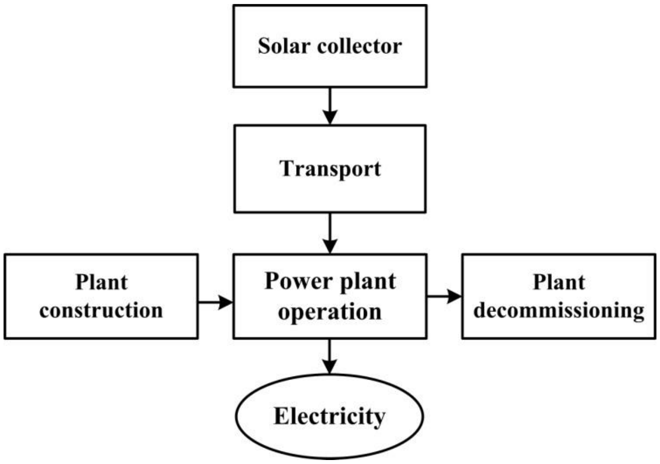

Figure 3-23 The life cycle of a solar thermal power plant (modified from Cavallaro and Ciraolo, 2006)

3.11.2 Environmental impacts of solar thermal electricity

The life cycle GHG emissions range between 11 and 345 g CO_2-eq./kWh for solar towers, and from 10 to 234 g CO_2-eq./kWh for parabolic troughs (Lechón et al., 2008). The higher values are related to hybrid operation using natural gas to produce electricity (Weinrebe et at., 1998; and Lechón et al., 2008; Viebahn et al., 2008). Dish-Stirling systems have GHG emissions of around 13 g CO_2-eq./kWh (Cavallaro and Ciraolo, 2006).

The contribution of solar thermal power systems to other environmental impacts is shown in Figures 3.3-3.11. The majority of the impacts are mostly related to the construction of infrastructure (Lechón et al., 2008; Viebahn et al., 2008) and they are as follows: ADP 0.1-1.2 g Sb-eq./kWh (Figure 3-3), AP 0.1-0.6 g SO_2-eq./kWh (Figure 3-4), EP 0.03-0.05 g PO_4-eq./kWh (see Figure 3-5), FAETP 5-6 g DCB-eq./kWh, HTP 9-90 g DCB-eq./kWh, MAETP 9-11 kg DCB-eq./kWh, and TETP 0.4-0.6 g DCB-eq./kWh (Figures 3.6-3.9, respectively), ODP 1.1×10^{-6} to 1.7×10^{-5} g R-11-eq./kWh (see Figure 3-10) and POCP 0.01-0.03 g ethene-eq./kWh (see Figure 3-11).

3.11.3 Economic costs and social aspects of solar thermal electricity

Current overnight capital costs for solar thermal power plants range from 4347 US$/kW to 5255 US$/kWh. At a 10% discount rate, the LCEO costs vary from 202 to 323 US$/MWh.

Social aspects of solar thermal electricity are mostly related to public acceptance due to large requirements of land for power plant operation, as suitable areas are often semi-arid and water scarcity might be an issue, and visual impact (Boyle, 2003; Wüstenhagen et al., 2007; Evans et al., 2009; del Rio, 2011).

3.12 Electricity from photovoltaics (PVs)

Photovoltaic (PV) systems directly convert solar energy into electricity. The basic building block of a PV system is the PV cell, which is a semiconductor device that converts solar energy into direct-current (DC) electricity (IEA/OECD, 2008a). Existing PV cell technologies comprise crystalline silicon-based (mono- and poly-crystalline, mc-Si and pc-Si, respectively) and thin films (e.g. Cadmium Telluride (CdTe) and Copper-Indium-Diselenide (CIS)).

The most common and mature PV systems are silicon-based cells. The efficiency of mc-Si PVs range from 13%-15% while the efficiency of pc-Si PVs is from 12%-14% (IEA/OECD, 2008a).

Germany, Japan and the United States currently hold 70% of the global PV capacity, also being the three largest PV-manufacturing nations, accounting for 63% of global PV production (IEA/OECD, 2008a).

Currently, solar energy (thermal and PV) generate 5 TWh per year with an installed capacity of 9 GW (IEA/OECD, 2009). Solar thermal and PV together could potentially provide 6%-11% of global electricity production in 2050 (IEA/OECD, 2008a).

3.12.1 The life cycle of PV systems

Figure 3-24 presents a schematic overview of the life cycle for silicon-based (mc-Si and pc-Si) PV power systems. As shown, the life cycle involves fabrication and transport of solar PV cells and PV plant construction, operation and decommissioning (Jungbluth, 2005; Jungbluth et al., 2005). The life time of a PV plant is typically 30 years.

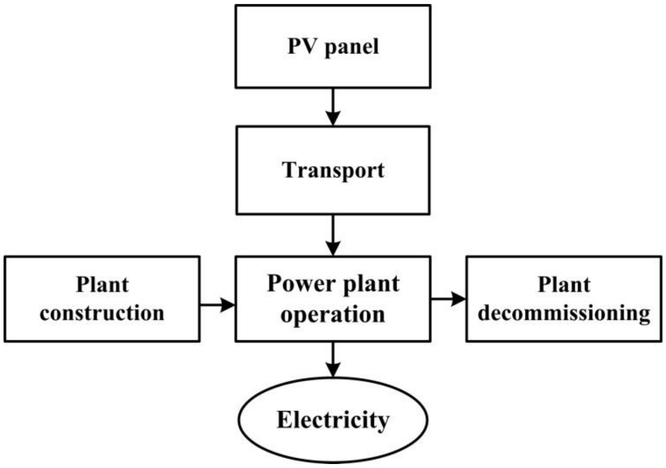

Figure 3-24 The life cycle of electricity from PVs (modified from Jungbluth et al., 2005)

PV cell fabrication comprises the extraction of sand, silicon purification, wafer, panel and laminate production, manufacturing of converter and supporting structure (Jungbluth, 2005; Jungbluth et al., 2005). PV panels are usually installed as integrated systems in buildings (e.g. mounted on top of houses and laminates are integrated into slanted roofs and façades). They can also be ground-mounted in centralised electricity production facilities. The majority of grid-connected systems are integrated in buildings (IEA/OECD, 2008a; Lior, 2010).

3.12.2 Environmental impacts of electricity from PVs

The life cycle GHG emissions of PV electricity range between 43 and 112 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007). Variations in the life cycle GHG emissions are due to a number of factors such as the quantity and grade of silicon, module efficiency and lifetime, as well as irradiation conditions. Unlike fossil fuel systems, most of the GHG emissions occur upstream of the life cycle with the majority of the emissions arising during the production of the PV cells and panel modules (between 50% and 80% of total; Weisser, 2007).

Figures 3.3-3.11 show the other environmental impacts from PVs. Emissions of NO_X and particulates are also significant along the life cycle, especially at the production stage of PV cells and panels, causing acidification (0.3-0.6 g SO_2-eq./kWh; Figure 3-4), eutrophication (0.03-0.3 g PO_4-eq./kWh; see Figure 3-5) and toxicity effects (Jungbluth, 2005; Jungbluth et al., 2005). The contribution of solar PV systems to other environmental impacts comprise: ADP 0.4-0.8 g Sb-eq./kWh (Figure 3-3), FAETP 11-20 g DCB-eq./kWh, HTP 50-91 g DCB-eq./kWh, MAETP 46-220 kg DCB-eq./kWh, TETP 0.5-1 g DCB-eq./kWh (Figures 3.6-3.9, respectively), ODP 2.6×10^{-6} to 1.9×10^{-5} g R-11-eq./kWh (see Figure 3-10) and POCP 0.03-0.07 g ethene-eq./kWh (see Figure 3-11). The majority of these impacts are related to the construction of infrastructure (Dones et al., 2007)

3.12.3 Economic costs and social aspects of electricity from PVs

Some of the most important barriers of PV systems are current high costs as well as the intermittency of electricity supply. The overnight capital costs of PV power plants range from 2878 to 7381 US$/kW; the LCOE vary from 185 to 932 US$/MWh (IEA/NEA, 2010).

The use of toxic materials in manufacture of some PV cells (silicon based), visual intrusion in rural and urban areas are the main aspects affecting the social acceptance of solar PV systems (Boyle, 2003; Wüstenhagen et al., 2007; Evans et al., 2009).

3.13 Electricity from wind

Electricity from wind can be generated from onshore and offshore power plants. The size of wind turbines ranges from a few kW to over 5 MW, with the largest turbines reaching more than 100 m in height. Wind turbines can operate from a wind speed of 3-

4 m/s up to about 25 m/s. The capacity factor of wind power plants is highly dependent on the site conditions, the characteristics of the wind turbine and the wind velocity conditions (Jungbluth et al., 2005; Dones et al., 2007; Weisser, 2007). The average capacity factor of wind power plants is 21% (IEA/OECD, 2009).

The application of wind turbines has grown rapidly in the recent years, with operations in around 50 countries. In terms of wind power market and country manufacturers, the German market is the largest, but there has also been significant growth in Spain, Denmark, India, China and the United States (Greenpeace and EREC, 2008).

Currently, wind energy produces 173 TWh per year worldwide with an installed capacity of 96 GW (IEA/OECD, 2009). Wind energy could potentially provide 2%-12% of global electricity production in 2050 (IEA/OECD, 2008a).

3.13.1 The life cycle of electricity from wind

As shown in Figure 3-25, the life cycle of wind power comprises fabrication of the wind turbine and construction, operation and decommissioning of the wind power plant (Jungbluth et al., 2005; Dones et al., 2007). The average life time of a wind power plant is around 20 years (Dones et al., 2007).

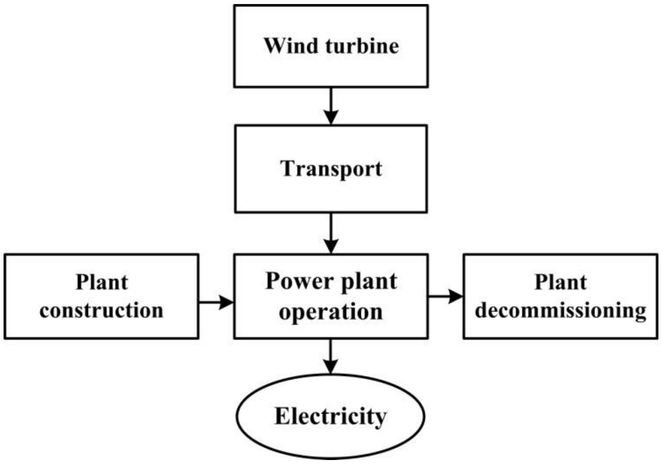

Figure 3-25 The life cycle of electricity from wind (modified from Dones et al., 2007)

3.13.2 Environmental impacts of electricity from wind

The life cycle GHG emissions form wind power plants vary between 8 and 55 g CO_2-eq./kWh (Dones et al., 2007; Weisser, 2007; see Figure 3-2), with the majority arising from the construction of infrastructure (turbine production and plant construction). In general, offshore turbines have higher life cycle GHG emissions than onshore turbines, given equal capacity factors (or wind conditions) due to the high level of emissions associated with the foundation and connection of off-shore turbines (Weisser, 2007).

The contribution of electricity from wind to other environmental impacts is shown in Figures 3.3-3.11. The majority of the impacts are related to the construction of the power plant (Dones et al., 2007) and are as follows: ADP 0.1-0.4 g Sb-eq./kWh (Figure 3-3), AP 0.05-0.3 g SO_2-eq./kWh (Figure 3-4), EP 0.01-0.04 g PO_4-eq./kWh (see Figure 3-5), FAETP 10-43 g DCB-eq./kWh, HTP 50-225 g DCB-eq./kWh, MAETP 12-53 kg DCB-eq./kWh, and TETP 1.6-6.3 g DCB-eq./kWh (Figures 3.6-3.9, respectively), ODP 6.3×10^{-7} to 3.1×10^{-6} g R-11-eq./kWh (Figure 3-10) and POCP 0.01-0.04 g ethene-eq./kWh (see Figure 3-11).

3.13.3 Economic costs and social aspects of electricity from wind

Current overnight capital costs for onshore wind power plants are between 1223 and 3716 US$/kWh, with LCOE ranging from 70 to 234 US$/MWh. The capital costs for offshore wind power plants range between 3464 to 6083 US$/kW, and LCOE are between 146 and 260 US$/MWh (IEA/NEA, 2010; see Figures 3-12 and 3-13).

Visual intrusion, land requirements, noise and bird strikes are the most important social aspects affecting the public acceptability of wind power plants (Boyle, 2003; Wüstenhagen et al., 2007; Evans et al., 2009).

3.14 Summary

An overview of the main sustainability aspects of different electricity-generating options has been presented in this chapter. The review shows that fossil fuel based power plants are still the most-widely applied technologies in the world but also that they contribute to the majority of life cycle environmental and social impacts.

Electricity from coal has the highest GWP ranging from 850 to 1300 g CO_2-eq./kWh, followed by oil and gas power plants of 500 - 1200, and 400 - 1000 g CO_2-eq./kWh, respectively. For all three options, this is mainly due to the combustion of fuels. Amongst the renewables, biomass and solar thermal power have the highest GWP, ranging from 17-388 and 10-345 g CO_2-eq./kWh, respectively. In the case of biomass, the highest life cycle GHG emissions arise during fuel production and transport; for solar thermal, the emissions are mainly due to hybrid systems operating with natural gas. Hydro power, wave energy converters, nuclear and wind power have the lowest GWP.

Electricity from coal has also the highest ADP ranging from 5-10 g Sb-eq./kWh, followed by oil and gas power plants, each ranging from 3-8 g Sb-eq./kWh, respectively. Coal and gas with CCS also have significant ADP values ranging from 3-6 g Sb-eq./kWh. Biomass and solar thermal power plants have the highest ADP among renewables, ranging from 0.1-1.1 and 0.1-1.2, respectively. Other energy systems such as hydro, ocean, solar PV, wind and nuclear have ADP values between 0.02-0.8 Sb-eq./kWh.

In the case of acidification, oil and coal-based power plants have the highest AP among energy sources, ranging from 2-17 and 0.7-11, respectively. This is because of their higher fuel sulphur content (Dones et al., 2007). The AP from coal with CCS ranges from 0.8-1.5 g SO_2-eq./kWh because of better environmental performance of new technologies with CCS (e.g. supercritical or IGCC) than the conventional systems. Gas range from 0.35-1.42 g SO_2-eq./kWh and gas with CCS from 0.3-0.5 g SO_2-eq./kWh.

AP of biomass, geothermal, solar PV and solar thermal power are also significant ranging from 0.2-0.8, 0.2-0.7, 0.3-0.6 and 0.1-0.6 g SO_2-eq./kWh, respectively.

Electricity from oil has the highest EP ranging from 0.4-1.1 g PO_4-eq./kWh because of high SO_2 and NO_x emissions from oil combustion, followed by coal and biomass ranging between 0.1-0.6 and 0.07-0.6 g PO_4-eq.kWh, respectively. The EP from coal with CCS ranges from 0.1-0.24 g PO_4-eq.kWh. Gas ranges from 0.05-0.22 g PO_4-eq./kWh mostly due to fuel combustion, and gas with CCS 0.04 g PO_4-eq./kWh. Solar PV has also significant emissions ranging from 0.03-0.33 g PO_4-eq./kWh. Other renewable energies and nuclear range between 0.002 (hydro) and 0.09 (geothermal) g PO_4-eq./kWh.

Electricity from oil has also the highest FAETP, HTP, TETP and MAETP (together with coal) ranging from 18-317, 82-2536, 2-93 g DCB-eq./kWh and 75-1877 kg DCB-eq./kWh, respectively, mostly because of emissions of heavy metals, NO_x, SO_2 and particulate matter. Coal power is also the second largest contributor to FAETP and HTP ranging from 5-111 and 58-286 g DCB-eq./kWh, respectively. Biomass and wind power have the highest HTP and TETP among renewable energies together ranging from 14-245 and 0.6-9.4 g DCB-eq./kWh, respectively. In the case of biomass, mostly due to transport and combustion of fuel and for wind power because of emissions arising during construction of power plant. Wind, biomass and solar PV have also FAETP values of concern ranging from 10-43, 3-27 and 11-20 g DCB-eq./kWh, respectively. MAETP emissions from solar PV are also significant ranging from 46-220 kg DCB-eq./kWh, arising during construction of infrastructure.

Electricity from gas has the highest ODP ranging from 1.6×10^{-5} to 1.9×10^{-4} g R-11-eq./kWh due to NMVOC emissions from gas production and transport (see Figure 3-10). Oil and nuclear power plants have also significant ODP ranging from 6.4×10^{-5} to 1.5×10^{-4} and from 5.2×10^{-7} to 6.2×10^{-5} g R-11-eq./kWh, respectively, also because of fuel supply. Renewable energies ODP range between 2.2×10^{-7} (hydro) to 1.9×10^{-5} (solar PV) g R-11-eq./kWh.

Electricity from oil has also the highest POCP, followed by biomass, coal and gas ranging from 0.2-0.9, 0.03-0.8, 0.08-0.6 and 0.04-0.3 g ethene-eq./kWh, respectively. Coal with CCS and solar PV range from 0.08-0.10 and 0.03-0.07 g ethene-eq./kWh, respectively. The POCP from gas with CCS is 0.08 g ethene-eq./kWh. Other renewable energies and nuclear range from 0.002 (hydro) to 0.04 (geothermal) g ethene-eq./kWh.

The highest average capital costs are for geothermal, followed by solar PV, solar thermal, hydro and wind offshore power plants, ranging from 1752-12887, 2878-7381, 4347-5255, 757-19930 and 3464-6083 US$/kW, respectively. In the case of geothermal, hydro and wind offshore, capital costs are high mostly due to site preparation and infrastructure installation, and for solar PV and solar thermal because of their early stage of market development (Neij, 2008; IEA/OECD, 2008a; IEA/NEA, 2010). The lowest average capital costs are for gas ranging from 520-1678 US$/kW, oil 461-1817 US$/kW, coal 602-4671 and wind onshore 1223-3716 US$/kW. CCS increases the capital costs of fossil fuel power plants by 105% for gas and 115% for coal power plants. Capital costs of biomass, ocean energy and nuclear range from 2500-7431, 2611-6354 and 1556-5863 US$/kW, respectively.

The highest average levelised costs of electricity are for solar PV, solar thermal, and oil power plants ranging from 185-932, 202-323 and 102-397 US$/MWh, respectively. In the case of solar power plants, levelised costs vary according to resource availability, power plant capacity and O&M costs, and for oil power plants because of high oil prices (IEA/NEA, 2010). The lowest average costs are for coal, gas and nuclear ranging from 33-114, 39-108 and 42-136 US$/MWh. Levelised costs of coal and nuclear are low due to low fuel costs, and for gas power plants because of low capital costs (IEA/NEA, 2010). Levelised costs of biomass, geothermal, hydro and wind power plants range from 63-197, 47-269, 23-459 and 70-260 US$/MWh, respectively.

The main social aspects of electricity generating options are mainly related to human health impacts, safety risks and public acceptability.

The environmental, economic and social aspects outlined in this chapter have been taken into consideration in this work to assess the sustainability of current and future energy scenarios for electricity production in Mexico. The next chapter presents the methodology used for these purposes.

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4. Integrated methodology for sustainability assessment of electricity options for Mexico

This chapter presents the methodology developed in this work for sustainability assessment of energy options for current and possible future electricity generation in Mexico. The methodology includes the definition and selection of sustainability indicators for the Mexican power sector, scenario analysis, life cycle assessment (LCA), economic and social analysis of current and future energy options, and multi-criteria decision analysis to help identify the most sustainable future power options for Mexico. Although the methodology is applied to the electricity sector of Mexico, it is generic enough to be applicable to other energy sectors in the country (transport, residential and industry) as well to any other country.

4.1 Sustainability assessment of energy systems

The energy sector is a major contributor to economic and industrial activities as well as a pre-requisite for the provision of basic human needs. As such, it has a potential to contribute to sustainable development. There are many definitions of sustainable development, but the most widely used is that by the Brundtland Commission which defined it as the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (WCED, 1987), with a balance among economic, social and environmental aspects. This is the definition used for the purposes of this research.

Efforts towards sustainable energy development are progressively becoming more important for policy and decision makers worldwide. Some of the main global energy policy objectives include mitigating the effects of climate change, reducing energy costs and improving security of energy supply (IEA/OECD, 2008; Streimikiene, 2010; Stamford and Azapagic, 2011). Meeting these policy aims is predicated on the identification of sustainable energy options based on various technical, economic, environmental and social sustainability indicators. This is an area of a lively research activity (e.g. IAEA, 2005; May & Brennan, 2006; Hirschberg et al., 2008; Evans et al., 2009; 2010; Chatzimouratidis and Pilavachi, 2009a;b; Jacobson, 2009; Kowalski et al., 2009; Roth et al., 2009; Wang et al., 2009; Gallego-Carrera and Mack, 2010; Rovere et al., 2010; Lior, 2010; Onat and Bayar, 2010; PSI, 2010; Gujba et al, 2010; 2011; Stamford and Azapagic, 2011).

Literature reveals several studies discussing sustainability aspects of energy systems (Hennicke and Fischedick, 2006; May & Brennan, 2006; Koskela et al., 2007; Ness et al., 2007; Anderson et al., 2008; Mander et al., 2008; Chatzimouratidis and Pilavachi, 2009a;b; Hirschberg et al., 2009; Jacobson, 2009; Karger and Hennings, 2009; Kowalski et al., 2009; Roth et al., 2009; Singh et al., 2009; Evans et al., 2009; 2010; Gujba et al., 2010; 2011; Dorini et al., 2010; Onat and Bayar, 2010; Jeswani et al., 2011; Keles et al., 2011; Stamford and Azapagic, 2011). These studies vary according to the system boundaries (e.g. global or at the national level), sustainability indicators (e.g. technical, environmental, economic and social), methodologies for the assessment of indicators (e.g. quantitative and qualitatively) and methods for ranking energy options (e.g. subjective, MCDA). Most of these studies focus on the power plant level (see for example Chatzimouratidis and Pilavachi, 2009a;b; Hirschberg et al., 2009; Jacobson, 2009; Roth et al., 2009; Evans et al., 2009; 2010; Stamford and Azapagic, 2011) and consequently literature does not reveal a framework by which the sustainability of an electricity mix might be assessed.

In an attempt to address this gap, this study presents a novel sustainability framework designed specifically for that purpose. Although the work is motivated by the need to assess the sustainability of electricity options in Mexico, the framework is generic and applicable to any electricity technology regardless of its location.

The methodology involves identification of sustainability issues and indicators, scenario definition (base case and future scenarios), data collection, environmental, economic and social assessment of scenarios and multi-criteria assessment. As far as the author is aware, this is the first time such a methodology has been proposed and used. This is described in the following sections.

4.2 Integrated methodology for sustainability assessment of electricity options for Mexico

As outlined in Figure 4-1, the first step in the methodology is definition of the aims and scope of the research. Definition of the scope involves specifying the system boundaries, electricity options to be considered and the time horizons. The aims and the scope of the research are described in Section 4.3. In the next stage, sustainability issues for the electricity options are identified, followed by the definition and selection of related sustainability indicators to allow the sustainability assessments of different electricity options and scenarios. The issues and the related indicators have been discussed in Chapter 3; the indicators are further discussed in Section 4.4 of this chapter. The electricity scenarios are defined in the following methodological step and are outlined in Section 4.5 and discussed in detail in Chapter 6.

The completion of the above steps helps to identify data needs so that data collection can be carried out as part of the next stage. It involves collection of technical, economic, environmental and social data. The data are then fed into different models and tools to enable electricity options and scenarios to be evaluated on sustainability. Life cycle assessment (LCA) has been used for the environmental sustainability assessment; capital, annualised and levelised costs have been estimated for the economic assessment and various social aspects have been considered for the analysis of social sustainability. The respective methodologies for the environmental, economic and social assessments are outlined in Sections 4.7.1-4.7.3. The results of the sustainability assessments can be found in Chapters 5, 7 and 8.

The results are then considered within multi-criteria decision analysis (MCDA) to help compare different options on a range of sustainability criteria in a more systematic and structured way. The MCDA methods used in this work are described in Section 4.8. This is followed by the sensitivity analyses to identify the criteria that influence the outcomes of the study and ensure that the results are robust. The results of the MCDA and sensitivity analyses are presented in Chapter 9. Finally, the conclusions and policy recommendations have been made based on the results of this work and these are presented in the final Chapter 10.

The following sections describe in more detail the individual methodological steps, following Figure 4-1.

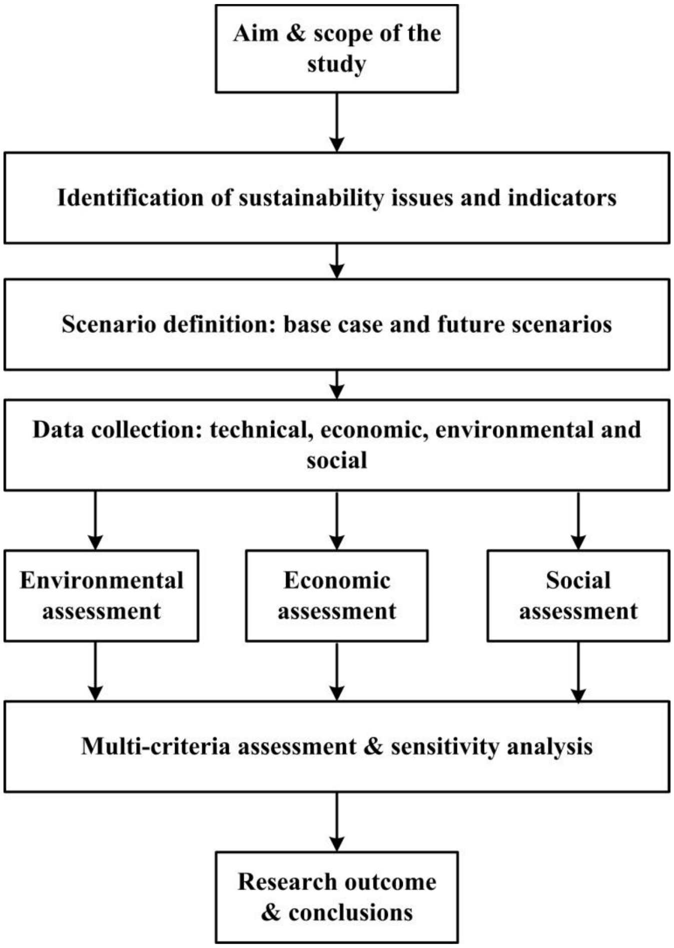

Figure 4-1 Integrated methodology developed in this work for the sustainability assessment of electricity options for Mexico

4.3 Aim and scope of the study

As mentioned previously, the aim of this work is to evaluate the environmental, economic and social implications of different electricity options for Mexico, and to determine the most sustainable options for the future. This work has been motivated by the current Mexico's objective to reduce by 50% its GHG emissions from the energy sector by year 2050 compared to 2000; this corresponds to 85% reduction of GHG emissions from its power sector. Alternative GHG reduction targets have also been considered in this work: stabilization of GHG emissions, 60% and 85% reduction, all on the 2000 levels, following the different IPCC reduction targets (IPCC, 2007). These are summarised in Table 4-1 Energy scenarios for the electricity sector in Mexico in 2050 (all relative to 2000).

The system boundaries in this work, for the environmental assessment, are drawn from 'cradle to grave' considering all activities from extraction and conversion of raw materials and fuels to electricity production (without considering transmission and distribution), also including construction and decommissioning of power plants. The socio-economic assessment comprises also fuel supply, construction of power plants and operation to produce electricity; except decommissioning. Therefore, a life cycle approach has been adopted in this work and the life cycles of different electricity options have been discussed in Chapter 3. The electricity options considered in this work have also been discussed in Chapter 3 and are further elaborated on in the subsequent chapters. The time horizon studied covers the period from 2006 to 2050. 2006 has been chosen as a base year since this is the year for which the most recent and complete data have been available (see Chapters 2 and 5 for details) and 2050 is the usual time horizon considered in studies that are climate-change motivated.

4.4 Identification of sustainability issues and indicators

Sustainability issues and indicators for the Mexican power sector have been selected following the current energy, environmental and wider sustainability drivers at the national and international levels (e.g. IAEA, 2005; Medina-Ross et al., 2005; May &

Brennan, 2006; Greenpeace and EREC, 2008a;b; SENER, 2008; Hirschberg et al., 2008; 2009; IEA/OECD, 2008; 2009; Chatzimouratidis and Pilavachi, 2009a;b; Evans et al., 2009; Jacobson, 2009; Wang et al., 2009; Gallego-Carrera and Mack, 2010; Rovere et al., 2010; Gujba et al., 2010; 2011; Stamford and Azapagic, 2011). The issues and indicators reported in literature have been used as a guide (as discussed in Chapter 3 and in Section 4.1) and have been adapted to Mexican conditions (as discussed later in the dissertation).

In this study, the environmental indicators used are those typically considered in LCA as discussed in Chapter 3; an overview of the LCA methodology used here is given in Section 4.7.1; for the definitions of LCA impacts see Appendix 1. These indicators have also been used in other LCA studies of electricity systems (e.g. May & Brennan, 2006; Koornneef et al., 2008; Lechon et al., 2008; Dorini et al., 2010; Frick et al., 2010; Gujba et al., 2010; 2011; Jeswani et al., 2011; Stamford and Azapagic, 2011; Singh et al., 2011).

Table 4-1 Energy scenarios for the electricity sector in Mexico in 2050 (all relative to 2000)

Scenario (Source)	GHG reduction target by 2050*	Main drivers
BAU (IEA, 2004; Greenpeace and EREC, 2008b)	None	• 85% of total electricity from coal and gas • Contribution from oil decreases • No CCS • Low contribution from renewables and nuclear
Green (Greenpeace and EREC, 2008b)	72% reduction of CO_2 emissions from 2005 levels	• 86% of total electricity from renewables (mainly wind and solar) • No contribution from oil and nuclear • No CCS
A [A1-A3] (Current study)	Stabilization (A-1), 60% (A-2) and 85% reduction (A-3) on 2000 levels	• High contribution from renewables (mainly wind, solar and hydro) • Diversity of supply (including fossil-fuel CCS and nuclear) • No oil power
B [B1-B3] (Current study)	Stabilization (B-1), 60% (B-2) and 85% reduction (B-3) on 2000 levels	• Based on fossil fuels (with CCS • Diversity of supply (including renewables and nuclear) • No oil power
C [C1-C3] (Current study)	Stabilization (C-1), 60% (C-2) and 85% reduction (C-3) on 2000 levels	• Based on nuclear power • Diversity of supply (including fossil-fuel CCS and renewable energies) • No oil power

*Refers only to reduction of direct emissions from the operation of power plants

For the economic sustainability assessment, three economic indicators have been selected: total capital costs; total annualised costs; and levelised costs (unit costs of electricity generation). These have been discussed in Chapter 3 for different electricity options; the methodology for estimating these costs is outlined in Section 4.7.2. These indicators are used to compare generation costs across technologies and give some indication of the attractiveness of investing in different electricity options (e.g. IEA/NEA 2005; 2010; UKERC, 2006; 2007; Roth et al., 2009; Streimikiene, 2010; del Rio, 2011; Gujba et al., 2010; 2011).

The social aspects of electricity options considered here are security and diversity of supply, public acceptability, health and safety, and intergenerational issues. These aspects are of great concern when assessing the sustainability of electricity generating options (e.g. Boyle, 2003; Medina-Ross et al., 2005; Grubb et al., 2006; Costantini et al., 2007; IEA/OECD, 2008; 2009; Azapagic and Perdan, 2011; Stamford and Azapagic, 2011). Most of these indicators have been discussed for the electricity technologies in Chapter 3. The description of these indicators is presented in section 4.9.

4.5 Scenario definition: base case and future options

Scenario analysis emerged in response to the limitations of forecasting approaches to forward planning and it was developed as means of exploring alternative futures, which may or may not happen (Dreborg, 1996; Robinson, 2003). Scenario development for energy analysis was first used by Shell in the 70s and has since become one of the main tools for addressing the complexity and uncertainty inherent in long-term strategy development in the energy arena (Kowalski et al., 2009).

Therefore, scenario analysis has been used in this work to help explore sustainability implications of different possible futures for the Mexican power sector. Eleven scenarios have been considered looking out to 2050 and are compared to the base case, corresponding to the current power sector in Mexico (based on the data for 2006). The future scenarios represent a combination of the previous work by other authors (IEA, 2004; Greenpeace and EREC, 2008b) and options developed within this work, as follows (see Table 4-1):

i) The International Energy Agency (IEA) scenario for Mexico which assumes business as usual (BAU) in terms of electricity mix and production and no climate change targets (IEA, 2004; Greenpeace & EREC, 2008b);

ii) The Greenpeace scenario for Mexico ('Green'), which considers efficiency improvements and reduction of energy demand as well as a 72% CO_2 reduction by 2050 from 2005 levels (Greenpeace and EREC, 2008b); and

iii) Own scenarios A, B and C, based on the climate change mitigation and security and diversity of energy supply drivers (but other sustainability aspects such as energy efficiency improvements and reduction of other related environmental impacts, have also been considered). Each of these three scenarios has further three sub-scenarios considering stabilization, 60% and 85% reduction of GHGs from 2000 levels. Scenario A is mainly based on the large-scale renewable energy technologies (wind, solar and hydropower). In scenario B, fossil fuels (gas and coal) remain as the main energy sources for the future but integrated with a large-scale CCS. Scenario C is based mainly on nuclear power, with significant contributions from renewable energies.

Unlike most other scenario analyses which focused mainly on direct CO_2 or GHG emissions (e.g. Greenpeace and EREC, 2008b; IMP, 2009) , this work takes a life cycle approach and considers not only GHG emissions but also a range of other environmental impacts of possible future electricity supply in Mexico. As far as the author is aware, this is the first time such a study has been carried out for the Mexican electricity sector.

The assumptions and data for the base case (current situation in Mexico) are given in Chapter 5 and the future electricity scenarios are described in detail in Chapter 6.

4.6 Data collection and sources

This step of the research methodology has involved collection of information and data related to technical, environmental, economic, social and policy aspects of the Mexican power sector (see Table 4-2). Examples of these include: historical and current data on energy consumption and production in Mexico, energy mix and technologies currently used, installed capacity and yearly electricity production, operating parameters for power plants (e.g. load factor, efficiency, lifetime, emission controls), capital and operating costs of power generation from different energy technologies. Scenario development and analysis have been informed by current and future energy policies, global and national energy and environmental drivers, life cycle impacts for new power plant technologies, electricity supply projections and cost trends (fuel, capital and operating costs).

Table 4-2 Data collected by scenario and data sources

Data collected	**Scenario**	**Data source**
Energy and technological data: e.g. installed capacity, electricity production, electricity fuel mix, power plant technologies, power plant efficiencies, load factors	• Base case (year 2006) • Future scenarios	• SENER (2006a, 2006b, 2006c, 2006d) • Greenpeace and EREC (2008b)
Environmental data: • Direct emissions from current power plants in Mexico • Life cycle emissions of current power plants (except direct emissions) • Life cycle emissions of future power technologies	• Base case • Base case • Future scenarios	• Estimated with Gemis (Oko Institute, 2005) • Estimated with GaBi (PE International, 2007) using Econivent (Dones et al., 2007) • NEEDS project (2009), Ecoinvent (Dones et al., 2007), and Gemis (Oko Institute, 2005)
Economic data: Fuel costs, capital, fixed and variable costs of power plant technologies	• Base case • Future scenarios	• IEA (2009), IEA/NEA (2010), EIA (2009) • NEEDS (2009), Greenpeace and EREC (2008a), EIA (2009)

Additional information and data were collected through personal communication with members from the Mexican Energy Sector (mainly from the Ministry of Energy and Environment and other government institutions as well as researchers). This information, gathered via interviews and emails, is related to current Mexican energy policies, energy sector interests and drivers for both today and for the future, and data availability (energy, technical, environmental, economical and social aspects).

As mentioned in the previous section, the data for the base case and the future scenarios can be found in Chapters 5 and 6, respectively.

4.7 Sustainability assessment

The sustainability assessment carried out in this work has involved environmental, economic and social assessments of the base case and future electricity scenarios for Mexico. The following sections outline the methodologies and tools used for each aspect of sustainability – LCA, economic costing and social indicators.

4.7.1 LCA methodology

LCA is an environmental sustainability assessment tool used to quantify the environmental impacts in the life cycle of a system (product, process, service or activity). LCA can be used for different purposes, including comparison of alternative systems or identification of opportunities for improvements in the system (Baumann and Tillman, 2004; Azapagic et al., 2004). LCA has been used in this work to compare different electricity technologies as well as the current electricity mix with future scenarios. The results of this work are presented in Chapters 5-7.

The following life stages are typically considered in the life cycle of a system: extraction and processing of raw materials; manufacturing; transportation and distribution; use, reuse and maintenance; recycling; and disposal (see Figure 4-1). The life cycle of different electricity options has been discussed in Chapter 3 and all these stages have been included within the system boundary for the analysis of the electricity options considered in this work. Furthermore, the construction and decommissioning of the power plants has also been considered.

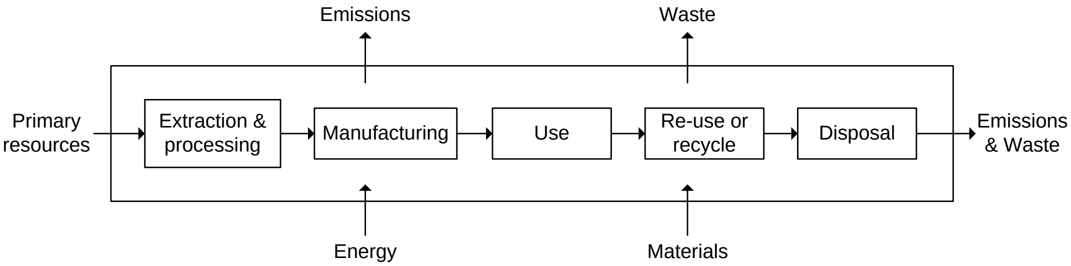

Figure 4-2 Stages in the life cycle of an activity considered by LCA (Azapagic, 1999)

The LCA methodology is standardised by the ISO standards (ISO 14040 and ISO 14044) and as shown in Figure 4-3 it involves four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a; b).

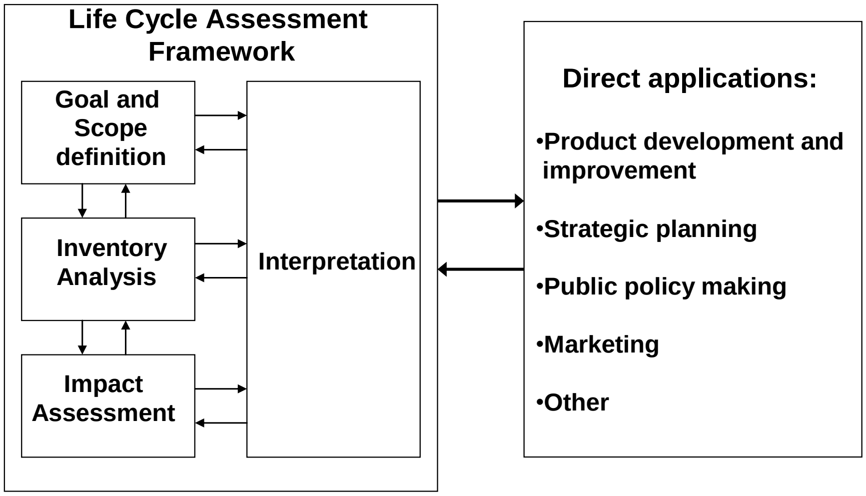

Figure 4-3 LCA framework and applications (based on ISO, 2006a).

The first, goal and scope definition phase, defines the purpose of the study, the system boundaries and the functional unit. The purpose of the LCA study in this work is to assess and compare the environmental sustainability of different electricity options for Mexico and the system boundaries are drawn from ‘cradle to grave’. Two functional units are defined:

i) generation of 1 kWh of electricity; and

ii) total generation of electricity in Mexico in one year.

The former is used to compare different electricity options and the latter to assess different future electricity scenarios, in comparison to each other and the base case. For the detailed description of the functional units, as well as the system boundaries and assumptions for the base case and future scenarios, see Chapters 5 and 6&7, respectively.

Inventory analysis involves detailed system descriptions, data collection, quantification of environmental burdens and if relevant, their allocation. The burdens are defined as the materials and energy used in the system and emissions to air, water and land. They also describe the type of data that need to be collected for each part of the system and the life cycle stage which are then summed up across the whole life cycle to calculate the burdens as follows (Azapagic et al., 2003):

$$B_u = \sum_{n=1}^{N} bc_{u,n} x_n \tag{4.1}$$

where $bc_{u,n}$ is the burden coefficient associated with the material or energy flow x_n in a process or activity. An example would be an emission of CO_2 (burden $bc_{u,n}$) generated per tonne of natural gas (material flow x_i) used to generate electricity (process or activity) (Bell, 2001; Azapagic et al., 2003). The same approach has been used in this work to calculate the burdens from the electricity systems considered here. The results of the inventory analysis can be found in Chapters 5 and 7.

The environmental burdens are then ‘translated’ into potential environmental impacts in the next, life cycle impact assessment (LCIA) phase of LCA. ISO 14044 specifies four stages within LCIA: i) impact classification, ii) characterisation, iii) normalisation, and iv) valuation (ISO, 2006b). The former two are mandatory and the latter two are optional.

Classification involves aggregation or assignment of environmental burdens according to the type of environmental impact they contribute to. The impacts most commonly considered in LCA are related to resource use, human health and ecological aspects. In turn, these impacts are classified into different impact categories, and the most commonly considered in LCA include: global warming, resource depletion, ozone depletion, acidification, eutrophication, photochemical ozone formation, human toxicity, aquatic and terrestrial ecotoxicity (Azapagic et al., 2004; Pehnt and Henkel, 2009; Finnveden et al., 2009). All these impacts have been considered in this research. In the characterisation step, the burdens calculated in the Inventory phase are multiplied by a 'characterisation' factor to determine a quantitative contribution of each burden to the appropriate impact categories as follows (Azapagic et al., 2003):

$$E_k = \sum_{u=1}^{U} ec_{k,u} B_u \tag{4.2}$$

where $ec_{k,u}$ represents the characterisation factor or contribution of burden B_u to impact E_k relative to a reference substance. For example, the characterisation factor for CO_2 quantifying its contribution to climate change is 1 kg CO_2 eq./kg CO_2. The characterisation factors for CH_4 and N_2O are expressed relative to CO_2 and are 25 kg CO_2 eq./kg CH_4, and 298 kg CO_2 eq./kg N_2O (IPCC, 2007).

Different methods can be used to calculate the impacts in LCIA. In this work, the CML 2001 method (Guinée et al., 2001) has been used as one of the most-widely applied approaches in LCA studies. It follows the problem-oriented approach summarised above and expressed by eq. 4.2. The impact categories used in this method are described in Appendix 1 and the results of the LCIA for the Mexican electricity sector can be found in Chapters 5 and 7.

The impacts can also be normalised on the total impacts in a certain area over a given period of time (Azapagic et al., 2003). However, normalisation results should be interpreted with care, as the relative contributions from some impact categories at the local and regional scale (e.g. human toxicity, acidification) may look considerably smaller and sometimes negligible compared to a total impact at a global scale (e.g.

global warming, abiotic depletion) (Azapagic et al., 2003; Gujba, 2009). Normalisation has not been performed in this work.

Valuation, the last step of LCIA, involves weighting of different environmental impact categories reflecting the relative importance they are assigned in the study (Finnveden et al., 2009). This reduces the multiple impacts to a single environmental impact function as a measure of environmental performance (Azapagic et al., 2003):

$$EI = \sum_{k=1}^{k} w_k E_k \tag{4.3}$$

where w_k is the weighting factor of the environmental impact E_k. For example, on a scale of 1 to 10, each impact can be assigned a score (or weight) w_k from 1 to 10 to indicate its importance in relation to other impacts; the higher the score the higher the 'importance' of the impact to the decision-makers (DM).

A number of multi-criteria decision analysis (MCDA) techniques have been suggested for use in Valuation. They are mainly based on expressing preferences either by decision-makers, 'experts' or the public. Some of these methods include multi-attribute utility theory, analytic hierarchy process, impact analysis matrix, and cost–benefit analysis among others. However, due to the subjectivity of the weighting approach, there is still no consensus at present on how to aggregate the environmental impacts into a single environmental impact function (Azapagic et al., 2003; Finnveden et al., 2009). Valuation of environmental impacts has not been performed at the LCA level; instead, multi-criteria decision analysis (MCDA) has been used to aggregate different sustainability indicators (environmental, economic and social), as discussed in Section 4.8.

Finally, in the last phase of LCA, Interpretation, the LCIA results are evaluated in order to draw conclusions and propose improvements. Interpretation includes: identification of major burdens and impacts in the system under study, sensitivity analysis, evaluation of results and final recommendations (ISO, 2006b). The LCA results from this work are discussed in Chapters 5 and 7.

4.7.2 Economic assessment

Economic assessment of electricity generation systems commonly involves(see e.g. May and Brennan, 2006; Krewitt et al., 2007; 2009; Gujba et al., 2010; 2011; Jeswani et al., 2011; McNerney et al., 2011):

i) capital;

ii) total annualised; and

iii) levelised costs. These costs have also been considered in this work and the methodology for their estimation is outlined below; for the ease of comparison with other works, all costs are expressed in US$. The results of the economic assessment of the Mexican power sector can be found in Chapters 5 and 8; an overview of the overnight and levelised costs of various electricity options was also given in Chapter 3.

i) Capital (or investment) costs comprise all costs of construction and installation of power plants within the energy system. In this work, they are calculated as ‘overnight’ costs, i.e. costs without paying any interest on the borrowing (IEA/NEA, 2010):

$$TC_C = \sum C_C E \quad \text{(US\$)} \tag{4.4}$$

where :

TC_C = total capital costs (US$)

C_C = Overnight capital costs of electricity generating option (US$/kW)

E = Installed capacity of electricity generating option (kW)

ii) The total annualised cost of an energy system is defined as (see e.g. Gujba, 2009; McKerney et al., 2011; UKERC, 2007):

$$TAC = \sum AC_C + \sum F_C + \sum V_C + \sum f_C \quad \text{(US\$/yr)} \tag{4.5}$$

where:

TAC = total annualised cost of generating electricity (US$/yr)

AC_C = annualised capital cost (US$/yr)

F_C = annual fixed costs (maintenance and repair) (US$/yr)

V_C = annual variable costs (all variable costs excluding fuel costs) (US$/yr)

f_C = annual fuel costs (US$/yr).

The annualised capital costs (AC_c) is calculated taking into account the total capital cost and an annuity factor (f) as follows:

$$AC_C = TC_C f \text{ (US\$)} \tag{4.6}$$

$$f = \frac{z(1+z)^t}{(1+z)^t - 1} \tag{4.7}$$

where:

TC_c = total capital costs (US$)

z = discount rate

t = lifetime of the power plant (years).

The annual fixed costs F_C comprise the costs to operate a power plant over a year and include operational staff costs, insurances, taxes, repair or spare parts costs. The variable annual costs V_C include expenses related, for example, to contracted personnel, consumed materials and costs for disposal of operational waste per year, excluding fuel costs (Gujba, 2009; Streimkiene, 2010). The annual fuel costs f_C represent the cost of fuels consumed for electricity production per year.

iii) The levelised costs or total generating costs represent the cost of electricity generated over the lifetime of a power plant, expressed per unit of electricity per year. It is calculated by dividing the total annualised cost (*TAC* in eq. 4.5) by the total annual electricity generation for the same year:

$$LC = TAC / AE \text{ (US\$/MWh)} \qquad (4.8)$$

where:

TAC = total annualised cost of generating electricity (US$/yr)
AE = Annual electricity generation (MWh/yr).

4.7.3 Social assessment

As mentioned previously, the selection of the social criteria selected for the social analysis in this work has been motivated by the following issues:

i) security and diversity of supply;
ii) public acceptability;
iii) health and safety;
iv) intergenerational issues.

The description of these indicators is given in the following sections. Most of these issues were outlined in Chapter 3 and are discussed for the Mexican power sector in Chapter 8.

i) Security and diversity of supply

Energy security and the diversity of energy supply, along with climate change mitigation, are the most important energy drivers globally and at the country level (IEA/OECD, 2008; 2009; Costantini et al., 2007). Security and diversity of supply is defined as ‘a system’s ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy’ (Grubb et al., 2006).

Among the most important factors affecting the security and diversity of supply are: rapid depletion of energy reserves (fossil fuels and uranium), uncertainty of future fossil fuel prices, together with the disruption of fuel supply because of political conflicts (especially related to oil) or due to intermittency of electricity supply and so affecting the reliability of an electricity system. Fuel import dependency has also become a critical aspect for sustainability of energy systems also because depletion of fossil fuel reserves (Gagnon et al., 2002; Boyle, 2003; Grubb et al., 2006; Costantini et al., 2007; Krewitt et al., 2007; 2009; Greenpeace and EREC, 2008a; IEA/ OECD, 2008; 2009; Kowalski et al., 2009; Lior, 2010).

The IEA/OECD (2008), together with other organizations (e.g. Greenpeace and EREC, 2008a), has argued that, in order to meet security of energy supply for the future, it is essential to promote a diversification of the energy sector based on low carbon technologies. For this reason, the financial support and appropriate energy policies are essential for the development of these technologies (Krewitt et al., 2007; Anderson et al., 2008; Jacobson, 2009; Kowalski et al., 2009; Gallego-Carrera and Mack, 2010; Nakata et al., 2010).

Security and diversity of electricity supply is an important aspect for Mexico since its energy mix is based on fossil fuels and, as discussed in Chapter 2, the existing fossil fuels reserves are insufficient to meet the country’s demand for more than nine years (Medina-Ross et al., 2005; PEMEX, 2008). Security and diversity of supply is also one of the most important drivers for sustainable development in Mexico, as discussed later Chapter 6 (SENER, 2008).

Aspects considered in this study to assess the security and diversity of electricity supply in Mexico comprise:

- depletion of fossil fuel reserves;
- import dependency;
- availability of energy resource; and
- reliability of supply.

Depletion of fossil fuel reserves is an important indicator for the security of electricity supply in Mexico because of the fast depletion of fossil fuels reserves and the potential to affect future generations. In this work, abiotic reserve depletion (ADP), calculated as part of LCA, has been used as the indicator to assess this social impact.

Import dependency has also been assessed especially for scenarios based on fossil fuels, based on the assumption that fossil fuels will have to be imported by 2050 to meet Mexico’s electricity supply (as indicated in Chapter 6). This aspect has become even more critical due to the significant increase of gas imports for electricity production in Mexico (SENER, 2006c; d). Moreover, it is expected that contribution from gas to the electricity mix will increase from 42% today to 55% in 2050. A similar concern applies for coal, expected to increase from 14% to 35% in 2050 (Greenpeace and EREC, 2008b).

Besides fossil fuels, availability of energy resource is also related to the renewable energy potential for electricity generation (Krewitt et al., 2008). This indicator has been discussed for future scenarios with high contribution from renewable energies to the electricity mix. The reliability of an electricity supply system reflects its ability to maintain service continuity which is difficult for intermittent sources such as wind, solar and ocean (Gagnon et al., 2002; Boyle, 2003). Literature does not reveal any methodology for accounting for the reliability of an energy mix; instead power plant availability (the percentage of time that a plant is available to produce electricity) is often used as one measure of reliability (e.g. Chatzimouratidis and Pilavachi, 2009; Stamford and Azapagic, 2011). For the current work, this indicator discusses the possible implication of high contribution of intermittent energy sources to the electricity mix of scenarios.

ii) *Public acceptability*

Public acceptability is key to implementation of any technology, and therefore, future electricity options (Gagnon et al., 2002; Evans et al., 2009; 2010; Lokey, 2009; Pehnt and Henkel, 2009; Wang et al., 2009; Gallego-Carrera and Mack, 2010; Onat and Bayar, 2010; Ruiz-Mendoza & Sheinbaum-Pardo, 2010).

This aspect has been considered for all the scenarios according to the public acceptability issues for electricity generating technologies outlined in Chapter 3. For example, main issues affecting the implementation of wind and solar are related to land requirements, visual intrusion, and noise. For large hydro power plants, lack of public acceptance is mainly associated with transformation of land use and relocation of population. Main social concerns for biomass are related to competition for agricultural land, water and food production. In the case of nuclear power, public acceptability is mainly affected by health and safety issues due to the likelihood of nuclear accidents, nuclear proliferation and radioactive waste management and storage. Public acceptance is also an important issue for fossil fuels-based power plants with CCS due to the uncertainty of possible impacts on humans and the environment.

iii) *Health and safety*

This indicator comprises human health impacts and safety risks and hazards along the life cycle of electricity generating options. These aspects have already been discussed in Chapter 3 for the different electricity technologies. For example, the main health concerns from fossil fuels arise from emissions of SO_2, NO_x, particulate matter and heavy metals from the operation of power plants.

Health issues have been quantified in the current work using human toxicity potential (HTP) estimated within LCA. A similar approach has been taken by some other authors, including Dorini et al. (2010) and Stamford and Azapagic (2011).

Safety risks are mostly related to occupational accidents and public hazards (e.g. injuries and fatalities affecting direct workers and the public) and accident risks along their life cycle (e.g. explosions, oil spills, etc.). Similarly, health and safety concerns for nuclear power include nuclear accidents, nuclear proliferation and risk from terrorism as well as intergenerational issues related to radioactive waste management and storage (Rashad &

Hammad, 2000; Krewitt et al., 2007; Greenhalgh and Azapagic, 2009; Gallego-Carrera and Mack, 2010; Lior, 2010; Azapagic and Perdan, 2011; Goodfellow et al., 2011). The health and safety issues for different scenarios, with emphasis on fossil fuels and nuclear are discussed in Chapter 8.

iv) *Intergenerational issues*

Within the sustainable development context (WCED, 1987), intergenerational aspects are referred to problems which affect current and future generations, and therefore addressing these problems is essential (Azapagic and Perdan, 2011).

Some of the most important intergenerational issues, outlined in Chapter 3, include mitigation of climate change and depletion of fossil fuel reserves (Krewitt et al., 2007, 2009; Greenhalgh and Azapagic, 2009; Lior, 2010; Stamford and Azapagic, 2011). In this work, GWP and ADP estimated by LCA, are used to assess these two issues. These indicators have also been used by other authors for the same purposes (e.g. May & Brennan, 2006; Gujba et. al., 2010; 2011). Intergenerational issues associated with long-term nuclear waste management has also been considered as part of this analysis.

4.8 Multi-criteria decision analysis

In real life, decisions are usually made by comparing different options on several, often conflicting, criteria (Dorini et al., 2010). In most cases, there is generally no overall best option, as switching from one option to another is likely to result in an improvement in one criterion and deterioration in some other criteria. MCDA provides effective techniques for assisting decision makers (DM) in solving such problems (Dorini et al., 2010; Streimikiene, 2010).

MCDA methods have become popular in decision making for sustainable energy because of the multi-dimensionality of the sustainability goals and the complexity of socio-economic systems. Generally, the MCDA problem for sustainable energy involves a number of alternatives that need to be evaluated on a number of sustainability criteria (Løken, 2007; Kowalski et al., 2009; Wang et al., 2009; Rovere et al., 2010).

MCDA typically starts by identification of alternatives and decision criteria. This can be followed (or carried in parallel) by elicitation from DMs of preferences for different criteria to indicate the relative importance of the selected criteria. For an overview of MCDA methods, see e.g. Azapagic and Perdan (2005a; b).

The MCDA approach used in this study is outlined in Figure 4-4. The steps followed are discussed below. Note that this analysis has been carried out without the involvement of DMs so that a range of potential preferences has been considered as part of sensitivity analysis to find out how the results and outcomes of the analysis may change. The result from the MCDA can be found in Chapter 9.

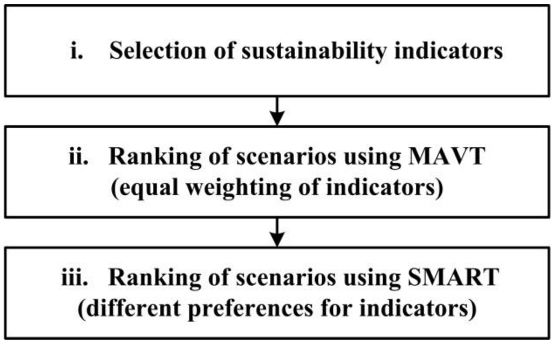

Figure 4-4 The MCDA approach applied for the sustainability assessment of scenarios for the Mexican power sector

i) Selection of sustainability indicators

The first step involves selection of the indicators to be considered in MCDA. In this work, all environmental and economic indicators are included. Apart from HTP, all other social indicators are excluded from MCDA due to their qualitative nature; however, they are discussed separately in light of the MCDA findings (see Chapter 9).

ii) Ranking of scenarios using MAVT (equal weighting of indicators)

In this step, all the indicators are considered to be of equal importance and the scenarios are ranked based on their performance on the individual criteria. Multi-attribute value theory (MAVT), as one of the most widely used MCDA methods, has been used for these purposes.

The MAVT method involves determination of partial value functions and establishing weights for each criterion to calculate a global value function *V(a)* and it is represented by the following equation (Azapagic and Perdan 2005b; Loken, 2007):

$$V(a) = \sum_{i=1}^{m} w_i u(a) \qquad (4.8)$$

where:
V(a): overall score for each alternative *a*
w_i: weight assigned to reflect the importance of criterion *i*
u(a): value function reflecting the performance of alternative *a* on criterion *i*

First, a value function *u(a)* reflecting the performance of alternative *a* on criterion *i* are estimated. These values are the environmental and economic criteria for each scenario. In the case for Mexico, the 11 alternatives (scenarios) are ranked (normalized) according to each environmental and economic criterion, using a scale from 1 to 11; with 1 being the best option while 11 being the worst option. Then, an overall sustainability score *V(a)* is estimated according to the weighting of criteria w_i and the value function *u(a)* (see eq. 4.8). The alternatives are ranked according to the sustainability scores using a scale from 1 to 11, with 1 being the most sustainable option (see for example Jacobson, 2009).

iii) Ranking of scenarios using SMART (different preferences for indicators)
In this step, sensitivity analysis is carried out to find out if the ranking of the scenarios changes with different weighting of the indicators. The simple multi-attribute rating technique (SMART) has been used for these purposes (Wang et al., 2009). In SMART,

the criteria are ranked according to their relative importance from the worst to the best levels. A value of 10 points is assigned to the least important criteria, and increasing number of points (without an explicit upper limit) are assigned to the other criteria to express their importance relative to the least important criteria; the weights are calculated by normalizing the sum of the points to one.

In this work, the weighting has been carried out in two ways:
i) first, higher preference is given to one indicator at a time with all other indicators assuming equal importance; GWP, HTP and annualised costs have been chosen as the most important indicators in this part of the analysis; and
ii) higher preference is assigned to three indicators (GWP, HTP and annualised costs) at the same time.

An example of the weighting of criteria used in this study can be found in Appendix 5.

4.9 Summary

This chapter has outlined the integrated methodology developed and used for the sustainability assessment of the Mexican power sector to help identify more sustainable electricity options for the future. The methodology involves identification of sustainability issues and indicators, scenario definition (base case and future scenarios), data collection, environmental, economic and social assessment of scenarios and multi-criteria assessment of future scenarios. As far as the author is aware, this is the first time such a methodology has been proposed and applied to the Mexican conditions.

The next chapter presents the results of the LCA study and economic analysis of the current electricity sector in Mexico. The future scenarios are discussed in Chapters 6-8. The MCDA analysis and final discussion of results are given in Chapter 9.

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5. Environmental and economic assessment of the Mexican power sector

This chapter presents the results of the Life Cycle Assessment (LCA) and economic analysis of the current electricity sector of Mexico. The chapter starts by defining the electricity system and the assumptions, followed by discussion and validation of the results. The study is based on the data for 2006 which represents the base year in this study. The methodologies for LCA and economic analysis have been outlined in chapter 4.The LCA study is based on the work that has already been published by the author of this dissertation as part of this research (Santoyo-Castelazo et al., 2011).

5.1 Life cycle assessment

The LCA methodology used in this study follows the ISO 14040 and 14044 guidelines (ISO, 2006a; 2006b). The data sources and the approach to estimating the environmental impacts are outlined in Figure 5.1 and are discussed further in the next sections. As shown in the figure, the LCA software GaBi has been used to estimate the environmental impacts (PE International, 2007)

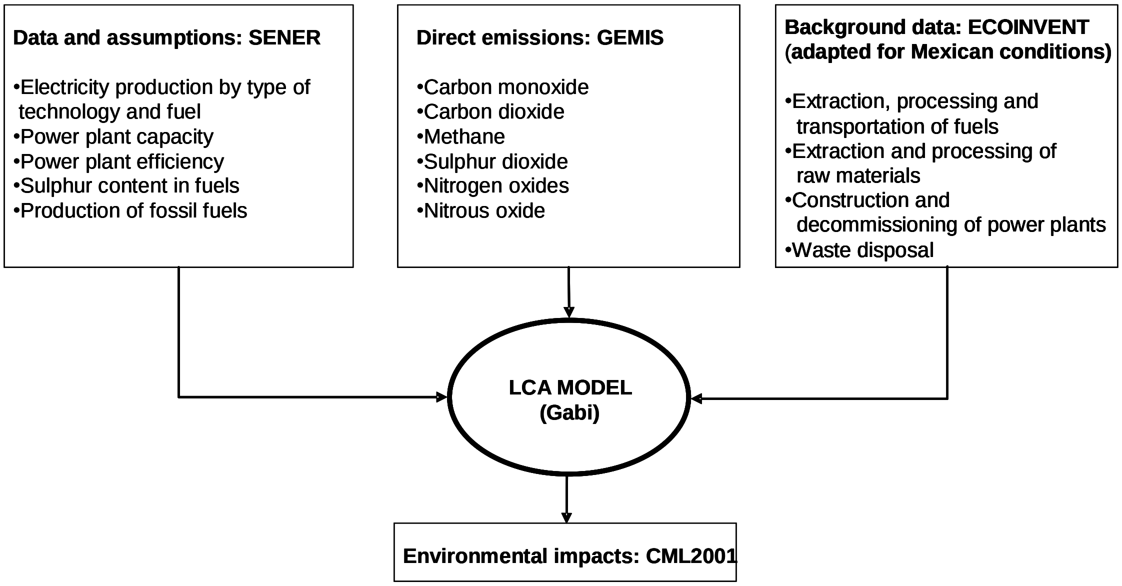

Figure 5-1 Methodology and data sources used to estimate the environmental impacts from the Mexican electricity sector (Source: Santoyo-Castelazo et al., 2011)

5.1.1 Goal and scope of the study

The main goal of this study is to evaluate the life cycle environmental impacts of electricity generation in Mexico, using year 2006 as the base year.

The system boundaries are from ‘cradle to grave’, comprising the following life cycle stages (see Figure 5-2): extraction of fuels and raw materials, processing and transportation of fuels; manufacture and construction of infrastructure; operation of power plants to generate electricity; construction and decommissioning of power plants; and waste disposal.

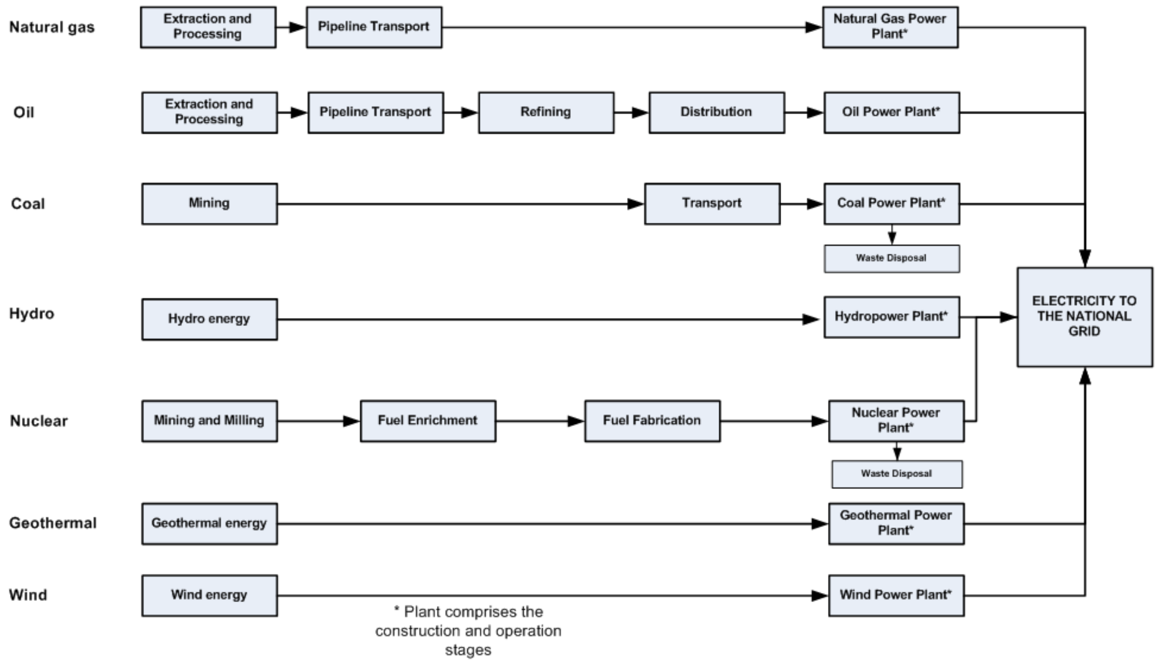

Figure 5-2 The life cycle of electricity generation in Mexico (Santoyo-Castelazo et al., 2011)

The functional unit is defined as the total annual amount of electricity generated by this sector in the base year, in this case 225 079 GWh generated in 2006 (SENER, 2006a). Of the total, fuels contributed 79%, hydro 13.5%, nuclear 4.8%, geothermal 3% and wind power 0.02% (SENER, 2006b).

The impacts per 1 kWh have also been calculated, to enable comparisons of individual electricity options as well as with the impacts from other countries with a similar electricity mix, including Italy, Portugal and the UK.

The data for this study are based on the 2006 National Energy Balance (NEB), reported by SENER (2006b). The NEB reports the total electricity produced by non-renewable fuels (heavy fuel oil, natural gas, coal, diesel and uranium) and renewable resources (hydro, geothermal and wind), including the total fuel or energy resource consumption.

The direct emissions from the power plants have been calculated using the operating parameters such as power plant efficiency, type of fuel and technology (see Table 2-4 in

Chapter 2) as well as fuel composition in Mexico (Appendix 2). The GEMIS database (Öko Institute, 2005) has been used for these purposes (see Figure 5-1).

The background data have been sourced from the Ecoinvent database (Frischknecht et al., 2004). These data have then been adapted to reflect Mexican conditions, e.g. using the appropriate electricity mix, fuel composition, waste disposal methods, etc.

The following assumptions have been made with respect to the source and production of fossil fuels:

- all heavy fuel oil is produced domestically, of which 20% is produced onshore and 80% offshore (Villasenor et al., 2003; EIA, 2007);
- 92% of natural gas is produced domestically and the remaining 8% is imported from the USA (PEMEX, 2006, SENER, 2006c); of this, 67% of gas is produced onshore and 33% offshore (EIA, 2007);
- 56% of coal is produced domestically and the remaining 44% is imported (SENER, 2006b); and
- gas venting (5%) and flaring (0.3%) during oil and gas production within the country have been taken into consideration (PEMEX, 2006).

To estimate the direct emissions from the power plants, the following assumptions have been made with respect to the power plants, fuel composition, efficiencies and emissions control:

- the average sulphur content in heavy fuel oil is 3.6% and in diesel 0.5%; in the domestic coal it is 1% and in imported coal it is 0.5% (Vijay et al., 2004);
- dual steam turbine (DST) uses only coal;
- all gas power generation is by combined-cycle power plants;
- the average thermal efficiencies for the power plants have been taken from the NEB database (SENER, 2006b); these are shown in Table 1; and
- no emission controls are installed as this is not compulsory in Mexico; the exception to this are particulates for which electrostatic precipitators are used (Vijay et al., 2004).

5.1.2 Life cycle inventory

Table 5-1 and Figure 5-3 show the life cycle emissions to air, expressed per kWh and GWh per year, respectively. Full inventory results can be found in Appendix 2. As can be seen from Table 5-1, the life cycle emissions of CO_2, SO_2, NO_x, and N_2O for the fossil fuel options are mainly contributed to by the direct emissions from the combustion of fuels. The highest total CO_2 emissions are from the coal (1045 and 1046 g/kWh for domestic and imported, respectively), followed by heavy fuel oil (898 g/kWh), diesel (809 g/kWh) and gas (446 g/kWh) power plants. Heavy fuel oil has the highest emissions of SO_2 (18.98 g/kWh) followed by domestic coal (8.14 g/kWh); it also contributes the highest emissions of NMVOC (1.46 g/kWh) and particular matter (2.60 g/kWh). Diesel power plants contribute the highest NO_x emissions (8.05 g/kWh). The emissions of N_2O are similar across the fossil fuel options. The life cycle emissions from the renewable energies and nuclear power are mainly from the construction of infrastructure (Frischknecht et al., 2004); the exception to this is geothermal power, where the majority of CO_2 and SO_2 are from direct emissions (Öko Institute, 2005).

Table 5-1 Direct and life cycle emissions from different electricity-generating options in Mexico (Frischknecht et al., 2004; Öko Institute, 2005; Santoyo-Castelazo et al., 2011)

Fuel		**Emissions (g/kWh)**						
		CO_2	**CH_4**	**SO_2**	**NO_x**	**N_2O**	**NMVOC**[a]	**PM**[b]
Coal (domestic)	Direct	980	0.02	7.58	4.3	0.04	0.02	0.62
	Life cycle	1045	1.45	8.14	5.16	0.04	0.13	2.23
Coal (import)	Direct	982	0.02	3.77	4.3	0.04	0.02	0.62
	Life cycle	1046	1.44	4.32	5.15	0.04	0.13	2.22
Heavy fuel oil	Direct	799	0.03	18.55	2.09	0.03	0.05	2.51
	Life cycle	898	2.27	18.98	2.41	0.03	1.46	2.6
Gas	Direct	412	0.04	0.003	1.57	0.03	0.04	0.004
	Life cycle	446	0.59	0.02	1.69	0.03	0.24	0.02
Diesel	Direct	709	0.05	2.25	7.75	0.02	0.89	1.63
	Life cycle	809	2.01	2.7	8.05	0.02	2.13	1.71
Hydro	Life cycle	4	0.01	0.01	0.01	0.0001	0.002	0.02
Nuclear	Life cycle	11	0.02	0.05	0.04	0.0005	0.009	0.03
Geothermal	Life cycle	130	0.02	2.71	0.02	0.0001	0.004	0.03
Wind	Life cycle	17	0.05	0.05	0.04	0.0007	0.01	0.06

[a] NMVOC = non-methane volatile organic compounds
[b] PM = particulate matter

Based on these results, the total life cycle emissions of CO_2 in 2006 were 121.3 Mt (Figure 5-3), to which heavy fuel oil and gas contributed around 36% each and coal 27%. The majority of emissions of CH_4 (51%), SO_2 (80%), NMVOC (70%) and particulate matter (63%) were also due to heavy fuel oil. Gas power is overall the second highest contributor to air emissions. Renewable energies and nuclear power contributed collectively less than 1% of the total emissions.

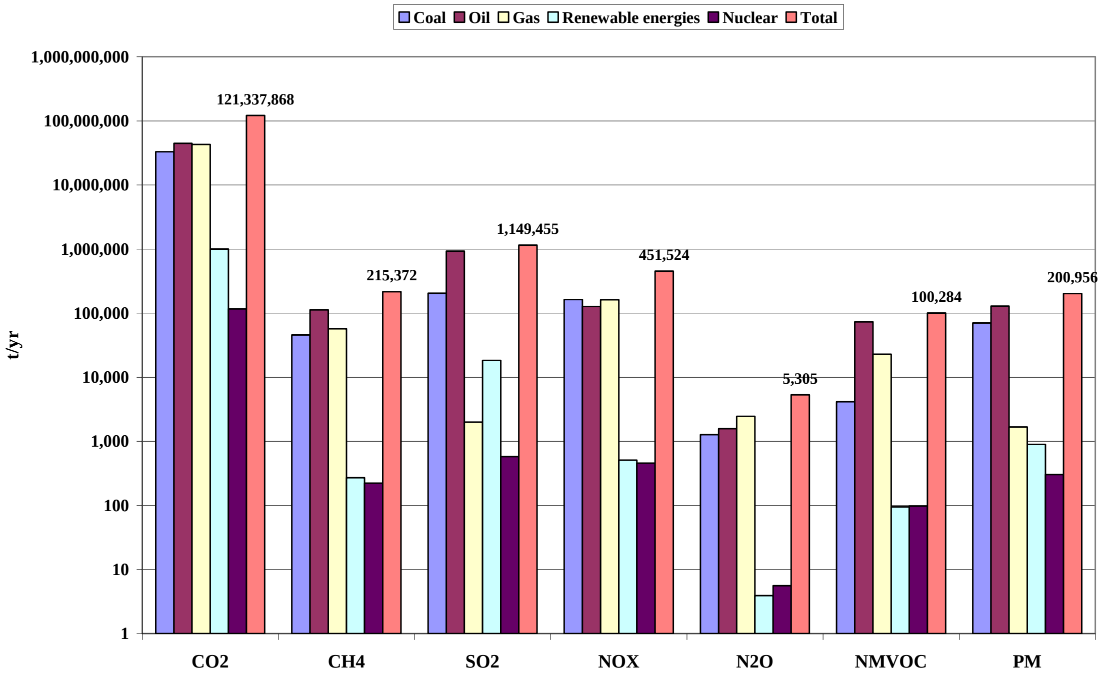

Figure 5-3 Selective life cycle environmental burdens from electricity generation in Mexico in 2006 [Oil comprises heavy fuel oil and diesel] (Santoyo-Castelazo et al., 2011)

5.1.3 Life cycle impact assessment and interpretation

The environmental impacts have been estimated using the CML 2001 method (Guinée et al., 2001). These results are presented in Figure 5-4 and Figure 5-5, showing the total annual and impacts per kWh, respectively. Figure 5-6and Figure 5-7 show the contributions to impacts of different electricity generating options in the integrated electricity system (GWP, and other impacts, respectively). The following sections discuss each impact in turn; the full results for each impact and the contribution of the life cycle stages can be found in Appendix 2.

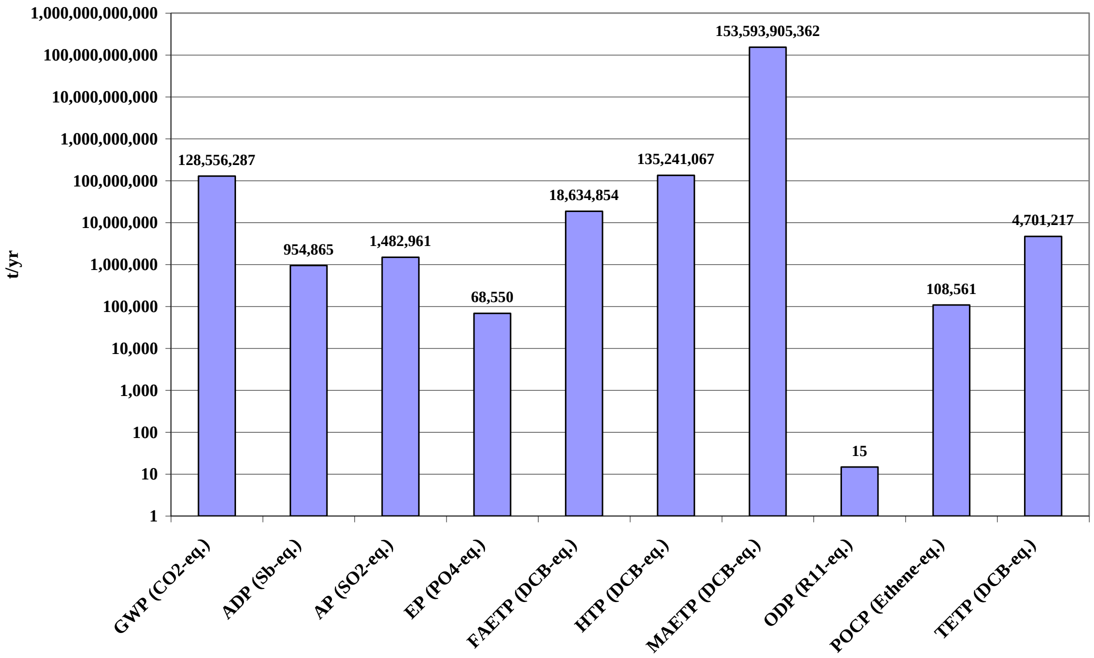

Figure 5-4 Total environmental impacts per year (2006) (Santoyo-Castelazo et al., 2011)[GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

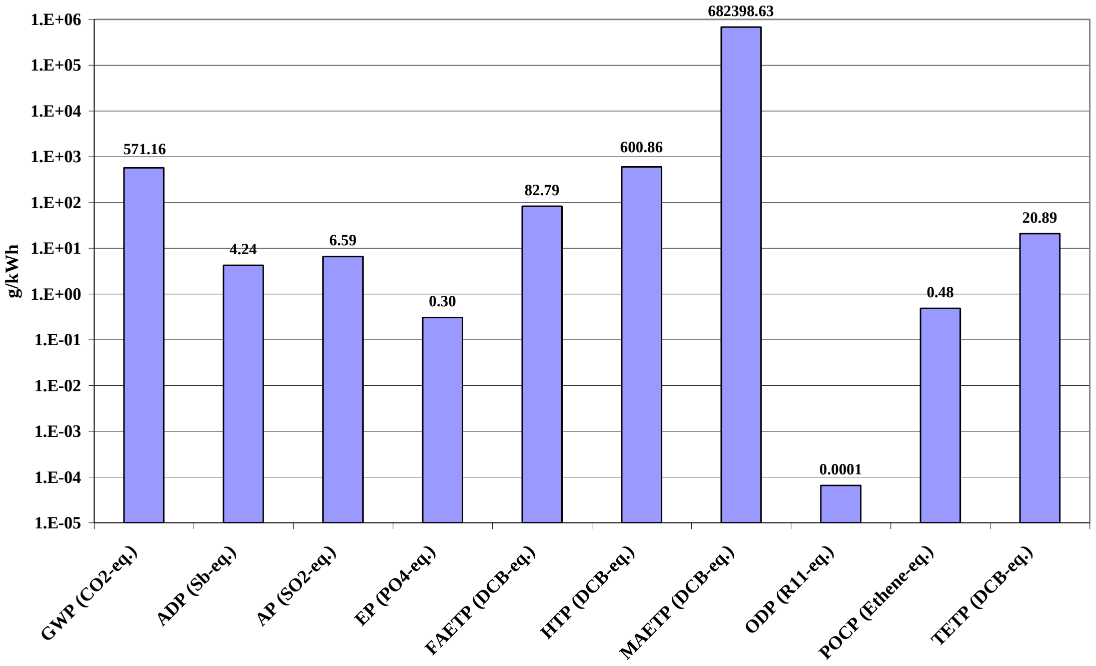

Figure 5-5 Environmental impacts per kWh (Santoyo-Castelazo et al., 2011)[GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential].

Global Warming Potential

The total GWP over 100 years (GWP100) from electricity generation in Mexico in 2006 is estimated at about 129 million t CO_2 eq./yr. The CO_2 emissions account for about 94% of the total GWP100, with contributions of 4.2% and 1.2% from CH_4 and N_2O, respectively. The estimated direct emissions are equal to 112.04 million t CO_2 eq./yr which is in close agreement with the data reported in the 2006 national GHG emissions inventory (112.46 million t CO_2 eq./yr) (CMNUCC, 2009). As discussed in the previous section, the main source of the GHGs emissions is the operation (combustion) of the fossil fuelled power plants, contributing 87% to GWP100 (see Figure 5-6). Production of fossil fuels contributes 11.8% to the total; of which extraction of oil and gas contribute 39.3%, mainly due to gas flaring during the extraction of fuels (see Appendix B for further details). Other energy options (hydro, wind, geothermal and nuclear) contribute only 1.1% to the total GWP100.

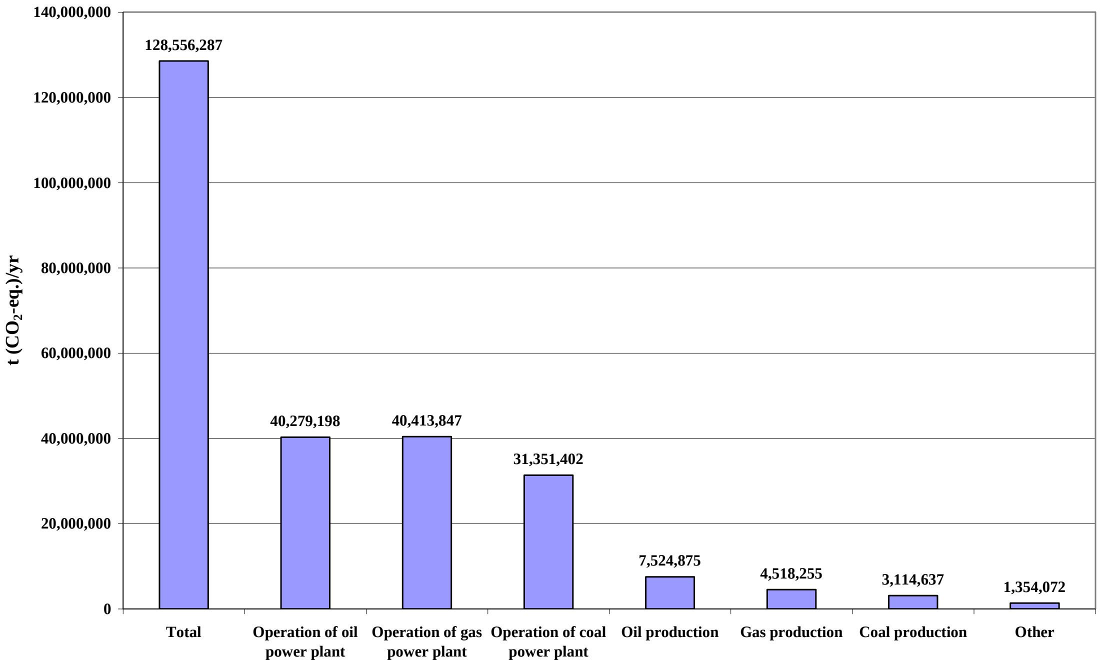

Figure 5-6 Contribution to GWP100 of different electricity options in Mexico (Santoyo-Castelazo et al., 2011) [Gas, oil and coal production comprise the extraction, processing, transport, storage and distribution of fuels. Oil comprises heavy fuel oil and diesel. Other represents hydro, geothermal, wind and nuclear power]

Other impacts

Like GWP, the operation of fossil-fuel based power plants is also responsible for the majority of other environmental impacts (Figure 5-7). This is discussed briefly below.

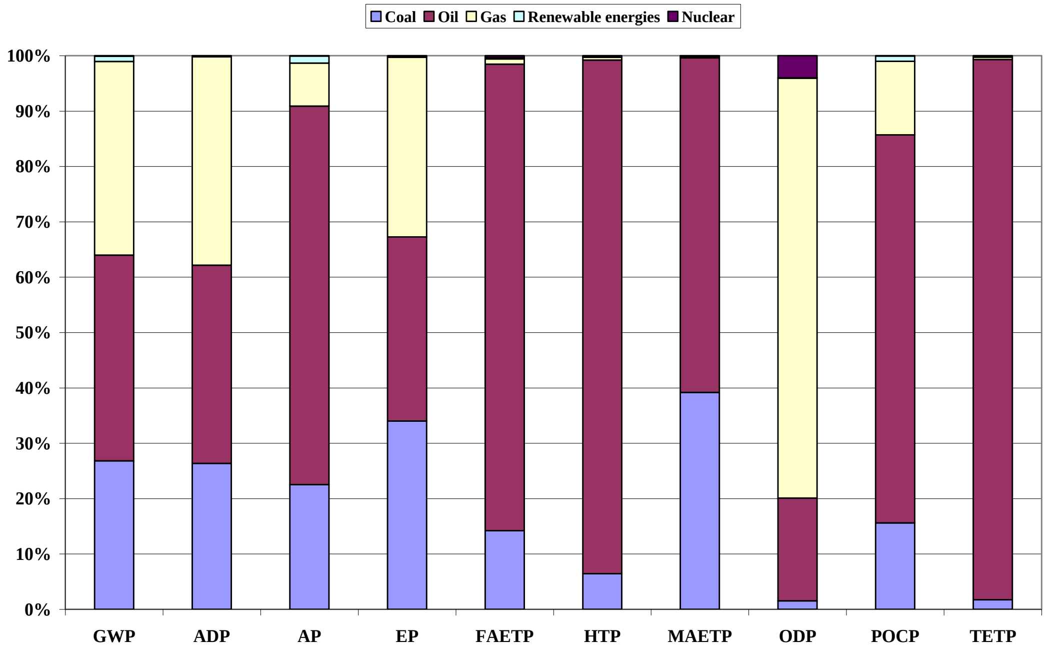

Figure 5-7 Contribution of different electricity technologies to the total impacts (Santoyo-Castelazo et al., 2011)

Abiotic depletion potential (ADP): Generation of electricity in Mexico in 2006 was responsible for an estimated 1 million t Sb-eq./year. Natural gas extraction accounts for about 36% of the total ADP, mainly due to the high contribution of natural gas to the electricity mix (42%). Crude oil extraction and coal mining contribute 32% and 25% to the total ADP, respectively.

Acidification potential (AP): Over 65% of 1.5 million t SO_2-eq./yr is from the operation of heavy fuel oil power plants, mainly due to the high sulphur content (3–4%) of the oil (see Appendix 2). The second largest contributor is the operation of the coal power plants (20%), mainly due to the sulphur content (1%) of the domestic coal and the imported coal (0.5%). Thus, the SO_2 from the operation of fuel oil power plants is the major burden, accounting for 77% of AP. NO_x emissions, mainly due to the operation of gas power plants, contribute a further 21% of this impact. The remaining small contributions are from hydrogen chloride (0.8%), ammonia (0.2%) and hydrogen fluoride (0.2%), emitted from coal power related activities.

Eutrophication potential (EP): The operation of coal, heavy fuel oil and gas power plants contributes 27%, 24% and 30% to the total of 69 kt PO_4-eq./yr, respectively. NO_x emissions from these power plants account for 86% of EP. Waterborne emissions to fresh and sea water contribute further 8%, mainly due to operation of heavy fuel oil power plants and heavy fuel oil production.

Freshwater aquatic ecotoxicity potential (FAETP): This impact is estimated at 19 million tonnes of dichlorobenzene (DCB) eq. per year. Like other ecotoxicity impacts, it is mainly caused by the operation of the fuel oil and coal power plants, which contribute 82% and 13%, respectively. The most significant burdens are emissions of heavy metals to air (63.9%) and to fresh water (35.7%). Operation of the heavy fuel oil power plants accounts for 99% of the total heavy metal emissions to air, mainly dominated by vanadium (89%) and nickel (9%). Heavy metals emitted to water comprise mainly vanadium (52%), beryllium (20%) and nickel (13%) from the operation of heavy fuel oil and coal power plants.

Human toxicity potential (HTP): Most of the 135 million t DCB eq./yr of the human toxicity impact is caused by the emissions related to fuel oil plants (92%); a further 5.8% is caused by the coal power plants. Emissions of heavy metals to air (mainly nickel, vanadium and arsenic) are the major burdens, accounting for almost 83% of the total impact, of which 98% is attributable to the operation of fuel oil plants. Other inorganic emissions to air, such as hydrogen fluoride (from coal power plants) and NO_x (mainly from gas and coal power plants) account for 2.9% and 0.4% of the total HTP, respectively.

Marine aquatic ecotoxicity potential (MAETP): Estimated at 154 Gt DCB eq./yr, this impact is also mainly due to the operation of the fuel oil and coal power plants which contribute respectively 59.3% and 38.5% to the total. The emissions to air of hydrogen fluoride (mainly from coal power plants) and vanadium (mostly from operation of heavy fuel oil power plants) are the major burdens contributing to this impact, accounting for 36.5% and 48.6%, respectively.

Ozone layer depletion potential (ODP): The estimated ODP of 15 t R11 eq./yr is mainly caused by the extraction of gas and oil and long distance transport of gas which contribute 52.5%, 14.1 and 17.4%, respectively. Emissions of non-methane volatile organic compounds (NMVOC), such as halons 1211, 1301 and R114 are the main contributors to this impact (72%, 24% and 4% of total ODP, respectively).

Photochemical ozone creation potential (POCP): The total POCP from electricity generation in Mexico is estimated at 109 kt/yr. Around 70% of this impact is from the operation of heavy fuel oil power plant, the extraction of oil and coal power plants (44%, 22% and 13%, respectively). The major contributing burdens include SO_2, NMVOC and NO_x emissions which account for 51%, 33%, and 12%, respectively. Most of the SO2 emissions are due to the combustion of heavy fuel oil; the NMVOC emissions are mainly from oil production while NO_x emissions are mainly from the operation of gas and coal power plants.

Terrestrial ecotoxicity potential (TETP): Similar to HTP, the operation of heavy fuel oil power plants is responsible for the majority (97%) of this impact, which is estimated at 5 million t DCB eq./yr. Emissions of heavy metals to air account for almost all TETP (99%) with vanadium from oil power plants contributing the majority (87%). Chromium and nickel, also mostly from oil, and mercury from coal power plants contribute 5.3%, 4.2% and 1.4%, respectively.

5.1.4 Validation of the LCA results

The validation of the findings of this study has been carried out at two levels:

i. at the level of the integrated national electricity mix whereby the results have been compared with the values reported for other countries with the similar electricity mix; and
ii. at the level of individual technologies and fuels contributing to the Mexican electricity generation.

Comparison with other countries

Three countries with a similar electricity mix to Mexico have been considered here: Italy, Portugal and the UK (see Appendix 2 for their respective electricity mix). As an example, a comparison of the GWP estimated in this study with the equivalent results for the other three countries is given in Figure 5-8.

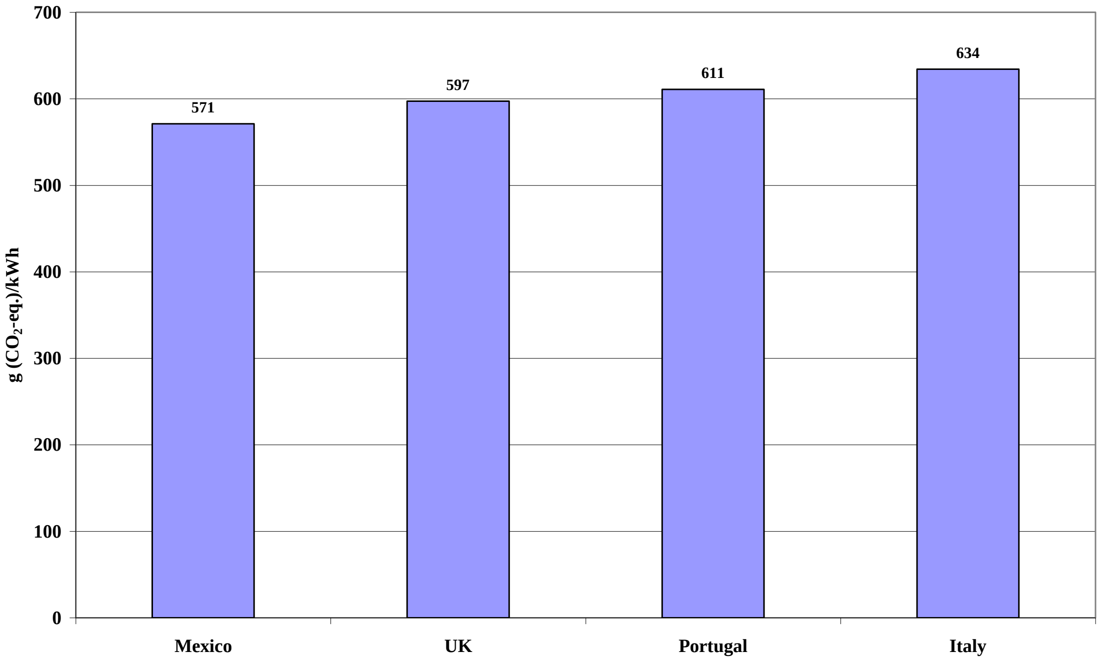

Figure 5-8 Comparison of the GWP100 for the Mexican electricity mix with other countries (Santoyo-Castelazo et al., 2011)

The GWP from the electricity mix in Mexico is estimated in this work at 571 g CO_2 eq./kWh (by dividing the total GWP in t CO_2 eq./yr by the amount of electricity generated in 2006). The GWP values reported in the Ecoinvent database for the UK, Portugal and Italy are 597, 611 and 634 g CO_2 eq./kWh, respectively (Frischknecht et al., 2007). The difference between the values for Mexico and Italy is mainly due to the efficiency and type of technology used in the gas power plants. According to the Ecoinvent database, only steam turbines are used for gas power generation in Italy while the combined-cycle (CC) power plants are used in Mexico. The average efficiency for the Mexican CC power plants is 44.5% (SENER, 2006b) against 37.5% reported for Italy in Ecoinvent (Frischknecht et al., 2007).

On the other hand, the slightly higher values for the UK and Portugal than for Mexico are mainly due to the larger contribution from coal to the electricity mix in these two countries (33.6% and 33%, respectively) compared to Mexico (14%). However, the values for the UK and Portugal are lower than for Italy due to the larger contribution from nuclear and hydro power to the electricity mix in the UK and Portugal, respectively (see Appendix 2).

Of the countries considered here, the Italian electricity mix is closest to the Mexican (e.g. 78.9% and 78.7% of fossil fuels, respectively), so that the results for the other environmental impacts obtained in this study are compared to the results for the Italian situation. These are shown in Figure 5-9.

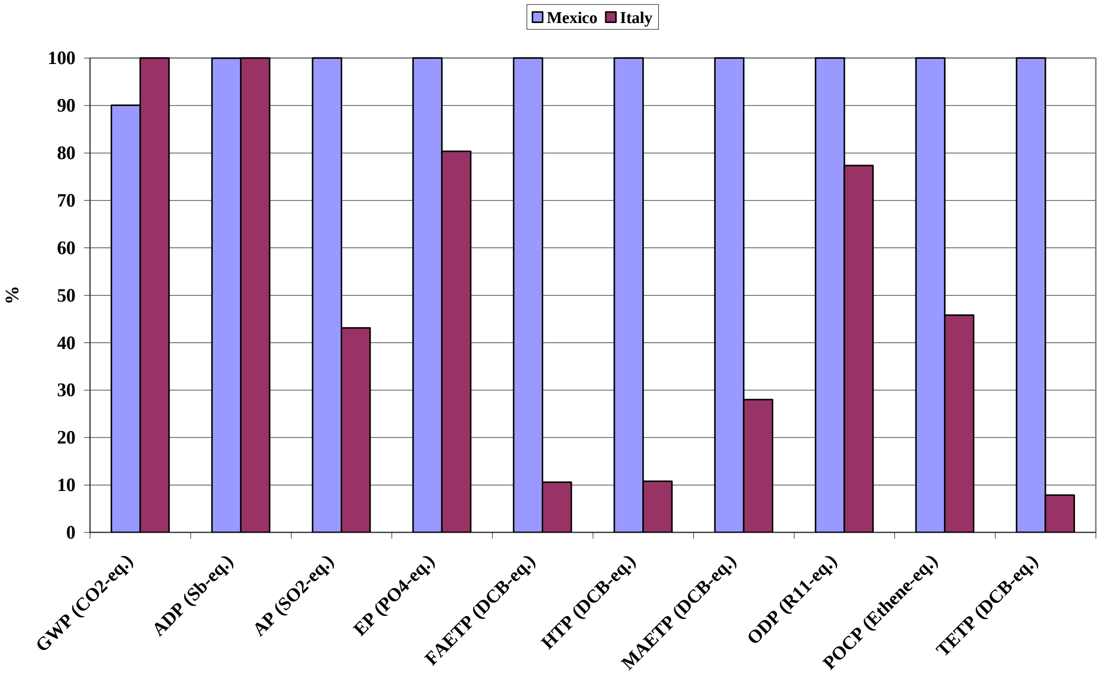

Figure 5-9 Comparison of environmental impacts for Mexico and Italy (Santoyo-Castelazo et al., 2011)

It can be observed from the figure that the majority of the impacts are higher for Mexico (apart from GWP100). This is mainly due to a higher contribution from heavy fuel oil to the electricity mix in this country (21.6% against 16.1% in Italy; Appendix 2) as well the lack of emission control technologies for coal power plants. According to Ecoinvent (Frischknecht et al., 2007), coal power plants operated in Italy include Selective Catalyst Reduction (SCR) and Flue Gas Desulphurisation (FGD) units for SO_X and NO_X emissions reduction respectively, as well as Electro Static Precipitators (ESP) for particle removal. Only the ESPs have been considered in the case of Mexico, to reflect the current situation in the country.

Comparison of electricity technologies and fuels

For the purposes of the validation of the results at the level of electricity-generating technologies and the fuels used in Mexico (as opposed to the integrated electricity mix discussed above), GWP has been considered as an example (Figure 5-10). Due to the high contribution of fossil fuels to the Mexican electricity mix, the focus is on these fuels and the related technologies. Each of the major three fossil fuel types (coal, oil and gas) is discussed in turn below.

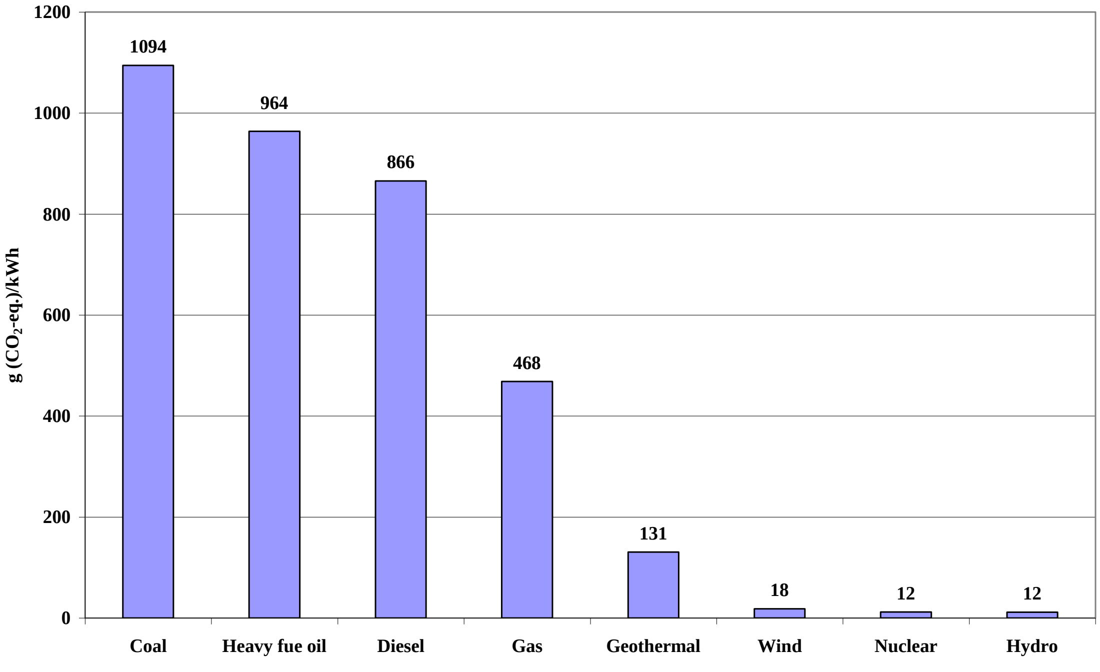

Figure 5-10 GWP for power plants operated in Mexico (Santoyo-Castelazo et al., 2011) [These results have been obtained using the data in Table 5.1 and applying the CML method (Guinée et al., 2001) for estimation of GWP]

GWP for coal-based technologies: As shown in Figure 5-10, with 1094 g CO_2 eq./kWh, power from coal has the highest GWP, approximately twice as much as the electricity from gas. Heavy fuel oil has the second highest GWP at 964 g CO_2 eq./kWh, followed closely by power from diesel. At the other end of the spectrum are hydro and nuclear power with the lowest GWP (about 12 g CO_2 eq./kWh), followed by wind (18 g CO_2 eq./kWh) and geothermal power (131 g CO2 eq./kWh). The comparison of these results with some other reported values is given in Table 5-2.

Table 5-2 Emissions of CO_2 and GWP100 for the Mexican electricity mix compared with the literature data (Hondo, 2005; Kannan et al., 2007; Weisser, 2007; Odeh and Cockerill, 2008)

Plant type	Study	Power plant specifications			CO_2 emissions (g CO_2/kWh)		GWP100 (g CO_2-eq./kWh)	
		Carbon content (%)	Load factor (%)	Efficiency (%)	Direct	Life cycle	Direct	Life cycle
Coal	Current study	67[a]; 67.5[b]	79	35.8	981[d]	1046[d]	992	1094
	Odeh and Cockerill (2008)	60	80	35	882	990	N/A[c]	N/Ac
	Weisser (2007)	N/A[c]	N/Ac	27–47	N/A[c]	N/A[c]	800–1000	950–1250
Oil	Current study	84.6	46	34.9	799	898	809	964
	Hondo (2005)	N/A[c]	70	36.2	704	742	N/A[c]	N/A[c]
	Kannan et al. (2007)	N/A[c]	80	36	N/A[c]	N/A[c]	N/A[c]	889
	Weisser (2007)	N/A[c]	N/A[c]	N/A[c]	N/A[c]	N/A[c]	700–800	740–910
Gas	Current study	0.02	67	44.5	412	446	420	468
	Kannan et al. (2007)	N/A[c]	80	50	N/A[c]	N/A[c]	N/A[c]	474–493

[a] Domestic; [b] Imported; [c] Not Available; [d] Average for domestic and imported coals

As can be seen from the table, direct emissions from coal-fired power plants range between 800 and 1000 g CO_2 eq./kWh, whereas the life cycle emissions are between 950 and 1250 g CO_2 eq./kWh (Weisser, 2007). The estimated direct emissions from a coal power plant in Mexico are well within this range, with 992 g CO_2 eq./kWh for the operation of the power plant and 1094 g CO_2 eq./kWh over the whole life cycle.

These results for coal power plant also compare well with the values reported by Odeh and Cockerill (2008). In that work, the combustion of coal at power plant accounted for 882 g CO_2/kWh while the total emissions of CO_2 over the life cycle were 990 g/kWh. These values are lower than those estimated for Mexico (981 and 1046 g CO_2/kWh for the operation and life cycle, respectively) mainly due to the carbon content in the coal. As shown in Table 5.2, a 60% carbon content was considered by Odeh and Cockerill (2008), while 67% and 67.5% has been assumed for the domestic and imported coal used in Mexico, respectively. Due to the limited data availability on coal composition in Mexico, these values were sourced from the generic values for coal composition in GEMIS (Öko Institute, 2005).

GWP for oil-based technologies: For oil-fired power plants, the reported GWP for the operation stage ranges between 700 and 800 g CO_2 eq./kWh (see Table 5-2). The upstream emissions, primarily during exploration and extraction of oil, transport and refinery, add further 40-110 g CO_2 eq./kWh, so that the total life cycle emissions range from 740 to 910 g CO_2 eq./kWh. Similar results have been found in this study, with the direct emissions of 809 g CO_2 eq./kWh and the life cycle emissions of 964 g CO_2 eq./kWh.

Hondo (2005) reported direct and life cycle emissions for an oil based power plant operated in Japan as 704 g CO_2/kWh and 742 g CO_2/kWh, respectively. The equivalent results for Mexico are 799 and 898 g CO_2/kWh. These are higher mainly due to the lower average power plant efficiency (34.9% against 36.2% for Japan) and load factor (46% compared to 70% for Japan; see Table 5-2).

A similar but smaller discrepancy is noticed with the results by Kannan et al. (2007) for Singapore. The authors report the life cycle GWP of 889 g CO_2 eq./kWh for an oil-fired power plant; this compares with the value reported in the present work of 964 g CO_2 eq./kWh. The difference in the results is also mainly due to the power plant thermal efficiency (34.9% for Mexico against 36% for Singapore) and the load factor (46% for Mexico compared to 80% for Singapore; Table 5-2).

GWP for gas-based technologies: As shown in Table 5-2, several authors reported quite different GWP values for natural gas technologies, ranging from 468 to 780 g CO_2 eq./kWh. The results obtained in this study are equal to 468 g CO_2 eq./kWh for a 400

MW combined-cycle plant and are closest to the results reported by Kannan et al. (2007) which are in the range of 474-493 g CO_2 eq./kWh for a 370 MW plant. The latter are higher despite the higher power plant efficiency (50%) assumed than for the power plant in Mexico (44.5%; see Table 5-2), mainly due to the higher upstream emissions from the gas production and transportation which account for 15% of the total life cycle emissions while in the current study the upstream emissions represent about 10.3% of the life cycle emissions.

According to Weisser (2007), the GWP from the operation of a gas fired power plant ranges between 360 and 575 g CO_2 eq./kWh with the life cycle impact being between 440 and 780 g CO_2 eq./kWh. The results estimated for Mexico at 420 g CO_2 eq./kWh for direct and 468 g CO2 eq./kWh for the life cycle impacts, also compare well with this range.

5.2 Economic assessment

The economic analysis presented in this section comprises the estimation of capital and total annualised costs (capital, fixed, variable and fuel) of the Mexican power sector for the base year (2006). Additionally, the levelised costs have been estimated and validated with the data reported in literature. The methodology for the estimation of costs has been described in more detail in Chapter 4.

5.2.1 Data sources and assumptions

The main data sources for this study are the current costs for electricity generation reported by the IEA/NEA (2010) and EIA (2009) as well as in Gemis database (Öko Institute, 2005). As for LCA, the costs are estimated for the situation in 2006, as the base year. However, the cost data are taken for the most recent year available, to ensure that the results are as current as possible. Since the costs data have not been available for one but rather for several different years, for consistency, all the costs used in this analysis have been converted to US$ 2008 using the Consumer Price Index (CPI).

The operating parameters for power plants in 2006 can be found in Table 2-4 in Chapter 2; the life times assumed for the power plants are given in Table 5-3 and Figure 5-4 show the data for the fuel costs and Table 5-5 gives the overnight capital, fixed and variable costs used for the power plants in Mexico.

Table 5-3 Lifetime values assumed for power plants in Mexico

Power plant	Lifetime (yr)	Source
Coal	30	SENER (2006c)
Diesel	25	SENER (2006c)
Gas	30	IEA/NEA (2010)
Geothermal	30	MIT (2006)
Heavy fuel oil	30	SENER (2006c)
Hydro	80	IEA/NEA (2010)
Nuclear	30	Gemis database
Wind	25	IEA/NEA (2010)

Table 5-4 Fuel costs for power generation in Mexico

Fuel	Cost (US$2008/GJ)	Source
Coal	3.32	Value for Mexico from IEA/NEA (2010)
Diesel	13.43	Value for Mexico from IEA (2008)
Gas	7.5	Value for Mexico from IEA/NEA (2010)
Heavy fuel oil	9.58	Value for Mexico from IEA (2008)
Nuclear	1.94	Generic value from IEA/NEA (2010)

A 10% discount rate has been assumed for the estimation of annualised capital costs, which is generally used for estimation of levelised costs (IEA/NEA, 2005; 2010); this value is also in close agreement with the average discount rate of 9.94% for Mexico for the period 1999-2008 (Banxico, 2000; 2004; 2008).

Table 5-5 Costs of power plant technologies used in Mexico (EIA, 2009)

Technology	Overnight capital cost[d] (US$2008/kW)	Fixed cost (US$2008/kW)	Variable cost (US$2008/GJ)
Coal	2,036[a]	28.58	1.32
Diesel	655[b]	12.12[c]	0.92[c]
Gas	1,019[a]	12.95	0.60
Geothermal	1,776	172.97	–
Hydro	2,327	14.15	0.70
Nuclear	3,444	93.44	0.14
Fuel oil	1,817[a]	12.12[c]	1.53[c]
Wind	1,996	31.45	–

[a] Overnight capital costs for a PCC (coal), CC (gas), and ST (heavy fuel oil) power plants operated in Mexico (IEA/NEA, 2010)

[b] Overnight capital generic costs for a GT (diesel) power plant (Gujba et al., 2011)

[c] Fixed and variable generic costs for a GT (diesel) and ST (heavy fuel oil) power plants (Gujba et al., 2011)

[d] The overnight construction cost is defined as the total of all costs incurred for building the power plant immediately (IEA/NEA, 2010, Streimikiene, 2010)

5.2.2 Overnight capital costs

The total capital costs for 48,790 MW of the installed capacity in Mexico in 2006 are estimated at US$82.6 billion (see Figure 5.11). As shown in Figure 5.12, the majority of the costs are from hydro power (30%), heavy fuel oil (28%) and gas power plants (22%). At 2327 US$/kW, the investment costs are highest for hydro power, followed by heavy fuel oil and gas at 1817 and 1019 US$/kW, respectively.

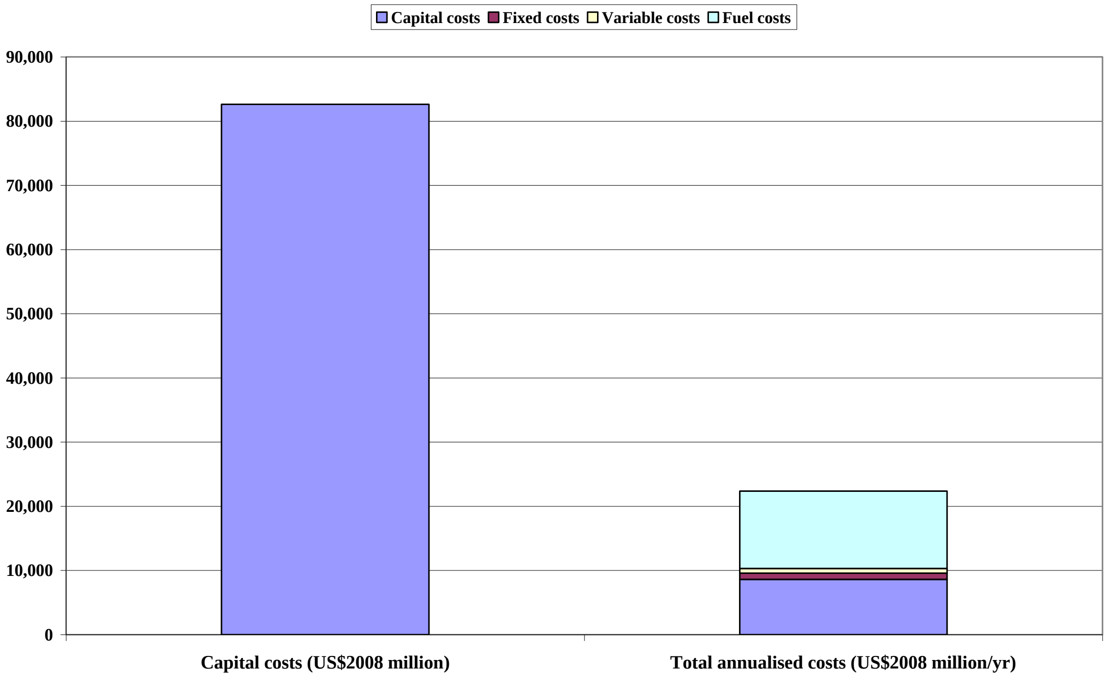

Figure 5-11 Capital and annualised costs of the Mexican power sector

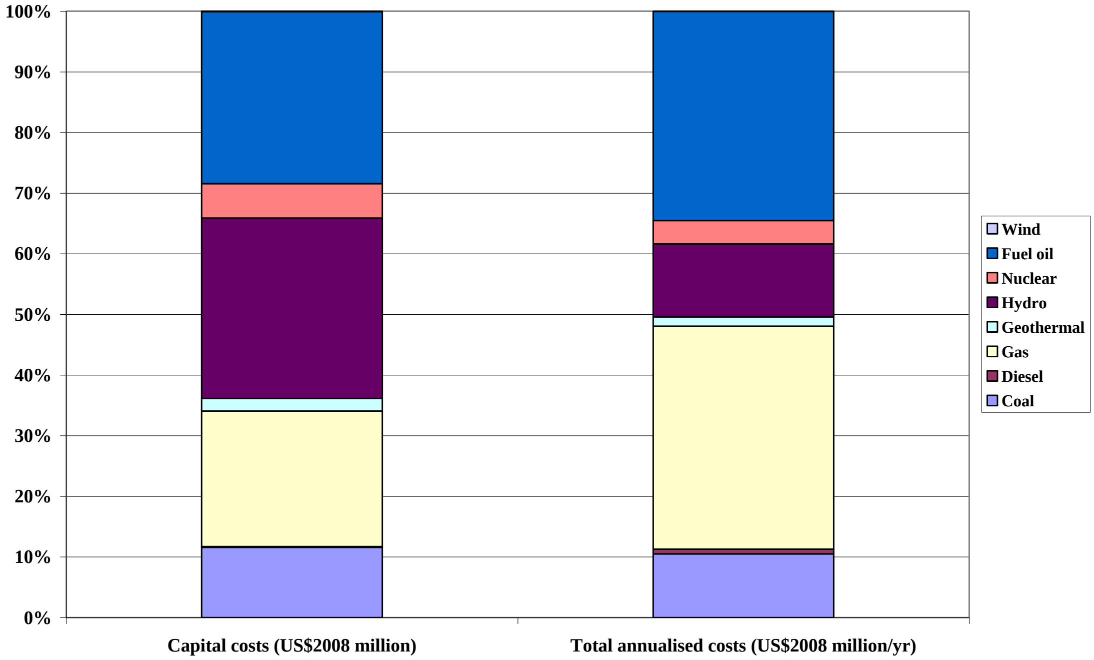

Figure 5-12 Contribution of different energy sources to the capital and annualised costs

5.2.3 Total annualised costs

In 2006, total annualised costs are estimated at US$22.4 billion (see Figure Figure 5-11). Fuel annual costs have by far the highest contribution (US$12.1 billion), accounting for more than half (54%) of the total. The capital costs contribute 39% while fixed and variable represent only 4% and 3% of total, respectively.

Gas and heavy fuel oil power plants together account for 71% of the total annualised costs (37% and 34% of total, respectively; see Figure 5-12); this mainly due to the high contribution of fuel costs (as shown in Figure 5-13 and Figure 5-14). The annualised costs of hydro and coal power plants are account for 12% and 11% of the total, respectively (see Figure 5-12). The contribution from diesel, geothermal, nuclear and wind power is low, collectively accounting for 6% of the total annualised costs, mainly due to the low contribution to the total electricity mix (for the latter, see in Chapter 2). Cost contributions from all energy sources are shown in Appendix 2.

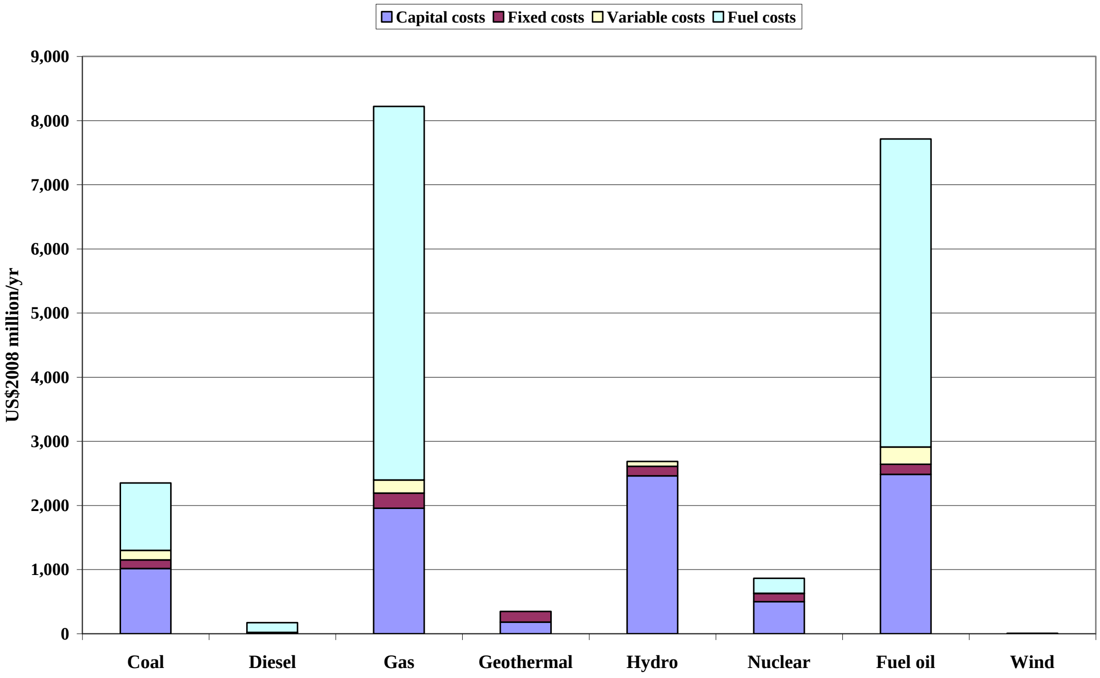

Figure 5-13 Total annualised costs by energy source

In the case of hydropower, capital costs represent the highest contributor to its total annualised costs (91%), as shown in Figure 5-13 and Figure 5-14. For coal power plants, on the other hand, fuel and capital costs together account for around 88% (45% and 43% respectively) of the total coal annualised costs.

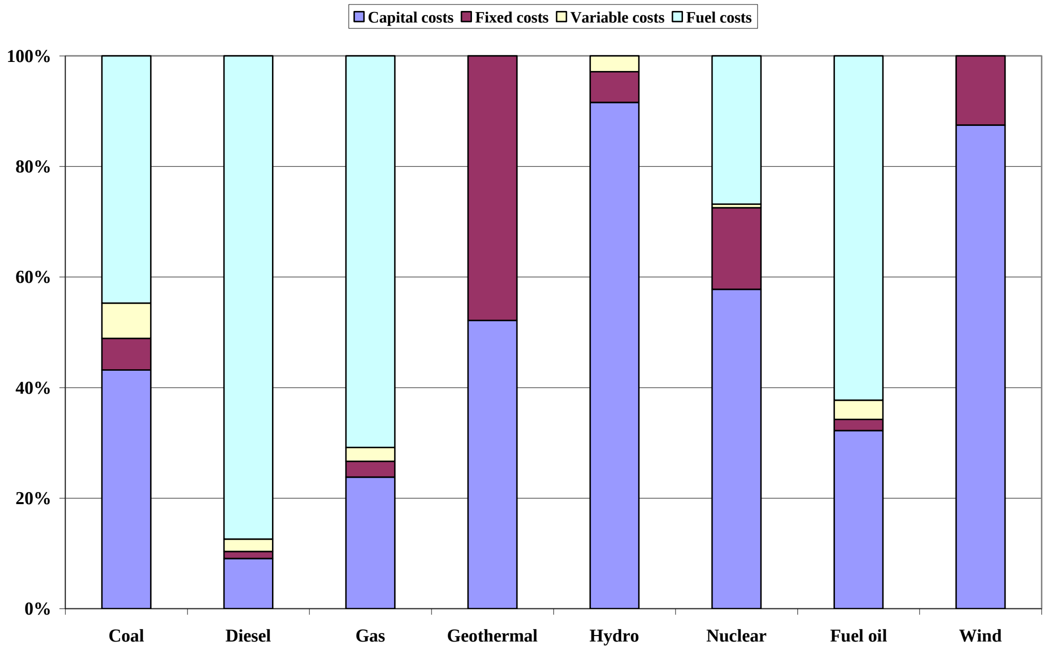

Figure 5-14 Contribution of capital, fixed, variable and fuel costs to the total annualised costs by energy source

5.2.4 Levelised costs

Levelised costs have been estimated: i) at the electricity-sector level, and ii) at technological level. These results have been compared and validated with literature (see Table 5-6) as discussed below.

Levelised costs of the electricity sector

Levelised costs for the Mexican power sector, based on 225,079 GWh generated in 2006, are estimated at 99.3 US$/MWh. This value is within the range of 48 to 104 US$/MWh reported for the Nigerian power sector by Gujba et al. (2010; 2011), which are the only levelised costs of an electricity mix available in literature for comparison.

The costs difference is mainly due to the differences in the electricity mix between Mexico and Nigeria.

Levelised costs of different technologies

The estimated levelised costs of electricity generation for different types of power plants in Mexico are listed in Table 5-6.

Table 5-6 Estimated levelised costs of electricity generation by energy source for Mexico compared with literature (IEA/NEA, 2005, 2010; del Rio, 2011)

	Levelised costs of electricity (US$ 2008/MWh)			
Technology	**Current study[A]**	**IEA/NEA (2005)[B]**	**IEA/NEA (2010)[C]**	**del Rio (2011)[D]**
Coal	75[E]	29–78	67–142	55–69
Diesel	145	–	397	138–172
Gas	86[F]	46–72	76–120	69–83
Geothermal	52	–	47–270	–
Hydro	89	30–272	23–459	48–200
Nuclear	79	34–77	42–137	69–117
Fuel oil	159	–	119	131–144
Wind Onshore	126	52–162	70–234	103–151

[A] Cost data include capital, O&M, and fuel costs, estimated using a 10% discount rate.

[B] Cost data include capital, O&M, and fuel costs, estimated using a 10% discount rate; reported worldwide.

[C] Cost data include capital, O&M, fuel, carbon, and decommissioning costs, estimated using a 10% discount rate; reported worldwide.

[D] Costs estimated by the European Commission (from del Rio, 2011). Cost data and discount rate not specified; However, due to costs range similarities with column B, it is assumed that unit costs reported by del Rio (2011) are based on comparable economic conditions as B.

[E & F] Costs for coal and gas power plants (just considering capital, O&M, and fuel costs) are in agreement with the levelised costs reported by IEA/NEA (2010) for power plants in Mexico.

As it can be seen from Table 5-6, estimates of unit costs for electricity generation vary among power plant technologies and information source. However, the majority of levelised costs estimated for power plants in Mexico are within the costs ranges reported by the other sources. The differences are mainly due to following aspects:

- Power plant technology (fossil fuels, nuclear or renewable energies);

- Power plant operating parameters (i.e. capacity, efficiency, capacity factor, lifetime, type of fuel);
- the location of the power plant (e.g. costs differ within a country, and even more between countries; in the case of renewable energies, the availability of energy resource differs widely among countries); and
- the economic data and assumptions (e.g. cost data, discount rate assumed for the economic analysis etc.).

5.3 Summary

The LCA results for this study show that for the base year of 2006 around 129 million tonnes of CO_2 eq. are generated annually from 225 TWh of electricity generated in Mexico by the public sector. CO_2 emissions account for about 94% of the total CO_2 eq. emissions; CH_4 contribute further 4.2% and N_2O 1.2%. As expected, the main source of the greenhouse gas emissions is the operation (combustion) of the fossil-fuelled power plants, contributing in total to 87% of GWP. The renewables and nuclear power contribute only 1.1% to the total CO_2 eq. Coal-based technologies generate 1094 g CO_2 eq./kWh, heavy fuel oil 964 g CO_2 eq./kWh, and gas 468 g CO_2 eq./kWh. By contrast, nuclear and hydro emit only 12 g CO_2 eq./kWh. The majority of other environmental impacts are caused by the combustion of fossil fuels in the power plants, with heavy fuel oil contributing the most (59-97%). The LCA results compare well with the values reported for other countries with similar electricity mix, including Italy, Portugal and the UK.

The results from the economic analysis for the base year show that total capital costs of the electricity sector are US$82.6 billion, with hydro power, heavy fuel oil and gas power plants contributing the majority of the costs (30%, 28% and 22% of total, respectively). The annualised costs are estimated at US$22.4 billion/yr, of which fuel costs contribute 54% (US$12.1 billion), mainly due to the gas and heavy fuel oil power plants. The levelised costs at both the sectoral and technology level have been also estimated and they show good agreement with the costs reported in literature.

Therefore, the results of this work demonstrate clearly that reducing the share of fossil fuel and particularly heavy fuel oil in the electricity mix would not only help to reduce the environmental impacts, but also lower the economic costs from electricity generation in Mexico. While the contribution of heavy fuel oil has gradually reduced over time with the introduction of the combined-cycle power plants, there is still a significant scope for improvement.

Furthermore, the country's current plan is to reduce its greenhouse gas emissions from the power sector by 85% by 2050 on the 2000 levels. This suggests that low-carbon technologies, such as renewable energies and nuclear power, will probably have a greater role to play in the future. However, before any irreversible changes are made, it is important to understand sustainability implications of future energy options for Mexico. This is discussed in the remaining chapters of this dissertation.

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6. Scenarios for future electricity production in Mexico

This chapter gives an overview of possible future scenarios for the electricity sector in Mexico. Several different scenarios are considered, including those developed within this work as well as by the IEA and Greenpeace. The timeframe for the scenarios is 2050. To set the context, first the main drivers for the electricity sector in Mexico are outlined, followed by the national energy plans.

6.1 Introduction

The increasing global energy demand, as a consequence of population and economic growth, has opened questions in terms of security of energy supply due to a high dependence on fossil fuels (i.e. variability of prices and depletion of fossil fuel reserves). Moreover, future development projections like, for example, those reported by the International Energy Agency (IEA/OECD, 2008), the European Renewable Energy Council (EREC) and Greenpeace International (Greenpeace & EREC, 2008a), have emphasised the need for transforming the current unsustainable global energy supply system into a system which would enable meeting the climate protection targets (Krewitt et al., 2009). For this reason, the IEA (2009; 2008) in its *Energy Technology Perspectives* and *World Energy Outlook* reports, and Greenpeace & EREC (2008a) within their *Energy Revolution* report, have presented target-oriented scenarios which aim at the global stabilisation of atmospheric CO_2 concentration at 550 and 450 ppm, and below 450 ppm, respectively, by year 2050. As shown by the IPCC (2007), the 450 ppm target is a fundamental prerequisite to limiting the global average temperature increase to 2 °C and thus preventing major consequences from anthropogenic global warming.

According to the IPCC (2007), only energy scenarios resulting in a 50% to 85% reduction of global CO_2 emissions by 2050 (compared to 2000 levels) can limit the global average temperature rise between 2.0 and 2.4 °C (350-400 ppm CO_2). Alternative GHG emission reduction scenarios have also been analyzed by the IPCC to maintain the atmospheric CO_2 concentration between 400 and 485 ppm, and GHG concentration between 490 and 590 ppm (as shown in Table 6-6-1).

Table 6-6-1 The relationship between GHG emissions and climate change (IPCC, 2007)

Temperature increase (°C)	All GHGs (ppm CO_2 eq.)	CO_2 (ppm)	Reduction of CO_2 emissions by 2050 (% of 2000 emissions)
2.0-2.4	445-490	350-400	50 to 85
2.4-2.8	490-535	400-440	30 to 60
2.8-3.2	535-590	440-485	5 to 30

The power sector has been identified as one of the most promising sectors for GHG reductions, as it has been estimated that it would contribute up to 50% of global emissions by 2050 if business as usual continues (IEA/OECD, 2008). Both the energy supply and demand will play a crucial role in meeting GHG reduction targets (Krewitt et al., 2007, 2009). From the energy supply point of view, decarbonisation of the power sector will require a more diverse energy mix based on low-carbon technologies (renewable energies, nuclear power and CCS), as well as energy efficiency improvements for all available power plant technologies (IEA/OECD, 2008). On the other hand, energy demand reduction (e.g. by improving energy efficiency in buildings and appliances, as well as reducing energy losses during the transmission and distribution of electricity) will be also required to complement the reduction of global GHG emissions (Greenpeace & EREC, 2008a).

6.2 Main drivers and targets for the Mexican energy sector

The Ministry of Energy in Mexico (SENER) has outlined energy security and the mitigation of climate change as the most important energy drivers for the Mexican Energy Sector (CICC, 2009; CMNUCC, 2009; PND, 2007; SENER, 2007a; CFE, 2010). For this reason, a new national strategy towards a sustainable energy future has been developed with the following main aims (SENER, 2008):

- to diversify the national energy supply;
- to reduce the energy dependence on fossil fuels;
- to promote the large-scale use of renewable energies and clean technologies that are economically, environmentally, socially and technically feasible for the country;
- to promote efficient use of energy;
- to reduce the GHG emissions from the production and use of energy; and
- to strength the national energy companies (PEMEX, CFE and LyFC) from the technological and administrative point of view.

The short-term GHG reduction target is to reduce 28 Mt of CO_2-eq. from the entire energy sector by 2012 and to increase the renewable energy capacity in the electricity mix from the current 24% to 26% by the same year (SENER, 2008). The long-term target is to reduce the GHG emissions by 50% by 2050 relative to the emissions in 2000 (PECC, 2009). If achieved, Mexico would contribute to the stabilization of CO_2 concentrations in the atmosphere below 450 ppm.

According to PECC (2009), in 2006 the power sector generated about 27% of total energy-related GHG emissions (112.5 Mt; this also corresponds to the GHG emissions estimated by the current work as shown in Chapter 5). To achieve the 50% reduction of GHG emissions by 2050, the power sector should cut its emissions by 85% on year 2000 (PECC, 2009), emitting only 16.2 Mt CO_2 eq. by 2050. This is a very challenging target and will require significant reductions in the short and medium terms, particularly as the electricity demand is projected to grow.

6.3 Electricity scenarios for Mexico to 2050

Eleven scenarios are considered in this work, two of which have been developed by the IEA (2004) and Greenpeace & EREC (2008b), respectively, and nine have been developed in this work. The motivation for using the former two scenarios is to compare their electricity mixes with the scenarios developed in this work with the aim of identifying the most sustainable future electricity options for Mexico in 2050. The scenarios developed in this work follow the climate change mitigation and security and diversity of energy supply drivers but also other aspects such as energy efficiency improvements and reduction of other environmental impacts. Each scenario is described in detail in the rest of the chapter. They are assessed in the subsequent chapters on the economic, environmental and social aspects discussed in Chapters 3 and 4.

6.3.1 'Busines-as-usual' (BAU) scenario

This scenario was originally developed by the IEA (2004) for the period 2010-2030 and then extrapolated to 2050 by Greenpeace and EREC (2008b). It is based on the assumption that the population in Mexico grows from 104 million in 2005 to 132 million in 2050 (CONAPO, 2005) and the GDP from US$2005 10,000/capita to US$2005 25,000/capita. It also assumes that the energy intensity goes down at an average annual rate of 1.1%, leading to a reduction in the final energy demand per unit of GDP of 40% between 2005 and 2050. However, electricity production increases annually by 2.9% from 225,079 GWh/yr in 2006 to 814,000 GWh/yr in 2050 (see Figure 6-1).

As the name suggests, the scenario assumes business as usual for the fuel and technology mix with fossil fuels, mainly gas and coal, continuing to dominate electricity generation in 2050: 53.6% of electricity is provided by gas and 31.2% by coal (see

Table 6-2). The contribution of oil decreases because of the country's oil depletion reserves and high uncertainty in oil prices (Greenpeace & EREC, 2008b).

According to this scenario, nuclear power maintains the production of 11,000 GWh/yr and hydropower grows slightly from 31,000 to 36,000 GWh/yr by 2050 (Figure 6-1). Even though wind power increases by 6.1% annually, it contributes only 2.8% to the total production by 2050. Other renewable energies such as biomass and geothermal power grow annually by 3.3% and 1.2%, respectively (together contributing 3.4% to the total electricity mix). From 2020, solar power increases by 3.5% annually, contributing 1% to the total electricity production by 2050 (see Figure 6-1 and Table 6-2).

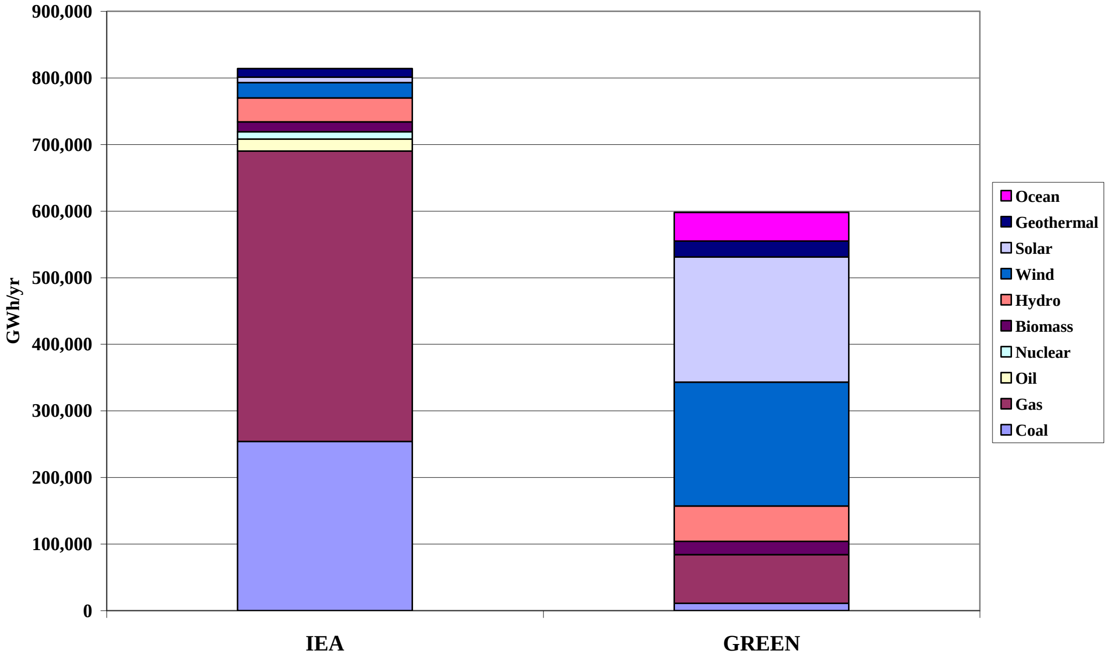

Figure 6-1 Business as usual (BAU) and Green scenarios for electricity production in Mexico in 2050 (Greenpeace & EREC, 2008b)

Table 6-2 Contribution of energy source to the total electricity mix for all scenarios by 2050

	Energy mix (%)										
Energy	**BAU***	**Green***	**A-1**	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Biomass	1.8	3.3	8.4	8.4	8.4	4.2	4.2	4.2	8.4	8.4	8.4
Coal	31.2	1.8	15.0	0.0	0.0	7.6	0.0	0.0	15.0	0.0	0.0
Coal CCS	0.0	0.0	0.0	10.0	5.0	27.4	35.0	12.1	0.0	10.0	5.0
Gas	53.6	12.2	26.1	17.6	3.3	35.1	9.4	0.0	26.2	17.7	3.5
Gas CCS	0.0	0.0	0.0	0.0	6.7	0.0	25.6	35.0	0.0	0.0	6.5
Geothermal	1.6	4.0	7.7	7.7	7.7	3.1	3.1	3.1	7.7	7.7	7.7
Heavy fuel oil	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro	4.4	8.9	10.0	12.5	15.0	6.3	6.3	6.3	6.3	6.3	6.3
Nuclear	1.4	0.0	10.0	10.0	10.0	5.0	5.0	10.0	20.0	25.0	30.0
Ocean	0.0	7.2	2.5	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar thermal	0.6	18.9	6.1	8.7	11.7	3.4	3.4	8.8	4.9	7.5	9.8
Solar PV	0.4	12.6	4.1	5.8	7.8	2.3	2.3	5.9	3.3	5.0	6.5
Wind Onshore	2.8	17.7	10.2	14.4	17.7	5.7	5.7	14.7	8.2	12.5	16.4
Wind Offshore	0.0	13.4	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Subtotal RE	12	86	49	62	75	25	25	43	39	47	55
Subtotal FF	87	14	41	28	15	70	70	47	41	28	15
Nuclear	1	0	10	10	10	5	5	10	20	25	30

*Sourced from Greenpeace & EREC (2008b)

6.3.2 ‘Green’ scenario

This scenario was developed by Greenpeace & EREC (2008b) and is based on the same projections as the BAU scenario regarding the population and GDP growth, but with different assumptions for the energy intensity which is reduced by 70% between 2005 and 2050. Due to the assumed improvements in energy efficiency and electricity distribution, the electricity demand goes down to 598,000 GWh in 2050 (see Figure 6-1). The installed capacity is 187,060 MW, representing the highest requirement for the installed capacity compared to all other scenarios (see Table 6-3). This is mainly because of the higher contribution from renewable energies (wind and solar) and their considerably lower capacity factors compared to fossil-fuel plants. It is important to note that in some cases, for example for wind and ocean power, the Green scenario assumptions exceed considerably the estimated renewable energy potential for electricity production in Mexico; for example, for wind power, the Green scenario requires an installed electric capacity of 70,357 MW (see Table 6-3) which exceeds by 75% its -estimated value of 40,000 MW (Table 6-6). Similarly, the required capacity for the ocean energy exceeds by 44% its estimated potential (see Table 6- 3 and Table 6- 6).

As this scenario aims to limit the temperature rise to 2 °C and reduce CO_2 emissions by 72% from the Mexican Power Sector in 2050 from 2005 levels, it is based on the significantly increased contribution of renewable energies to the electricity mix, achieved at the expense of fossil fuels. As shown in and summarised in Table 6-2 wind and solar contribute 62% to the total electricity generation by 2050. The next largest contributor is gas with a share of 12.2%; the only other fossil fuel remaining in the mix is coal contributing only 1.8%. The oil power plants continue to be decommissioned at an annual rate of 5.9% from 2010 to 2030, so that by 2040 oil is completely replaced by other electricity sources. The current nuclear power plant reaches its end of life by 2020. No further developments of nuclear power are planned under this scenario because of current sustainability issues related to nuclear proliferation and radioactive waste management (Greenpeace & EREC, 2008a;b).

Table 6-3 Power capacity required for all scenarios in 2050

	Power capacity (MW)[a]										
Energy	**BAU[b]**	**Green**	**A-1**	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Biomass	1,469	2,700	6,674	6,674	6,674	3,333	3,333	3,333	6,674	6,674	6,674
Coal	27,182	2,000	13,067	0	0	6,620	0	0	13,067	0	0
Coal CCS	0	0	0	8,711	4,356	23,868	30,489	10,523	0	8,711	4,356
Gas	42,609	9,711	20,779	13,977	2,657	27,882	7,446	0	20,850	14,088	2,800
Gas CCS	0	0	0	0	5,338	0	20,397	27,843	0	0	5,139
Geothermal	1,249	3,200	6,006	6,006	6,006	2,401	2,401	2,401	6,006	6,006	6,006
Heavy fuel oil	2,204	0	0	0	0	0	0	0	0	0	0
Hydro	9,550	20,000	21,594	26,993	32,392	13,561	13,561	13,561	13,561	13,561	13,561
Nuclear	1,029	0	7,611	7,611	7,611	3,805	3,805	7,611	15,222	19,027	22,833
Ocean	0	9,100	3,164	6,328	6,328	0	0	0	0	0	0
Solar CSP	441	15,473	4,557	6,476	8,723	2,561	2,570	6,588	3,691	5,597	7,328
Solar PV	1,704	54,520	17,619	25,042	33,730	9,902	9,937	25,475	14,272	21,643	28,337
Wind Onshore	6,391	40,015	23,005	32,663	40,015	12,916	12,984	33,251	18,616	28,230	36,984
Wind Offshore	0	30,342	0	0	3,981	0	0	0	0	0	0
Total	**93,829**	**187,060**	**124,075**	**140,481**	**157,809**	**106,851**	**106,922**	**130,587**	**111,959**	**123,537**	**134,017**

[a] For comparison among scenarios, the installed capacities have been estimated assuming an electricity production of 598,000 GWh in 2050.

[b] The installed capacity of 93,829 MW, which compared to the other scenarios, represents the lowest required capacity due to a higher contribution from fossil-fuel power stations and their high operating factors.

Table 6-4 Electricity generation by energy source for all scenarios in 2050

	Electricity generation (GWh/yr)										
Energy	**BAU**[a]	**Green**[b]	**A-1**	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Biomass	11,020	20,000	50,053	50,053	50,053	24,996	24,996	24,996	50,053	50,053	50,053
Coal	186,600	11,000	89,700	0	0	45,448	0	0	89,700	0	0
Coal CCS	0	0	0	59,800	29,900	163,852	209,300	72,238	0	59,800	29,900
Gas	320,305	73,000	156,198	105,069	19,973	209,599	55,973	0	156,736	105,906	21,050
Gas CCS	0	0	0	0	40,126	0	153,327	209,300	0	0	38,631
Geothermal	9,550	24,000	45,926	45,926	45,926	18,359	18,359	18,359	45,926	45,926	45,926
Heavy fuel oil	13,224	0	0	0	0	0	0	0	0	0	0
Hydro	26,447	53,000	59,800	74,750	89,700	37,554	37,554	37,554	37,554	37,554	37,554
Nuclear	8,081	0	59,800	59,800	59,800	29,900	29,900	59,800	119,600	149,500	179,400
Ocean	0	43,000	14,950	29,900	29,900	0	0	0	0	0	0
Solar CSP	3,526	112,800	36,454	51,811	69,787	20,487	20,559	52,708	29,529	44,778	58,628
Solar PV	2,351	75,200	24,303	34,540	46,524	13,658	13,706	35,138	19,686	29,852	39,085
Wind Onshore	16,897	105,786	60,817	86,351	105,786	34,146	34,325	87,906	49,215	74,630	97,773
Wind Offshore	0	80,214	0	0	10,525	0	0	0	0	0	0
Total	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000

[a] Estimated using the original electricity mix by IEA (Source: Greenpeace & EREC, 2008b), and a total electricity generation of 598,000 GWh/yr.
[b] Sourced from Greenpeace & EREC (2008b).

6.3.3 Scenarios A, B and C

In addition to the BAU and Green scenarios, three further scenarios for electricity production in Mexico have been developed in this work following the new national strategy for mitigation of climate change, security and diversity of energy supply, and promotion of renewable energies. As already mentioned in Chapter 4 (Table 4-1) they are as follows:

- Scenario A is based on large-scale renewable energy, mainly wind, solar and hydro;
- Scenario B is based on fossil-fuel power plants, mainly gas and coal power with and without CCS; and
- Scenario C is based on nuclear power and renewable energies (mainly wind and solar).

The scenarios are divided into three sub-scenarios (A-1- A-3; B-1- B-3; C-1- C-3), each considering different energy mixes based on different CO_2 reduction targets for 2050:

stabilisation of emissions; 60%; and 85% reduction[13]. The characteristics of these scenarios are summarised in Table 6-5; these characteristics are discussed further in the next section.

The electricity generation for scenarios A, B and C is the same as in the Green scenario, recognising the fact that, to cut emissions from the power sector, it is also important to reduce the energy intensity and electricity demand (compared to the BAU scenario), and consequently the electricity production. However, the required installed capacities (106,851-157,809 MW; see Table 6-3) are considerably below the Green scenario because of higher contribution from fossil fuels than in Green scenario (see Table 6-2). On the other hand, scenarios B scenarios (B1 and B2) are comparable with the BAU scenario, due to the high contribution from fossil fuels (around 55% and 77% of their total installed capacity for B and BAU scenario, respectively).

The following other main assumptions apply for all A, B and C scenarios:

- Due to the depletion of domestic oil reserves, continuing price rise as well as the need to reduce climate change and other impacts, heavy fuel oil is not used for electricity production by 2050. Instead, the country's remaining oil reserves are prioritised for use in the transport sector. This assumption is in agreement with Mexico's current projections (SENER, 2006a; 2007b) and the world trends (IEA/OECD, 2008; Greenpeace & EREC, 2008a;b).
- By 2050, all coal and gas used for power generation are imported (assuming no further discovery and exploitation of domestic fossil fuel reserves).
- All current power plants operating in Mexico reach end of life before 2050. requiring new installed capacity in all scenarios. The only exception are dam hydropower plants 65% of which are still available by 2050 (based on own estimates using the CFE (2011) data and assuming the lifetime of 80 years).
- Electricity from coal (with and without CCS) is shared equally between the ultra-supercritical (USC) and IGCC power plant technologies by 2050.

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[13] Note that all the reduction targets are based on direct CO_2 emissions from the operation of power plants.

- The potential for renewable energy is as follows (Frankl et al., 2005; Islas et al. (2007); Krewitt et al., 2008; Greenpeace & EREC, 2008b; Viebahn et al., 2008; SENER-GTZ, 2009; see Table 6-7 for more detail):
    - all estimated potential (3000 MW) for small hydropower plants is realised by 2050;
    - 60% of solar power is from solar thermal power plants and 40% from PVs;
    - biomass mix: 80% of wood and forestry residues, 15% of agricultural residues (sugar cane bagasse), and 5% of biogas from waste;
    - solar PV technology mix: 30% from multi-crystalline silicon (mc-Si), and 70% from cadmium telluride (CdTe);
    - solar thermal technology mix: 40% each from parabolic trough and Fresnel and 20% from solar tower.

Table 6-5 Main drivers and characteristics of different scenarios for electricity production in Mexico in 2050

Scenario	Source	CO_2 target	Scenario description
BAU	IEA-WEO (2004) extrapolated to 2050 by Greenpeace & EREC (2008b)	None	Current energy trend based on fossil fuels (mainly gas and coal power together contributing 87% to the total by 2050); small, or no support for the development of other low carbon technologies such as renewable energies and nuclear power, which only contribute 12% and 1% to the total by 2050, respectively; the use of CCS is not considered in this scenario.
Green	Greenpeace & EREC (2008b)	72% CO_2 reduction by 2050 from 2005 levels	Energy policy supporting the development of renewable energies which contribute 86% to the total electricity mix by 2050; other sources such as gas and coal power together contribute 14% of the total energy mix by 2050; due to energy security and environmental concerns, nuclear power, oil, and CCS are not considered in this scenario.
A-1	Current study	Stabilization of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply and encouraging investment in low-carbon options with emphasis on renewable energies; wind, solar and hydro power contribute 49% of the total by 2050; gas, coal and nuclear power contribute 26%, 15% and 10% to the total; CCS and oil power plants are not considered.
B-1	Current study	Stabilization of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for fossil fuels: gas, and coal with and without CCS, representing 70% of the total by 2050; renewable energies (wind and solar), and nuclear power contribute 25%, and 10% to the total, respectively. No contribution from oil power.
C-1	Current study	Stabilization of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for nuclear power and renewable energies (wind and solar) contributing 20%, and 39% to the total by 2050, respectively; gas and coal together contribute 49%; CCS and oil power plants are not considered.
A-2	Current study	60% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply and encouraging investment in low-carbon options with emphasis on renewable energies; wind, solar and hydro power contribute 62% of the total by 2050; gas, coal with CCS and nuclear power contribute 17.6%, 10% and 10% to the total; no contribution from oil power plants.
B-2	Current study	60% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for fossil fuels: gas with and without CCS, and coal with CCS representing 70% of the total by 2050; renewable energies (wind and solar), and nuclear power contribute 25%, and 10% to the total, respectively. No contribution from oil power.
C-2	Current study	60% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for nuclear power and renewable energies (wind and solar) contributing 25%, and 47% to the total by 2050, respectively; gas, and coal with CCS together contribute 28%; no contribution from oil power plants.

A-3	Current study	85% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply and encouraging investment in low-carbon options with emphasis on renewable energies; wind, solar and hydro power contribute 75% of the total by 2050; gas with and without CCS, coal with CCS and nuclear power contribute 10%, 5% and 10% to the total; no contribution from oil power plants.
B-3	Current study	85% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for fossil fuels: gas and coal with CCS, representing 47% of the total by 2050; renewable energies (wind and solar), and nuclear power contribute 43%, and 10% to the total, respectively. No contribution from oil power.
C-3	Current study	85% reduction of GHG by 2050 from 2000 levels	Energy policy supporting diversification of electricity supply, and investment in low-carbon options, with strong support for nuclear power and renewable energies (wind and solar) contributing 30%, and 55% to the total by 2050, respectively; gas with and without CCS, and coal with CCS together contribute 15%; no contribution from oil power plants.

Table 6-6 Estimated potential for renewable electricity in Mexico

Energy source	Potential	Contribution to electricity mix[f] (%)
Biomass	50,000[a] GWh/yr	5─10
Geothermal	12,000[b] MW	5─10
Hydro	42,000[c] MW	10─15
Solar	1,900─2,200 or more[d] (kWh/m^2/yr)	10─20
Wind	40,000[e] MW	15─20
Ocean	N.A.[*]	0─5

[a] This is just the potential which is proven to be economically feasible, but the total potential is even greater (Islas et al., 2007; Greenpeace & EREC, 2008b; SENER-GTZ, 2009).

[b] Potential of high temperature resources for electricity production (Alonso, 1985, SENER-GTZ, 2009), from which at least 2,400 MW are estimated to be economically feasible.

[c] 39,000 MW for large hydro, and 3,000 MW for small hydropower plants (SENER-GTZ, 2009).

[d] Mexico's solar potential is within the optimal regions around the world (Greenpeace & EREC, 2008b; SENER-GTZ, 2009), for both solar thermal and solar PV technologies.

[e] This is mostly the estimated potential for the region of La Ventosa in Oaxaca State, but the total country's potential could be even greater (Greenpeace & EREC, 2008b; SENER-GTZ, 2009); in the current work, this estimated potential is assumed to be only for wind onshore power plants.

[f] Estimated potential by Krewitt et al. (2008) for electricity production in Mexico.

[*] Not available due to a high uncertainty (Greenpeace & EREC, 2008b; SENER-GTZ, 2009; Cancino-Solórzano et al., 2010).

Table 6-7 Assumptions for the contribution of different sources to the total electricity mix in scenarios A, B and C

Energy	**Scenario**								
	A-1	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Fossils fuels	Gas without CCS: 26% Coal without CCS: 15%	Gas power without CCS and coal with CCS contributing 17.6% and 10% to the electricity mix, respectively	Gas with and without CCS, and coal with CCS contributing 10% and 5% to the electricity mix, respectively	Gas power without CCS, and coal power with and without CCS contributing 35% each to the electricity mix, respectively	Gas power with and without CCS, and coal with CCS contributing 35% each to the electricity mix, respectively	Gas and coal power with CCS contributing 35% and 12% to the electricity mix, respectively	Gas and coal power without CCS contributing 26% and 15% to the electricity mix, respectively	Gas power without CCS, and coal with CCS contributing 17.7% and 10% to the electricity mix, respectively	Gas with and without CCS, and coal with CCS contributing 10% and 5% to the electricity mix, respectively
	Fossil fuels without CCS contribute 41%	Fossil fuels without and with CCS contribute 17.6% and 10%, respectively	Fossil fuels without and with CCS contribute 3.3% and 11.7%, respectively	Fossil fuels without and with CCS contribute 42.7% and 27.4%, respectively	Fossil fuels without and with CCS contribute 9.4% and 60.6%, respectively	Fossil fuels with CCS contribute 47%	Fossil fuel without CCS contribute 41%	Fossil fuels without and with CCS contribute 17.7% and 10%, respectively	Fossil fuels without and with CCS contribute 3.5% and 11.5%, respectively
Nuclear	Contributing 10% to the electricity mix			Contributing 5% to the electricity mix		Contributing 10% to the electricity mix	Contributing 20% to the electricity mix	Contributing 25% to the electricity mix	Contributing 30% to the electricity mix
Biomass	100% of electricity generation potential (50,000 GWh/yr); contributing 8.4% to the electricity mix			50% of electricity generation potential (25,000 GWh/yr); contributing 4.2% to the electricity mix			100% of electricity generation potential (50,000 GWh/yr); contributing 8.4% to the electricity mix		
Geothermal	50% of estimated potential (6,000 MW); contributing 7.7% to the electricity mix			20% of estimated potential (2,400 MW); contributing 3.1% to the electricity mix			50% of estimated potential (6,000 MW); contributing 7.7% to the electricity mix		
Hydro	35% of estimated potential (14,727 MW) + 65% of existing power plants (6,868 MW); contributing 10% to the electricity mix	48% of estimated potential (20,125 MW) + 65% of existing power plants (6,868 MW); contributing 12.5% to the total electricity mix	61% of estimated potential (25,524 MW) + 65% of existing power plants (6,868 MW); contributing 15% to the total electricity mix	16% of estimated potential (6,693 MW) + existing power plants (6,868 MW); contributing 6.3% to the electricity mix			16% of estimated potential (6,693 MW) + existing power plants (6,868 MW); contributing 6.3% to the electricity mix		

Ocean	Wave power contributing 2.5% to the electricity mix	Wave power contributing 5% to the electricity mix		No contribution	No contribution	No contribution	No contribution	No contribution	No contribution
Solar	Solar thermal and PV contributing 6.1% and 4.1% to the electricity mix, respectively	Solar thermal and PV contributing 8.7% and 5.8% to the electricity mix, respectively	Solar thermal and PV contributing 11.7% and 7.8% to the electricity mix, respectively	Solar CSP and PV contributing 3.4% and 2.3% to the electricity mix, respectively		Solar CSP and PV contributing 8.8% and 5.9% to the electricity mix, respectively	Solar CSP and PV contributing 4.9% and 3.3% to the electricity mix, respectively	Solar CSP and PV contributing 7.5% and 5% to the electricity mix, respectively	Solar CSP and PV contributing 9.8% and 6.5% to the electricity mix, respectively
Wind	58% of estimated potential: 23,005 MW (Onshore); contributing 10.2% to the total electricity mix	82% of estimated potential: 32,663 MW (Onshore); contributing 14.4% to the total electricity mix	110% of estimated potential: 40,015 MW (Onshore) + 3,981 MW (Offshore); contributing 19.5% to the total electricity mix	32% of estimated potential:12,916 MW (Onshore); contributing 5.7% to the electricity mix		83% of estimated potential: 33,251 MW (Onshore); contributing 14.7% to the electricity mix	47% of estimated potential: 18,616 MW (Onshore); contributing 8.2% to the electricity mix	71% of estimated potential: 28,230 MW (Onshore); contributing 12.5% to the electricity mix	92% of estimated potential: 36,984 MW (Onshore); contributing 16.3% to the electricity mix

Scenarios A-1 – A-3

For these scenarios, it has been assumed that policies in the country support the development of all renewable energies available in the country, with a larger contribution from wind and solar, followed by hydro, geothermal, biomass and ocean power. This assumption is mainly based on the renewable energies potential (see Table 6-6) as well as the expected reduction of capital costs by 2050 (Greenpeace & EREC, 2008a;b). In the case of scenario A-1 (stabilization of GHG emissions), the contribution from renewable energies is 49% by 2050, mainly from wind, solar and hydro power (around 10% each), followed by biomass, geothermal and ocean power (with 8.4%, 7.7%, and 2.5%, respectively).

The main differences in scenario A-2 are from the increase in the contribution from wind, solar and hydro power (14.4%, 14.4% and 12.5%, respectively). The contribution from theses sources for scenario A-3 is 19.5%, 19.5% and 15%, respectively. The contribution from other renewable energy sources (biomass and geothermal) for scenarios A-2 and A-3 remains the same as for A-1 (see Table 6-7); the exception is ocean energy the contribution of which increases from 2.5% (in scenario A-1) to 5% (in scenarios A-2 and A-3).

Even though the main contribution in these scenarios is from renewable sources, due to aspects of diversity of energy supply and ambitious GHG reduction targets, fossil fuels power plants (with and without CCS) and nuclear power also have significant contributions to the electricity supply. Gas power plays a more important role than coal, due to its lower environmental impacts (as demonstrated in Chapter 5). Depending on the GHG reduction target, contribution from gas ranges from 10% in scenario A-3 to 26%, in Scenario A-1. Gas power plants with CCS are only considered in scenario A-3 because of its more ambitious GHG reduction target of 85% (Table 6-5). Coal contribution ranges from 15% in scenario A-1 to 5% in A-3. The use of coal CCS is crucial for scenarios A-2 and A-3 to meet their respective GHG reduction targets (60%

and 85%). Being low carbon, nuclear power contributes 10% to the electricity mix in all scenarios.

Assumptions for the contribution of different sources to the total electricity mix in scenarios A, B and C are shown in Table 6-7.

Scenarios B-1 – B-3

In these scenarios, fossil fuel power plants remain the most important power sources by 2050, contributing 70% of total generation. Gas power contributes 35% of the total with varying contribution of gas CCS, depending on the GHG targets (see Table 6-5): while no CCS is required in scenario B-1, gas CCS represents 74% and 100% of the total gas power in scenarios B-2 and B-3, respectively. Coal power also contributes 35% of total electricity production in scenarios B-1 and B-2, but is limited to only 12% of the total in scenario B-3 (due to the 85% GHG reduction target).

The contribution from renewable energy sources for scenarios B-1 and B-2 is assumed at 25% of the total, mainly from hydro (6.3%), wind (5.7%) and solar (5.7%), followed by biomass (4.2%) and geothermal (3.1%). In scenario B-3, contribution from renewables increases to 43%, mostly due to the increase of wind and solar power (together contributing around 70% of the total renewable energy production).

The contribution of nuclear power in scenarios B-1 and B-2 remains almost the same as in BAU scenario (5% of total electricity mix); in scenario B-3, it increases to 10%.

Scenarios C-1 – C-3

It is assumed that the use of large-scale of nuclear power gets the political and economical support from the government. By 2050, nuclear power contributes 20%, 25% and 30% of the total electricity in scenarios C-1, C-2 and C-3, generating 15,200 MW, 19,030 MW, and 22,830 MW in each scenario, respectively.

Renewable energy is also crucial in these scenarios, contributing 39%, 47% and 55% of the total production in scenarios C-1, C-2 and C-3, respectively. Similarly to scenarios A, the contribution from renewable sources is driven by the diversity of supply. The main renewable energy sources are wind and solar, followed by biomass, geothermal and hydro power (see Table 6-2). Contribution from fossil fuels decreases from 41% in C-1, to 15% in C-3. Gas power remains the most important fossil fuel option, with contributions of 26%, 17.7% and 10% in scenarios C-1, C-2 and C-3, respectively. CCS is used for both gas and coal power plants in scenarios C-2 and C-3 (see Table 6-7).

6.3.4 Power generation technologies

The technological description of power plant used for electricity scenarios for Mexico and operational parameters (i.e. efficiency, capacity factor and lifetime) are presented in Table 6-8 and Table 6-9, respectively. The majority of these data represent the technological characteristics of power plants for the future with a time horizon of 2050. These data have been mainly sourced from NEEDS (2009), and Ecoinvent life cycle inventories (Dones et al., 2007, Jungbluth et al., 2007) among other sources (see below); where future data were not available (i.e., for heavy fuel oil, hydro, geothermal, and biomass power plants), existing power plant technologies were assumed.

Table 6-8 Description of power plant technologies used in all scenarios

Energy	Technology	Description
Biomass[a]	Steam turbine (ST), and cogeneration	Electricity from wood and forestry residues (ST), electricity from sugar cane bagasse (cogeneration), and electricity from biogas (cogeneration using micro gas turbine)
Coal[b]	Ultra-supercritical (USC) pulverized combustion, and integrated gasification combined cycle (IGCC)	600 MW ultra-supercritical and 450 MW IGCC coal power plants. The USC configuration includes: FGD, SCR, and ESP as emission controls for SO_2, NO_X, and PM with removal efficiencies of 90-95%, 90%, and 99.5%, respectively.
Coal CCS[b]	Ultra-supercritical (USC) pulverized combustion, and integrated gasification combined cycle (IGCC)	500 MW ultra-supercritical, and 400 MW IGCC coal power plants; both systems integrated with carbon capture (CC) process with a removal efficiency of 90% of CO_2 emissions from: post-combustion (for USC), and pre-combustion capture (for IGCC); also including the processes of carbon transport and storage in depleted gas reservoir. The USC configuration includes: FGD, SCR, and ESP as emission controls for SO_2, NO_X, and PM with removal efficiencies of 90-95%, 90%, and 99.5%, respectively.
Gas[b]	Combined cycle (NGCC)	500 MW NGCC power plant.
Gas CCS[b]	Combined cycle (NGCC)	500 MW NGCC power plant with post-combustion carbon capture (CC), transport and storage in depleted gas reservoir; Removal efficiency of 90% of CO_2 emissions from fuel combustion.
Geothermal[c]	Steam turbine (ST)	Same technology as for the base case scenario
Heavy fuel oil[c]	Steam turbine (ST)	Same technology as for the base case scenario
Hydro[c]	Water turbine (WT)	Large (dam-reservoir) and small (run-of-river) hydro power plants. Same technology as for the base case scenario.
Nuclear[d]	European Pressurized Reactor (EPR)	The EPR with an electric capacity of 1,600 MW, using an ultra-centrifugation enrichment process.
Ocean[e]	Wave energy converter	Wave Dragon energy converter of 7 MW.
Solar CSP[f]	Parabolic trough, fresnel, and central receiver system (solar tower)	200 MW parabolic trough, and a 200 MW fresnel, both using steam as heat transfer fluid (HTF) and 16 hours phase changed material (PCM) storage; and a 180 MW solar tower with salt as HTF, and 16 hours of molten salt storage.
Solar PV[g]	Building integrated PV modules: Crystalline silicon and thin film	Building integrated PV modules: Multi-crystalline silicon (mc-Si) and Cadmium Telluride (CdTe), with an average module efficiency of 22%.
Wind[h]	Offshore wind turbine	Offshore wind farm (81 wind turbines). Characteristics of wind turbine: i) capacity: 24 MW, ii) hub height: 160 m, iii) rotor diameter: 250 m, and iv) water depth: >100 m.

Sources: [a] Ecoinvent (Dones et al., 2007); Jungbluth et al., 2007) ;[b] Bauer et al. (2008) ; [c] SENER (2006a, 2006b), Ecoinvent (Dones et al., 2007) ; Gemis (Öko Institute, 2005) ; [d] Lecointe et al. (2007) ; [e] Sørensen & Naef (2008) ; [f] Viebahn et al. (2008) ; [g] Frankl et al. (2005); [h] DONG Energy (2008)

Notes:
FGC: Flue gas desulphurization; SCR: Selective catalytic reduction; ESP: Electrostatic precipitator

Table 6-9 Operating parameters of power plants used in all scenarios

Technology	Efficiency (%)	Lifetime (yr)	Capacity factor[a] (%)
Biomass	40[b]	30[b]	86
Coal	54[c]	35[c]	78
Coal CCS	49[c]	35[c]	78
Gas	65[c]	25[c]	86
Gas CCS	61[c]	25[c]	86
Geothermal	36[d]	30[e]	87
Heavy fuel oil	35[d]	30[b]	68
Hydro	36[d]	80[f]	32
Nuclear	37[c]	60[c]	90
Ocean	90[c]	80[c]	54
Solar thermal	19; 12; 18[c]	40[c]	91
Solar PV	22[c]	40[c]	16
Wind	36[d]	30[c]	30

[a] Capacity factors sourced from Greenpeace & EREC (2008b)
[b] Gemis (Öko Institute, 2005)
[c] Coal and gas with and without CCS : Bauer et al. (2008) ; solar PV : Frankl et al. (2005) ; nuclear : Lecointe et al. (2007) ; wind : DONG Energy (2008) ; ocean : Sørensen & Naef (2008) ; solar thermal (parabolic trough, Fresnel trough and solar tower, respectively): Viebahn et al. (2008)
[d] SENER (2006b)
[e] MIT (2006)
[f] IEA/NEA (2010)

6.4 Summary

Mexico's objective is to reduce its GHG emissions from the energy sector by 50% by 2050 compared to the levels in 2000; this corresponds to an 85% reduction from the power sector. This chapter has outlined a range of scenarios that consider this target but also alternative targets (stabilisation of GHG emissions and 60% reduction), 60% reduction of CO_2 emissions, and situations whereby the targets are not met. The business as usual (BAU) scenario considers the latter. The next chapters (7, 8, and 9) present the results of the sustainability assessment of the different scenarios with the aim of identifying the most sustainable future electricity options for Mexico.

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7. Environmental assessment of future scenarios for electricity production in Mexico

This chapter presents the results of environmental sustainability assessment of the electricity scenarios outlined in Chapter 6. Life cycle assessment (LCA) has been used as a tool for these purposes and the ISO 14044 methodology has been followed. The LCA modelling has been carried out using GaBi v4.3 and the environmental impacts have been estimated using the CML 2001 method. The results are first presented for the business as usual (BAU) scenario in comparison with the base year (for which the LCA results were presented in Chapter 5). This is followed by the comparison of the results for the Green, A, B and C scenarios relative to BAU and the base year.

7.1 Goal and scope of the study

The goal of this study is to evaluate the life cycle environmental impacts of future electricity scenarios for Mexico, up to 2050. As far as the author is aware, this is the first study of its kind for the Mexican power sector.

Similar to the LCA study of the base year (2006) presented in Chapter 5, the system boundaries are from ‘cradle to grave’ (see Figure 5-2), comprising the extraction and processing of fuels, transport of the fuels to the power plants, electricity generation and construction and decommissioning of the power plants.

Two functional units are considered:

i. ‘high electricity demand’: electricity generation of 814,000 GWh/yr only for the BAU scenario; and
ii. ‘low electricity demand’ of 598,000 GWh/yr for all the scenarios, including BAU.

The data have been sourced from the Gemis (Öko Institute, 2005), Ecoinvent (Dones et al., 2007; Jungbluth et al., 2007), and NEEDS (2009) databases, as well as from own work (as presented in Chapter 5).

7.2 High electricity demand: Impact assessment and interpretation for the BAU scenario

Figure 7-1 and Figure 7-2 show the estimated LCA impacts for the BAU scenario for the functional unit of 814,000 GWh/yr (‘high electricity demand’). These are compared in Figure 7-3 with the LCA results for the base year. These results are discussed in the following section.

7.2.1 Global warming potential

The GWP for the BAU scenario is estimated at 503 Mt CO_2-eq./yr (see Figure 7-1), increasing by almost 300% (Figure 7-3) compared to the base year. This increase is mainly due to a 262% increase in electricity demand compared to the base year and a high contribution from gas and coal (55% and 35%, respectively; see Table 6.10). Electricity from coal is the main contributor to GWP (55% of total), followed by gas (40.6%) and heavy fuel oil (3.5%).

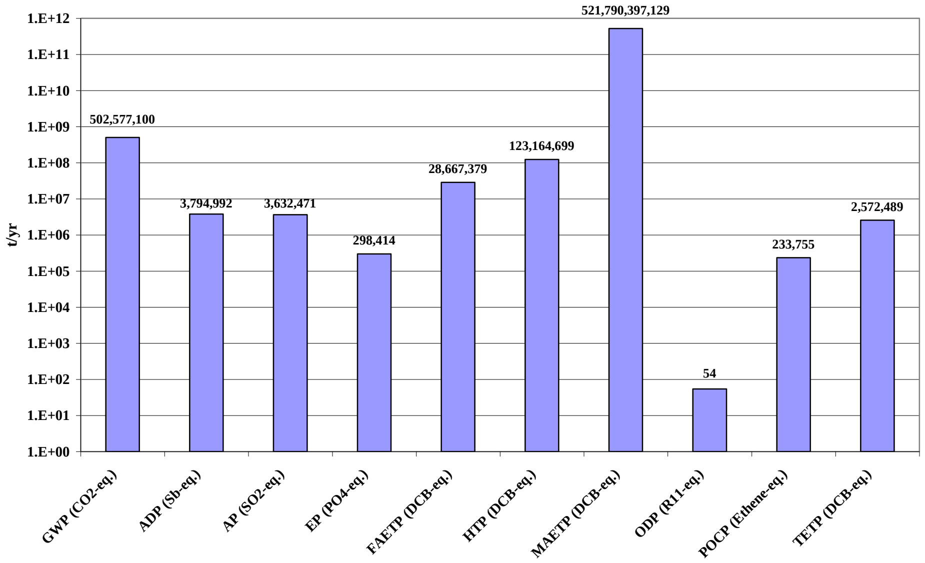

Figure 7-1 LCA impacts of BAU scenario assuming high electricity demand in 2050 (functional unit: 813,000 GWh/yr); [GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

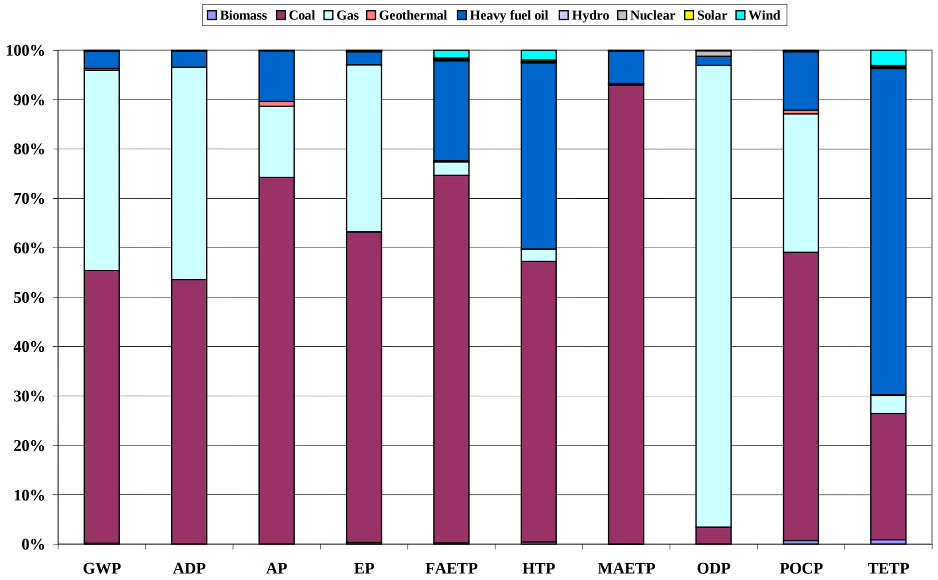

Figure 7-2 Contribution to the life cycle environmental impacts from each energy source in the BAU scenario (functional unit: 813,000 GWh/yr); [GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

7.2.2 Other impacts

Compared to the base year, the majority of the life cycle environmental impacts from electricity production in Mexico increase significantly (see Figure 7-3); the exception to this are HTP and TETP which are reduced because of the significant reduction of oil power (decreasing from 22% to 3%) and thus reduced emissions of heavy metals.

The main environmental impact increases are for ADP, EP, MAETP and ODP. Like GWP, ADP increases by almost 300% (Figure 7-3), reaching 3,794,992 t Sb-eq. emissions per year (see Figure 7-2), primarily due to the coal and gas consumption (representing 53% and 43% of the total ADP). EP increases by almost 340%, due to the direct NO_X emissions from coal and gas power plants (each contributing 63% and 34% to the total EP, respectively). MAETP also increases by 240% mainly from HF emissions from coal power and heavy metals from oil power plants (each contributing 92.9% and 6.6% to the total MAETP, respectively). The ODP increase (of around 270%) is related mainly to NMVOC emissions from gas power, representing 93.5% of the total R11-eq. emissions.

Significant increases have also been estimated for AP, FAETP and POCP. For example, AP increases by 150% compared to the base year, emitting 3,362,471 t SO_2-eq. Coal, gas, and heavy fuel oil power contribute 74%, 14%, and 10% to the total AP, mostly because of the SO_2 emissions from coal and oil and NO_X emissions from coal and gas.

FAETP increases by 54%. The main contributors are coal and oil power plants, responsible for 74% and 20% of the total FAETP, respectively.

Estimated at 233,755 t ethene-eq./yr, POCP is 115% higher than in the base year (see Figure 7-3); with the main sources being coal, gas and oil power (contributing 58%, 28% and 12%, respectively).

HTP and TETP emissions are estimated at 123,164,699 and 2,572,489 t DCB-eq., decreasing by 9% and 45% on the 2006 values (see Figure 7-2). The main sources of these impacts are still coal and oil power plants contributing 57% and 38% to the total HTP, and 26% and 66% to the total TETP. The breakdown of the contribution of each energy source to all environmental impacts can be found in Appendix 3.

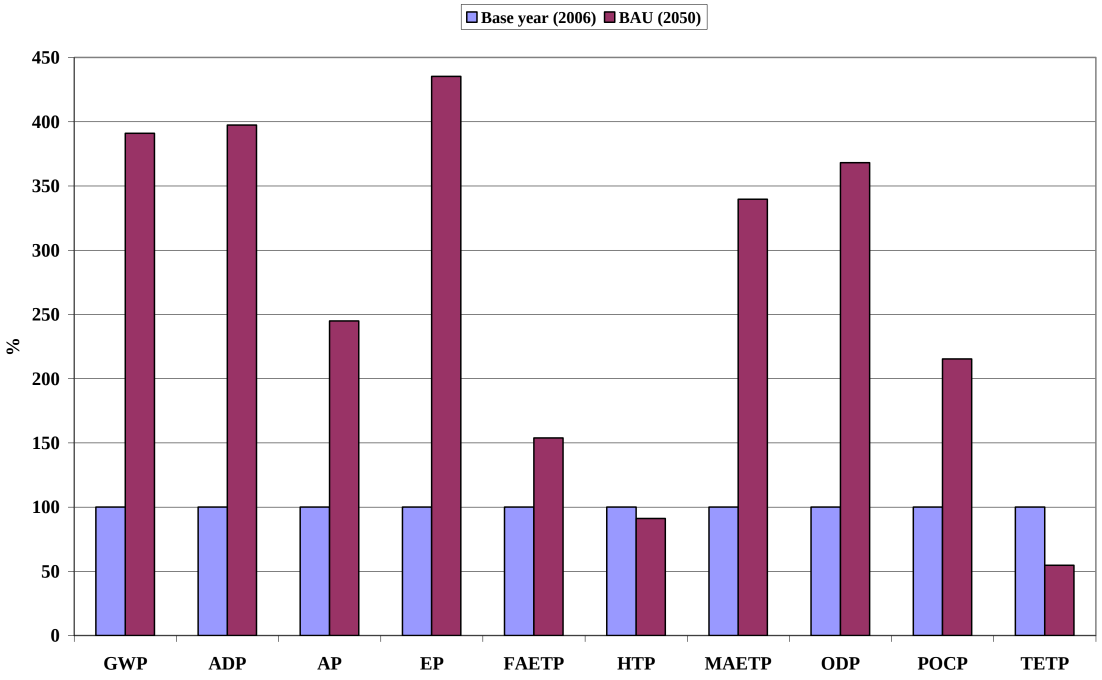

Figure 7-3 LCA comparison of the BAU scenario and the base year (2006); [GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential]

7.3 Low electricity demand: Impact assessment and interpretation for BAU, Green, A, B and C scenarios

7.3.1 Life cycle inventory

Table 7-1 presents life cycle emissions of selected environmental burdens from electricity scenarios for Mexico in 2050. As expected, BAU scenario is the major contributor to most of the burdens, emitting 243 Mt CO_2/yr, and 394, 176, 77, 176 kt/yr of SO_2, NO_x, NMVOC and PM emissions, respectively. This is mostly due to operation of coal and heavy fuel oil power plants. Also, scenarios B-1 and B-2 have significant contributions to CH_4, NO_x, N_2O and PM, emitting 544-563, 162-170, 9, and 178-183 kt/yr, respectively, due to high contribution of fossil fuels with and without CCS.

On the other hand, Green scenario with the highest contribution from renewable energies, presents the lowest emissions to most of the burdens (see Table 7-1); except for CO_2, being scenarios A-3 and C-3 the lowest contributors (emitting 22.6 and 22.7 Mt CO_2/yr, respectively). The contribution of scenarios to life cycle environmental impacts and their interpretation is discussed in the following sections.

Table 7-1 Life cycle emissions from scenarios for electricity generation in Mexico in 2050

Scenario	**Life cycle emissions (t/yr)**						
	CO_2	**CH_4**	**SO_2**	**NO_x**	**N_2O**	**NMVOC**	**PM**
BAU	2.43E+08	5.42E+05	3.94E+05	1.76E+05	7.85E+03	7.71E+04	1.76E+05
Green	3.84E+07	6.35E+04	8.77E+04	2.96E+04	3.42E+03	1.50E+04	2.80E+04
A-1	1.20E+08	2.53E+05	1.90E+05	8.40E+04	5.50E+03	3.16E+04	9.16E+04
A-2	5.18E+07	1.87E+05	1.71E+05	6.88E+04	5.02E+03	2.40E+04	7.71E+04
A-3	2.26E+07	1.03E+05	1.56E+05	4.66E+04	4.13E+03	1.64E+04	5.47E+04
B-1	1.22E+08	5.44E+05	1.60E+05	1.62E+05	9.05E+03	4.65E+04	1.78E+05
B-2	5.69E+07	5.63E+05	1.61E+05	1.70E+05	9.46E+03	5.00E+04	1.83E+05
B-3	2.81E+07	2.73E+05	1.13E+05	8.88E+04	5.58E+03	4.27E+04	7.79E+04
C-1	1.20E+08	2.53E+05	1.90E+05	8.43E+04	5.40E+03	3.18E+04	9.08E+04
C-2	5.19E+07	1.87E+05	1.71E+05	6.92E+04	4.93E+03	2.43E+04	7.60E+04
C-3	2.27E+07	1.02E+05	1.56E+05	4.71E+04	3.96E+03	1.66E+04	5.32E+04

7.3.2 Global warming potential (GWP)

Figure 7-4 presents the life cycle GWP for all the scenarios assuming low electricity demand (i.e. 598,000 GWh/yr of electricity as the functional unit). The results show that even though there is a considerable reduction in electricity generated compared to the ‘high electricity production’, the BAU scenario still has the highest GWP of about 259 Mt CO_2-eq per year. This doubles the GWP of 129 Mt estimated for 2006 (see Chapter

5). As mentioned previously, this is due to the high contribution from fossil fuels to the electricity mix (mainly coal and gas, together contributing 85% to the total mix).

Conversely, the scenarios with the highest contribution from renewable energy sources (aiming to reduce the GHG by 85%) have the lowest carbon footprints. Scenarios C-3 and A-3 are the best with the GWP values of 27.3 and 27.7 Mt CO_2-eq/yr, respectively, with the GHG emissions contributed equally by biomass, coal with CCS, gas, gas with CCS, and geothermal (Figure 7-4). The next best is scenario B-3 with the GWP of 37.3 Mt CO_2-eq./yr, mainly from coal and gas power plants with CCS contributing 33% and 52% to GWP.

In spite of the Green scenario having the highest share of renewable energies (86%), its GWP is still 41.6 Mt CO_2-eq./yr, essentially due to the direct emissions from coal and gas power plants as this scenario does not consider CCS.

Scenarios A-2, C-2 and B-2 (60% reduction target) emit between 59 and 75 Mt of CO_2-eq./yr, respectively, with the emissions related to gas with and without CCS, and coal with CCS (mainly due to the emissions in the fuel supply chain). The scenarios aimed at GHG stabilization (A-1, B-1, and C-1) have GWP between 129 and 139 Mt of CO_2-eq (but still considerably lower than the BAU scenario); the main GHG sources for these options are again coal with and without CCS, and gas power plants contributing 42%-48% and 44%-54% to GWP, respectively.

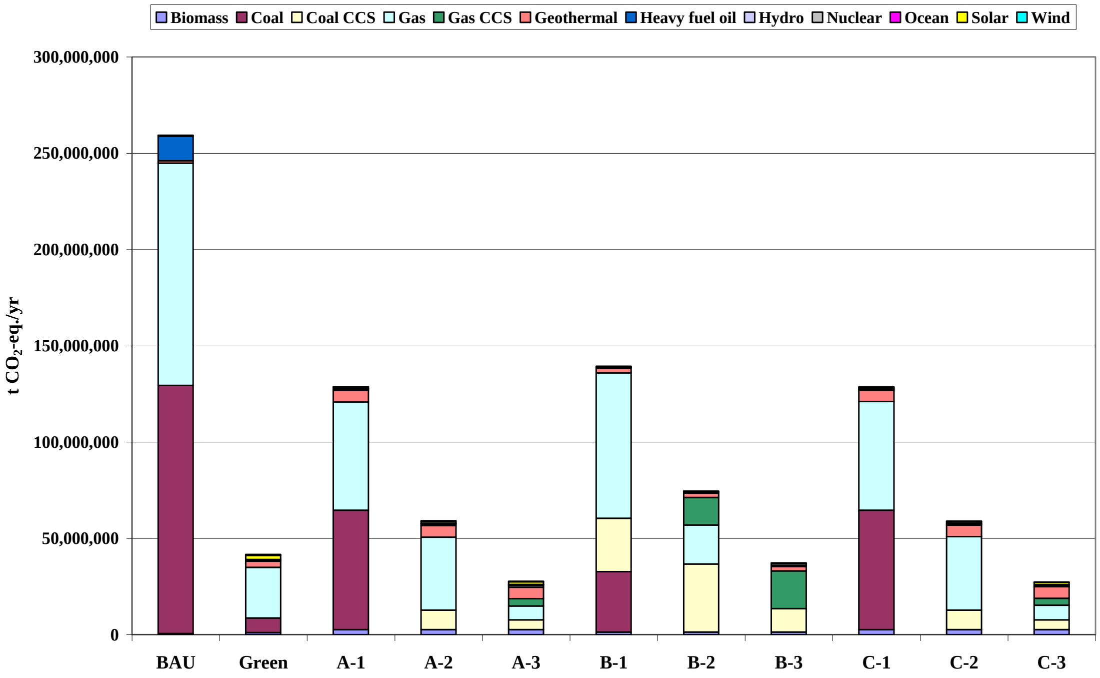

Figure 7-4 GWP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

7.3.3 Other impacts

Abiotic Depletion Potential (ADP)

As expected, the BAU scenario has the highest ADP with 1,856,531 t Sb-eq./yr (see Figure 7-5). This is again due to a high share of gas and coal power to the total electricity mix. On the other hand, the Green scenario, because of its high contribution from renewable energies, has the lowest ADP value of 298,543 t Sb-eq./yr.

As shown in Figure 7-5, scenarios A and C have similar ADP values due to the similar shares of fossil fuels (coal and gas) (see Table 6-2). Specifically, for A-3 and C-3 the ADP of 377,136 and 373,826 t Sb-eq./yr, respectively, is mainly from coal and gas power plants with CCS and gas without CCS contributing 41%, 33%-34% and 15%-16% to ADP, respectively. Gas and coal power plants with and without CCS are the main contributors to ADP in scenarios A-1, A-2, C-1 and C-2 with the total ADP values ranging from 644,680 (scenario A-2) to 880, 567 t Sb-eq./yr (scenario C-1). In contrast, scenarios B-1 and B-2 have a higher ADP equal to 1,671,258 and 1,745,800 t Sb-eq./yr, respectively; this is comparable to the BAU scenario.

Regardless of B-1 and B-2 having the same share of fossil fuels (70%), scenario B-2 has a higher ADP value than scenario B-1, mainly due to a greater use of CCS (see Table 6-2 and Figure 7-5). Whilst the share of fossil fuels is considerably lower in scenario B-3 (47%) than, for example, in scenarios B-1 and B-2, its ADP is still 1,060,124 t Sb-eq./yr, again primarily due to the use of CCS in coal and gas power plants (see Figure 7-5).

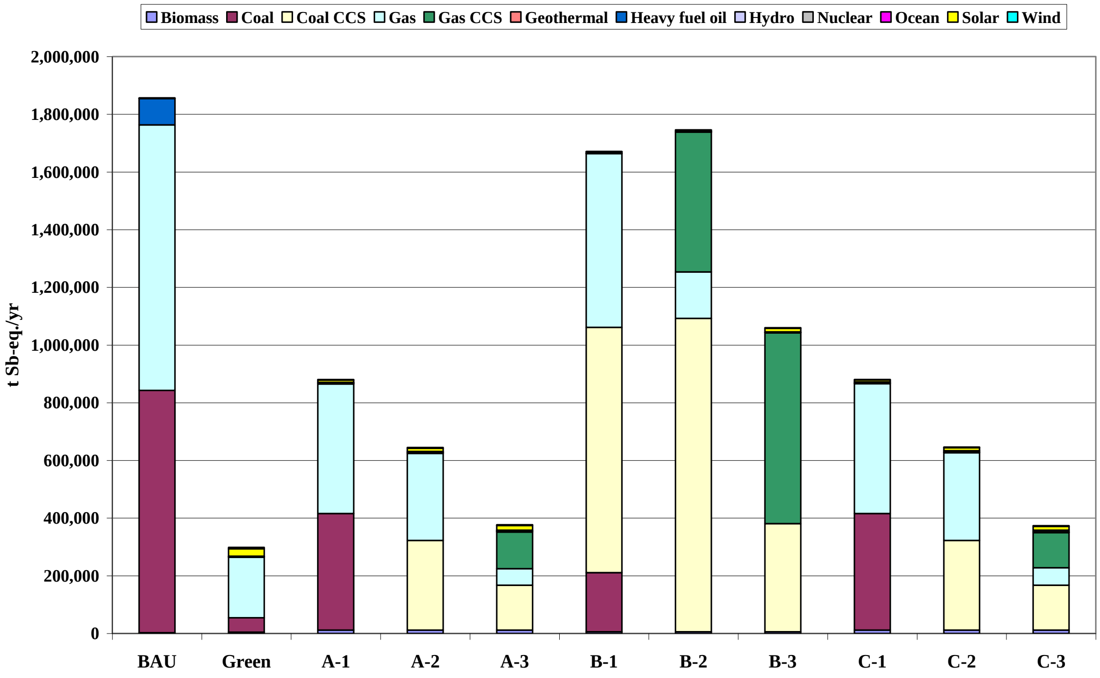

Figure 7-5 ADP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Acidification Potential (AP)

The AP estimated for all the scenarios is shown in Figure 7-6. The BAU scenario exhibits the highest value of 531,222 t SO_2-eq./yr, mainly due to the SO_2 emissions from heavy fuel oil and coal power plants. The Green scenario has the lowest AP of 112,895 t SO_2-eq./yr; this is five times lower than BAU. The AP in Green is mainly due to the direct SO_2 emissions from geothermal power plants.

The next best options are A-3, B-3, and C-3 scenarios, generating 201,495; 200,076; and 202,473 t SO_2-eq./yr, respectively. In the case of A-3 and C-3 scenarios, these emissions are also mainly from geothermal power plants (62% of AP) followed by coal (16%); while for scenario B-3, coal and gas with CCS, and geothermal power plants are the main contributors to its AP (39%, 27% and 25% of total). As shown in Figure 7-6, other scenarios (A-1, A-2, B-1, B-2, C-1, and C-2) emit between 240,000 and 340,000 t SO_2-eq. per year. For the A and C sub-scenarios, this is mainly due to geothermal energy and for B it is due to coal with CCS.

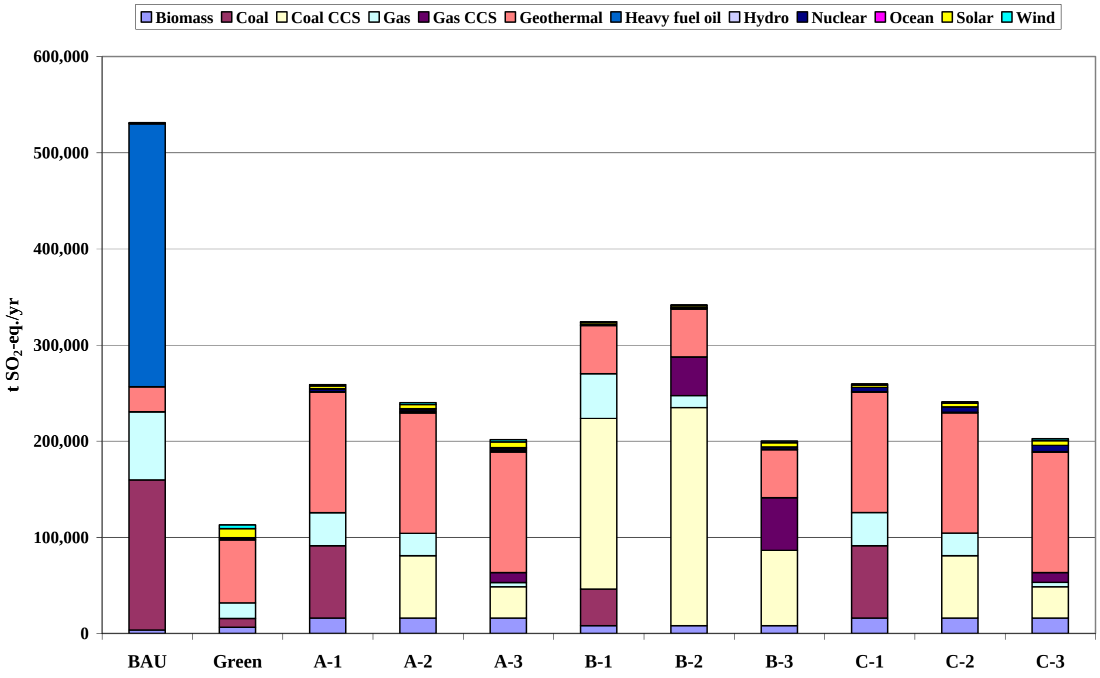

Figure 7-6 AP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Eutrophication potential (EP)

Here, the highest EP values are found for scenarios B-2 and B-1, followed by the BAU scenario; these are respectively 41,995; 37,979 and 32,436 t PO_4-eq./yr (see Figure 7-7). The main contributors for scenarios B-2 and B-1 are the NO_X and NH_3 emissions from coal power plants with CCS contributing 79% and 68% to EP, respectively; in B-1, there is also a significant contribution from coal and gas power plants without CCS contributing 12% and 13% to EP, respectively.

The estimated EP from the scenarios A and C range between 13,428 and 18,183 t PO_4-eq./yr. In the case of scenarios A-3 and C-3, the main contributors are NO_X and NH_3 emissions from coal with CCS, and biomass power plants.

The scenario with the lowest EP is Green with 8,806 t PO_4-eq./yr, mainly related to NO_X, N_2O and NH_3 emissions to air, and emissions to water from the construction of infrastructure for the solar power plants.

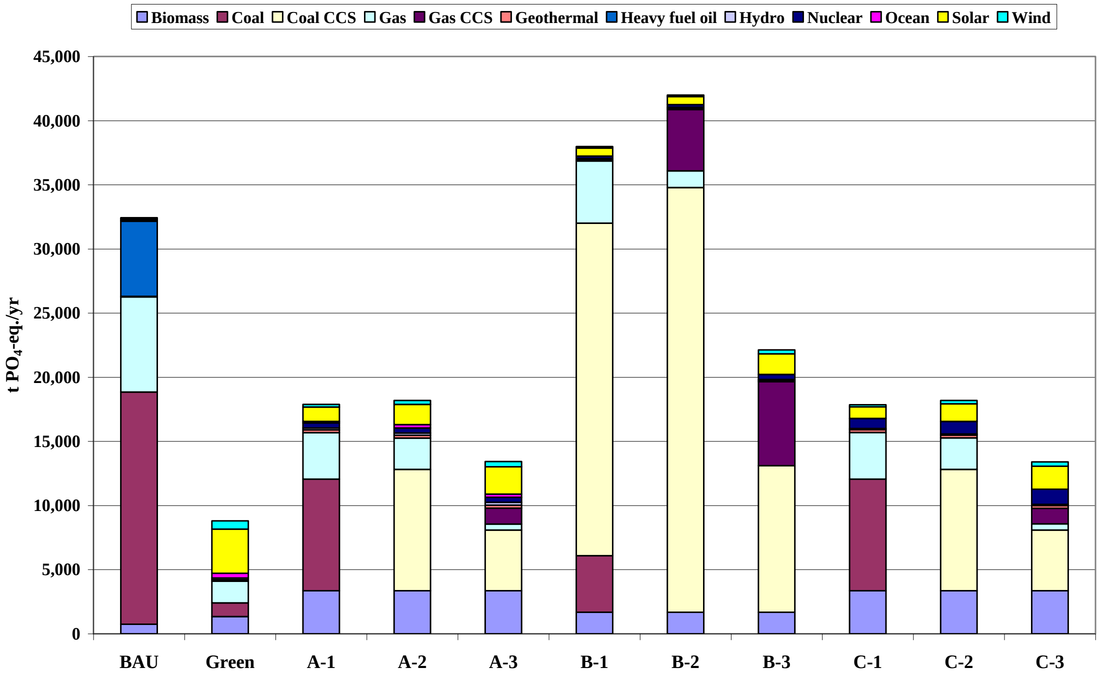

Figure 7-7 EP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Freshwater Aquatic Ecotoxicity Potential (FAETP)

As shown in Figure 7-8, the BAU scenario has the highest FAETP emitting 6,573,483 t of DCB-eq./yr, mainly due to heavy metal emissions to air and water from heavy fuel oil and coal power plants (each contributing 65%, and 23.5% to the total). On the other hand, the Green scenario has the lowest FAETP value, estimated at 1,663,788 t DCB-eq./yr or four times lower than BAU. These emissions are mainly from heavy metal emissions to water from the life cycle of solar, wind and ocean-based power plants contributing 42$, 19% and 12% to FAETP, respectively.

The second best option is A-3 with the FAETP of 1,947,437 t DCB-eq./yr, closely followed by A-1, C-3, A-2, C-1, C-2, and B-3 emitting between 2,105,032 and 2,264,379 t DCD-eq./yr. The FAETP emissions for scenarios B-1 and B-2 are 3,037,665 and 3,290,440 t DCB-eq./yr, mainly related to the life cycle of coal power plants with CCS contributing 58% and 69% to FAETP, respectively.

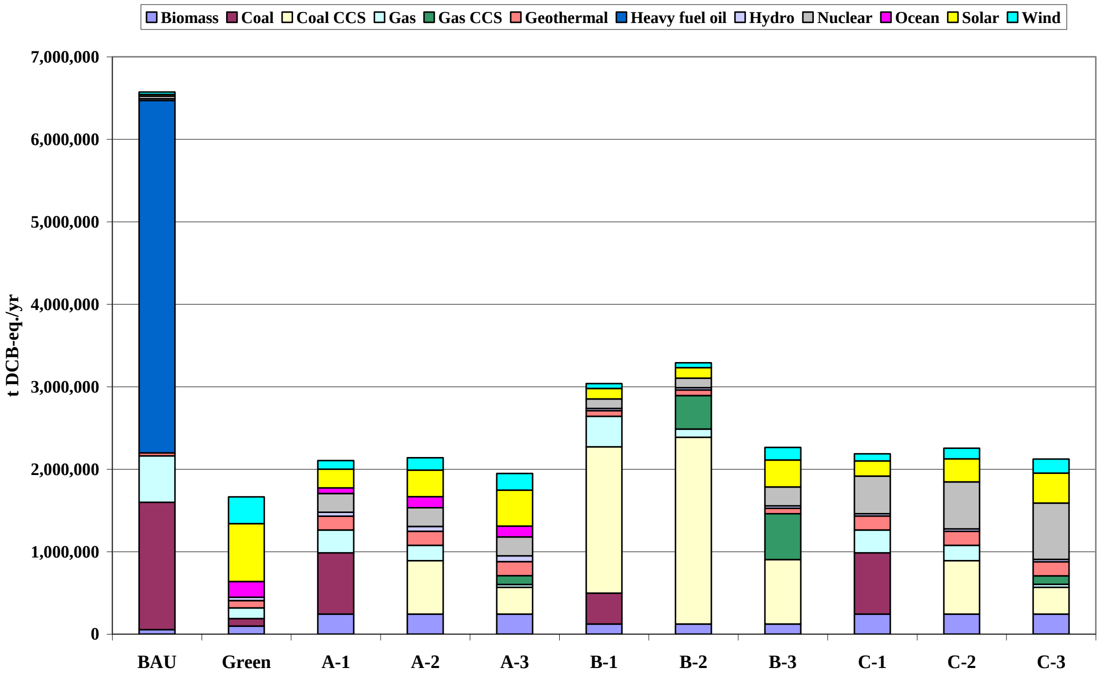

Figure 7-8 FAETP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Human Toxicity Potential (HTP)

The HTP values for all the scenarios are given in Figure 7-9. The BAU scenario again has the highest impact, estimated at 46.8 Mt DCB-eq./yr, mainly due to the emissions of heavy metals to air from oil and coal power plants. The best option is the Green scenario with 6.2 Mt DCB-eq./yr; this is 7.5 times lower than the BAU scenario. The HTP for Green is mainly due to the emissions of heavy metals to air from the construction of infrastructure of solar, wind and wave power plants (each contributing 34.4%, 19%, and 13.7% to the total HTP).

The next best options are scenarios A-3, A-1, C-3, C-1, A-2, and C-2 with 9.9, 10.3, 10.4, 10.5, 11.4 Mt DCB-eq./yr, respectively. Finally, the HTP values for the B scenarios range between 15.7 Mt (for B-3) to 25.9 Mt DCB-eq./yr (B-2), mainly due to coal and gas power plants with CCS contributing 42%-75% and 15%-35% to HTP, respectively.

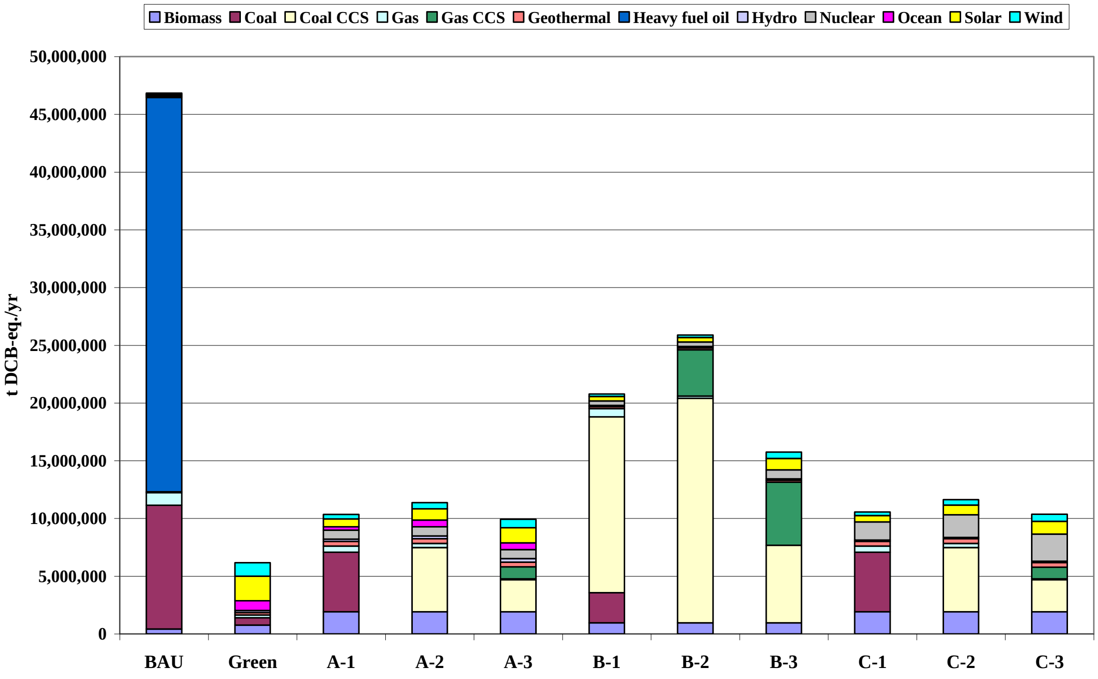

Figure 7-9 HTP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Marine Aquatic Ecotoxicity Potential (MAETP)

Figure 7-10 indicates that the BAU scenario is the worst option with 85,656 Mt DCB-eq./yr (mainly from coal and heavy fuel oil power plants) and the Green the best with

5,859 Mt DCB-eq./yr(mainly due to the HF emissions from the operation of coal power plants).

All the A and C scenarios as well as scenario B-3 also perform well in comparison with the BAU scenario, ranging from 13,335 to 29,884 Mt DCB-eq./yr, with the best options being scenarios A-3 and C-3 (as shown in Figure 7-10).

The MAETP values for B-1 and B-2 are close to the BAU scenario, estimated at 74,139 and 76,791 Mt DCB-eq./yr, respectively with the coal power plants with CCS being by large the main source.

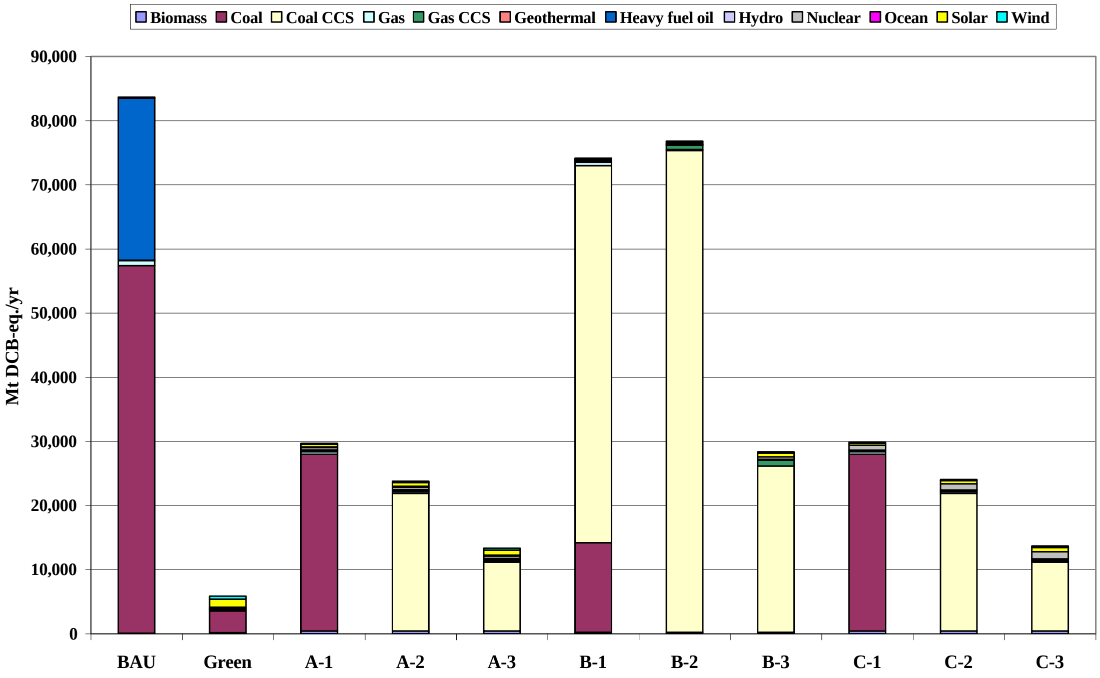

Figure 7-10 MAETP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Ozone Depletion Potential (ODP)

For this impact, scenarios C-3 and A-3 perform best, each emitting 3.5 t R11-eq./yr with the main sources being gas power with and without CCS (Figure 7-11). This is in contrast with the BAU scenario which is the worst option with 16 t R-11-eq./yr. This is mainly due to the NMVOC emissions from gas power.

The Green scenario is closely followed by C-3 and A-3 the with an EP of 4.1 t R-11-eq./yr. The values for A-2, C-2, A-1, C-1 are between 6 and 8 t R-11-eq./yr, again with the gas power plants as the primary source. The ODP for scenarios B is between 10.8 and 11.5 t R11-eq./yr, mainly due to the higher share of fossil fuels with and without CCS. Nevertheless, these values are still around 28%-33% lower than for the BAU scenario (see Figure 7-11).

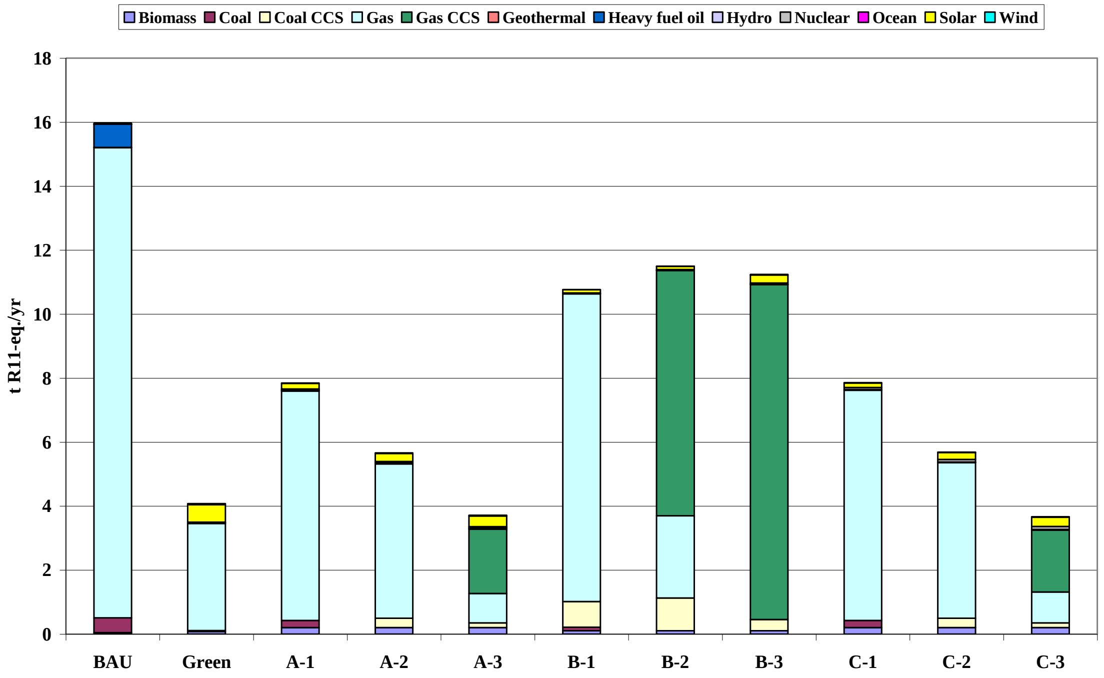

Figure 7-11 ODP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Photochemical Ozone Creation Potential (POCP)

As for most other impacts, the BAU scenario has the highest POCP with approximately 55,283 t Ethene-eq./yr, related to SO_2, NO_X, and NMVOC emissions from heavy fuel oil, coal and gas power plants (Figure 7-12). The Green scenario shows the best performance with POCP of 12,606 t ethene-eq./yr; this is mainly due to the operation of geothermal, gas, and biomass power plants. Scenarios A-3 and C-3 follow closely after Green with 19,870 and 19,858 t ethene-eq./yr, respectively. The major contributors here are biomass and geothermal power, collectively contributing around 50%. The POCP values for the other options range from 24,383 (scenario C-2) to 36,288 t ethene-eq./yr (for scenario B-2).

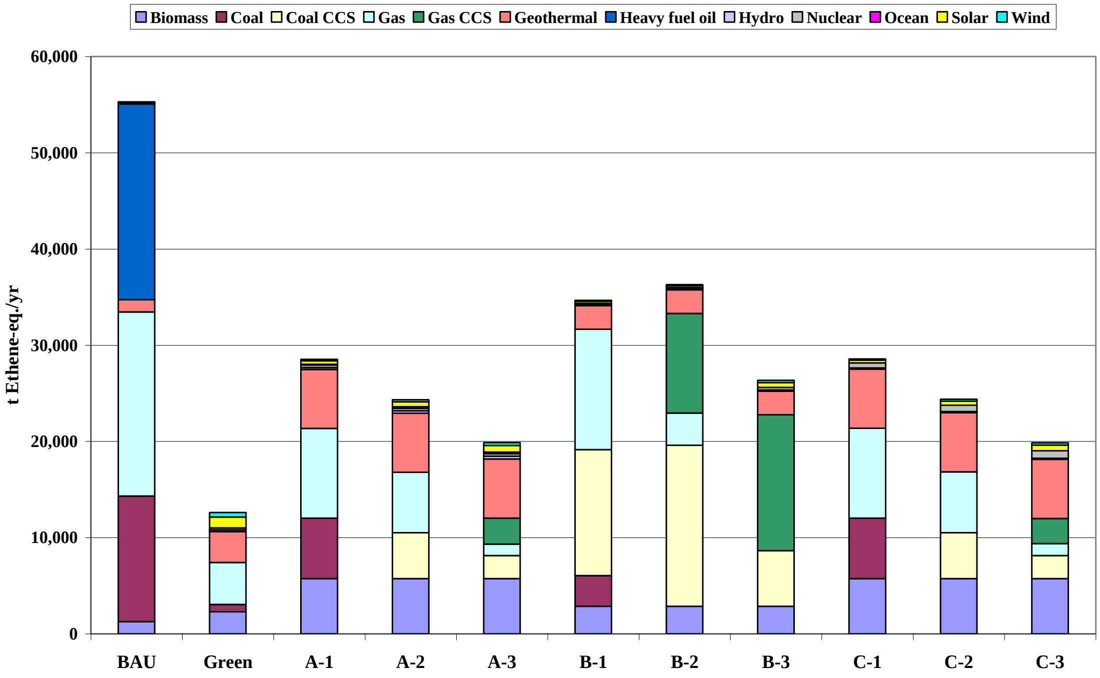

Figure 7-12 POCP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

Terrestrial Ecotoxicity Potential (TETP)

It is clear from Figure 7-13 that the BAU scenario is the worst option for TETP, emitting 1.5 million t DCB-eq./yr, mainly due to the air emissions of heavy metals from the operation of heavy fuel oil power plants contributing 81.5% to TETP. At 175,242 t DCB-eq./yr; the Green scenario is the best option, with the main contributors being emissions of heavy metals to air from solar PV power plants (contributing about 35.8% to the total EP). This is followed by scenarios A-3 and C-3 with the TETP of 249,826 and 252,637 t DCB-eq./yr, respectively. The rest of the scenarios have the values between 280,738 (scenario A-2) to 448,587 t DCB-eq./yr (scenario B-2).

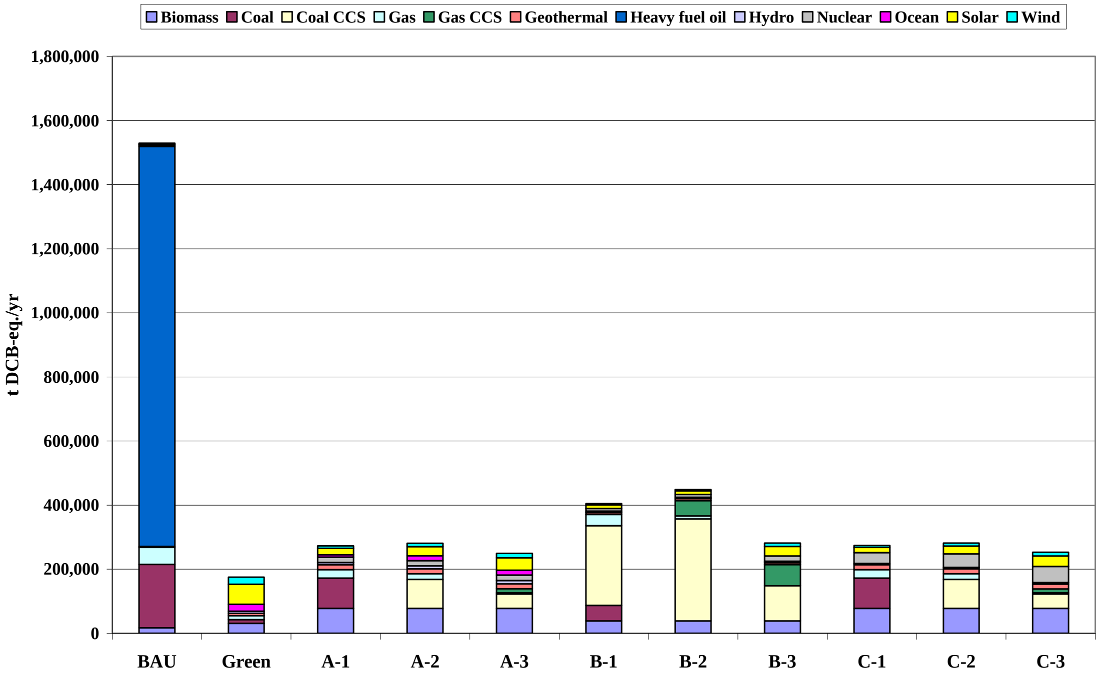

Figure 7-13 TETP for all scenarios assuming low electricity demand in 2050 (functional unit: 598,000 GWh/yr)

7.3.4 Comparison to base year

The LCA results for all the scenarios for ‘low electricity demand’ (598,000 GWh/yr) are compared here with the base year. The LCA results trends from 2006-2050 for all scenarios are presented in Figure 7-14to Figure 7-23, while their normalised values relative to 2006 are shown in Table 7-2.

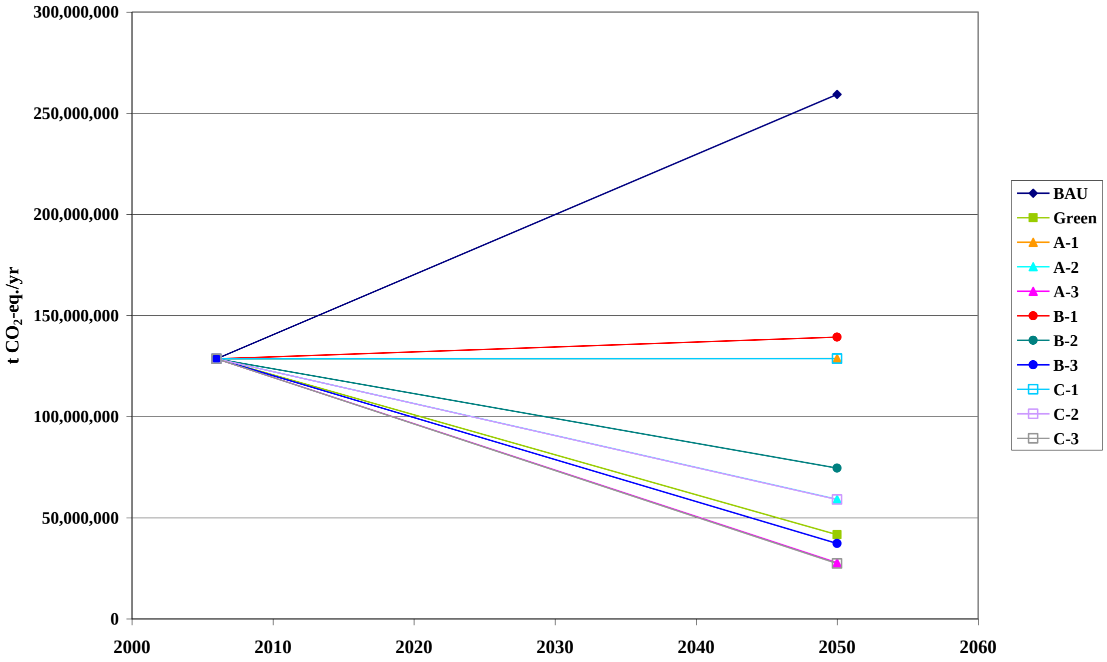

Figure 7-14 GWP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

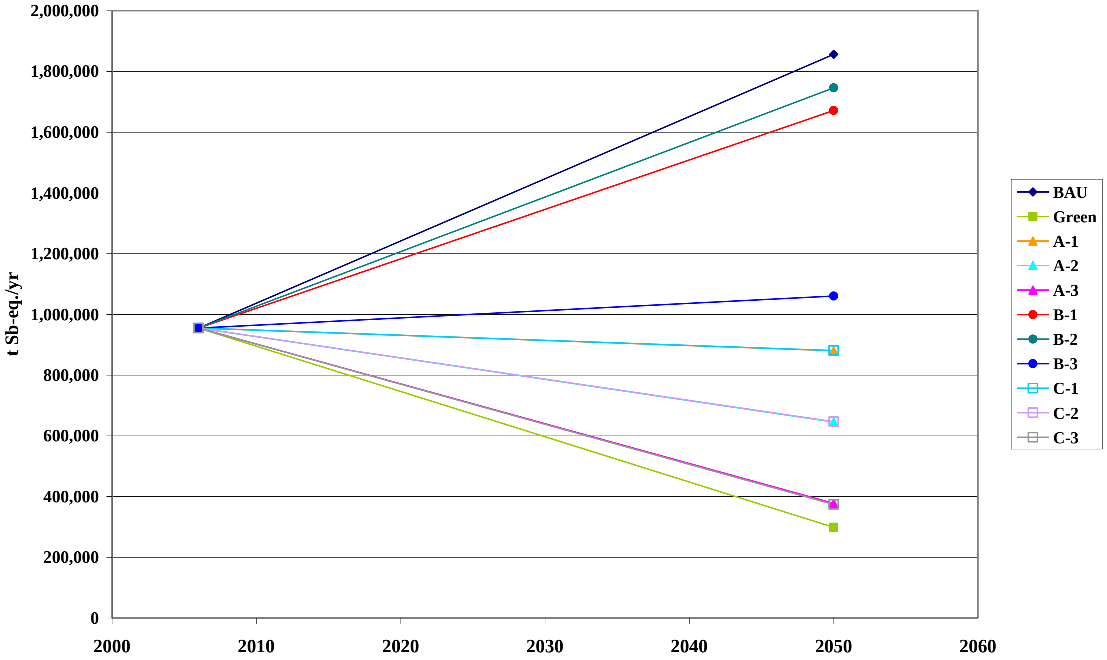

Figure 7-15 ADP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

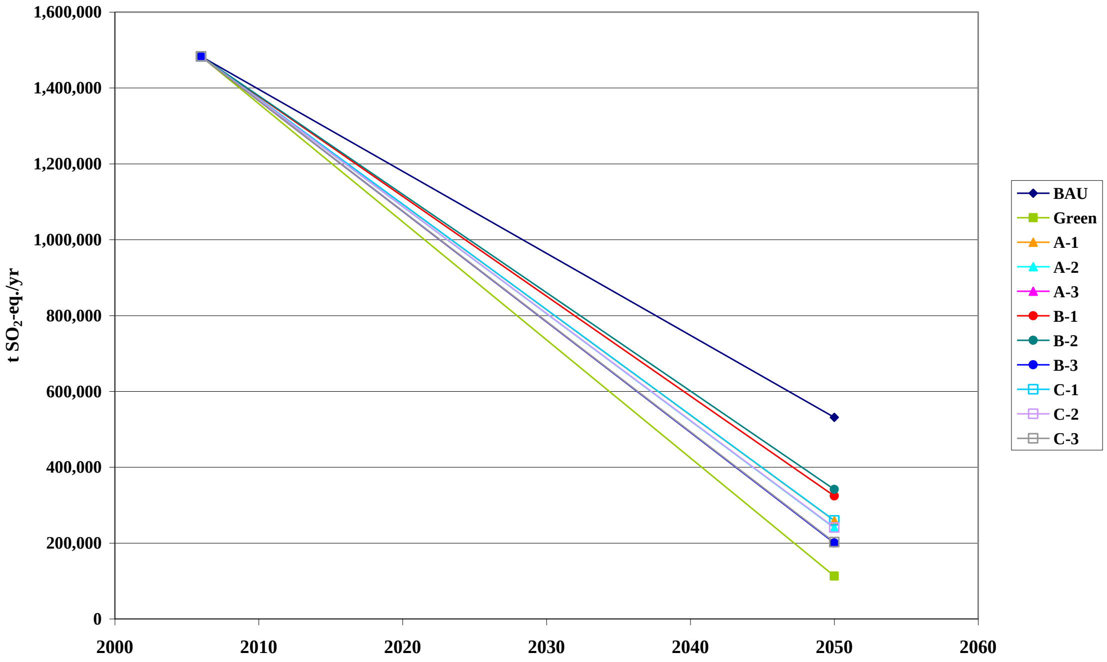

Figure 7-16 AP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

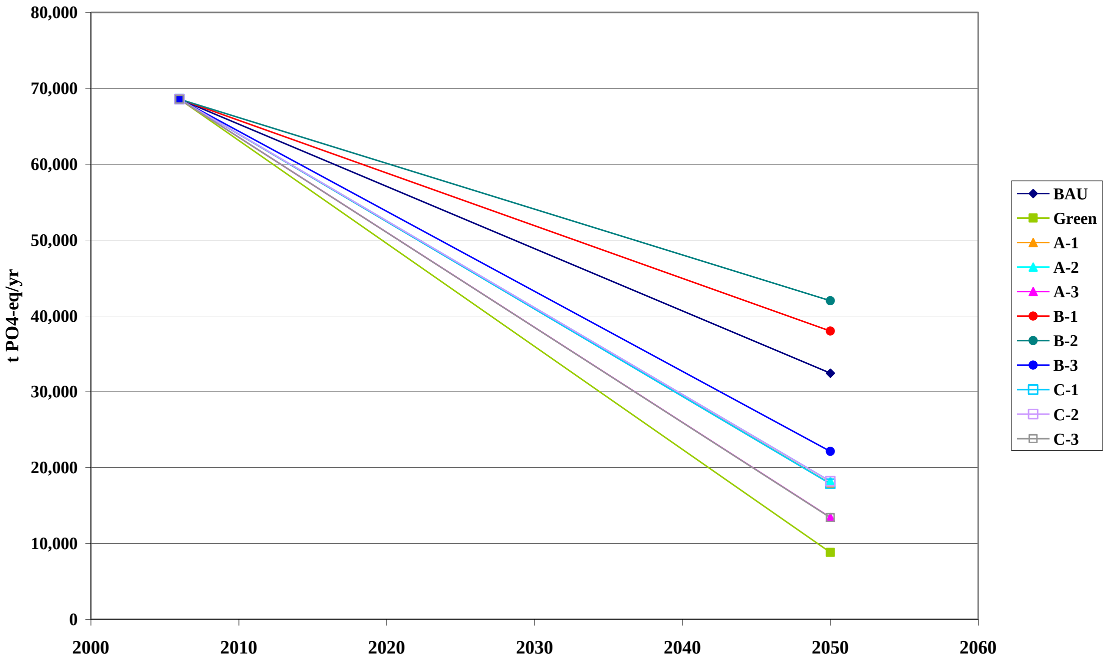

Figure 7-17 EP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

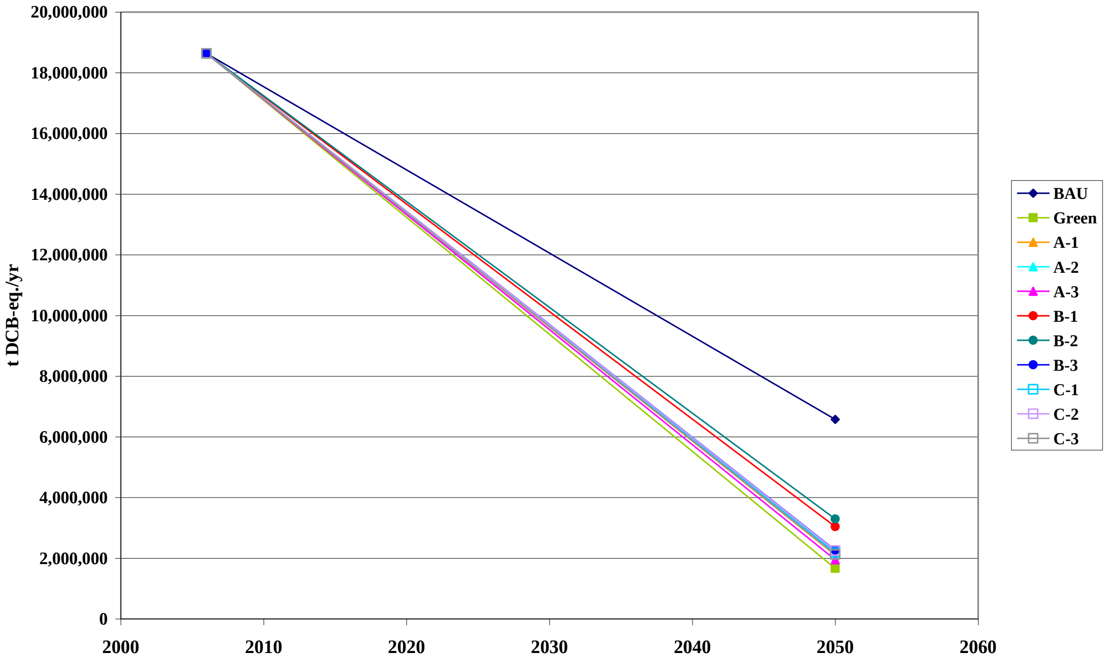

Figure 7-18 FAETP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

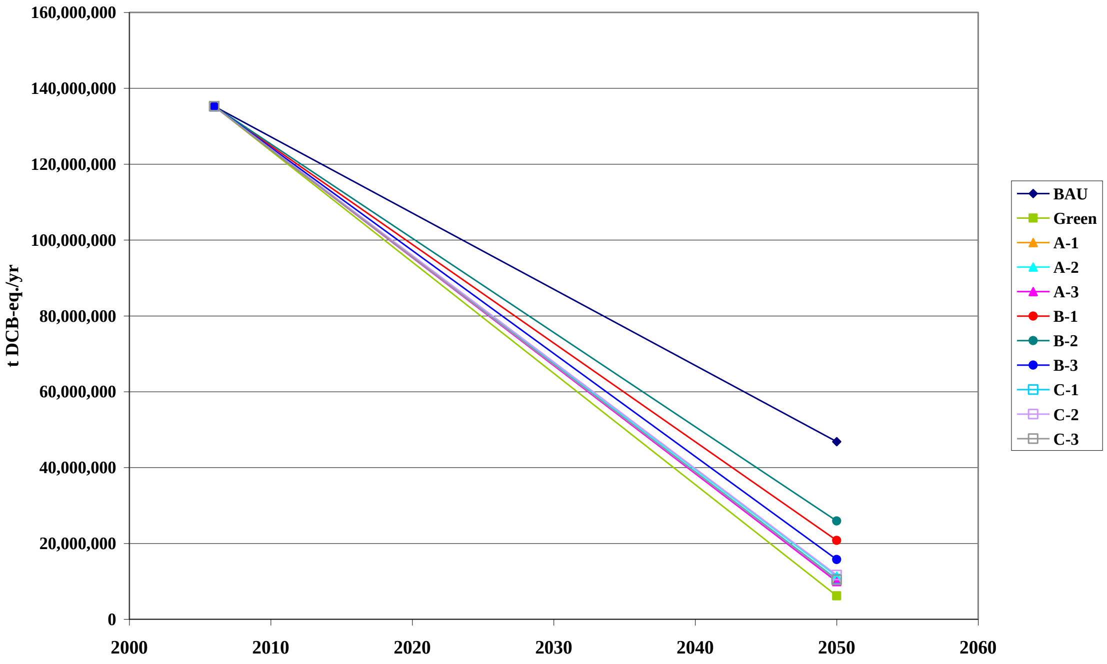

Figure 7-19 HTP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

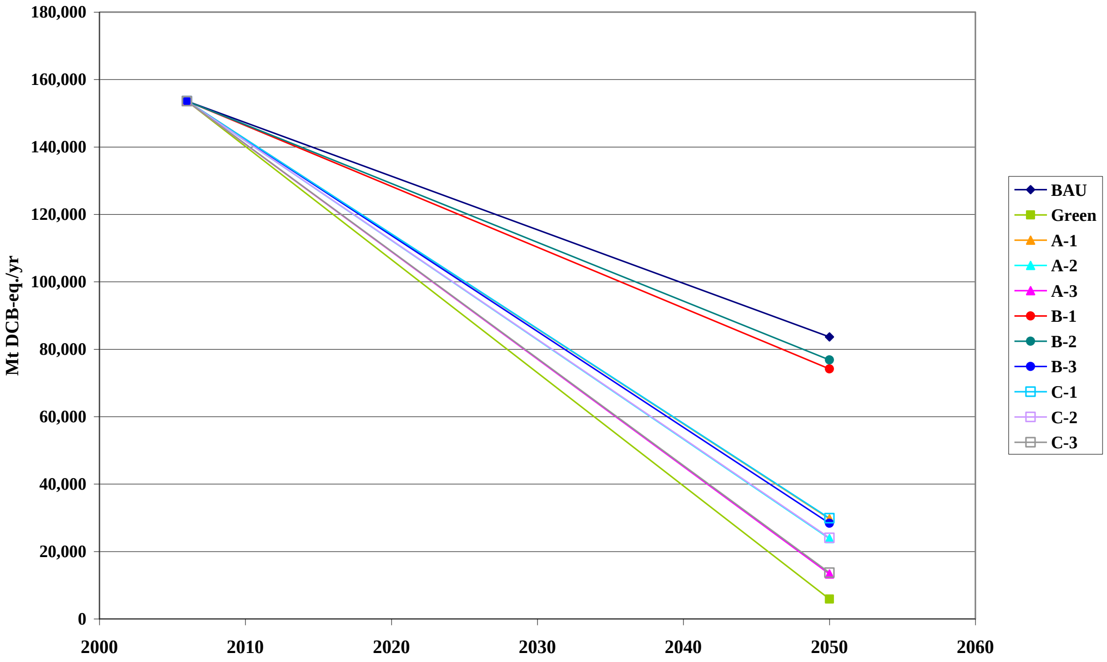

Figure 7-20 MAETP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

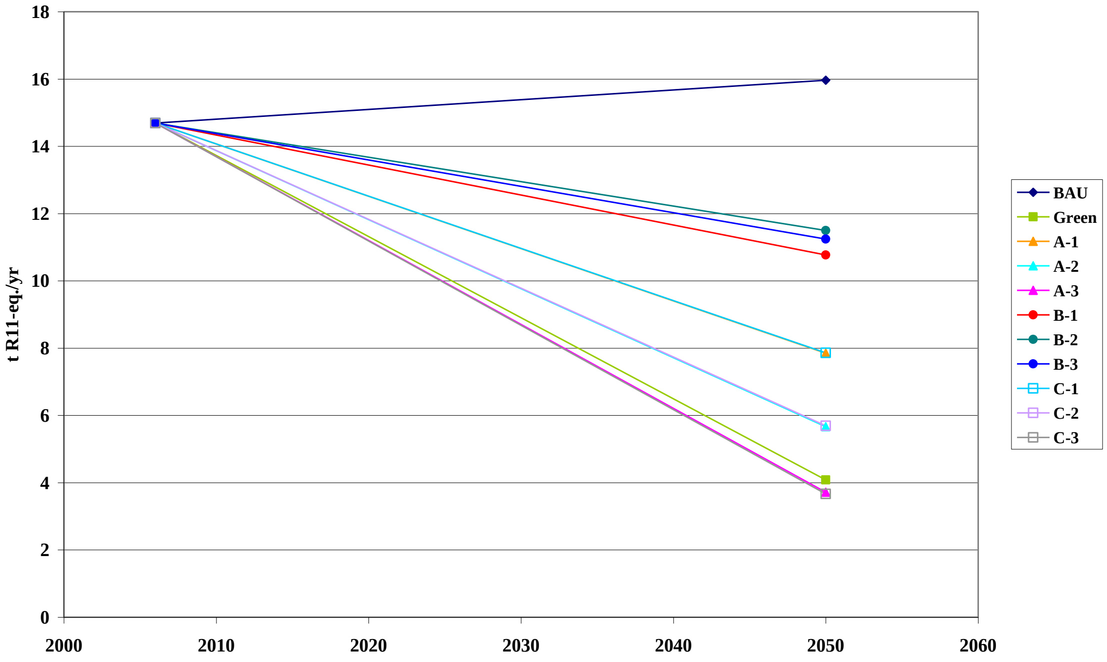

Figure 7-21 ODP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

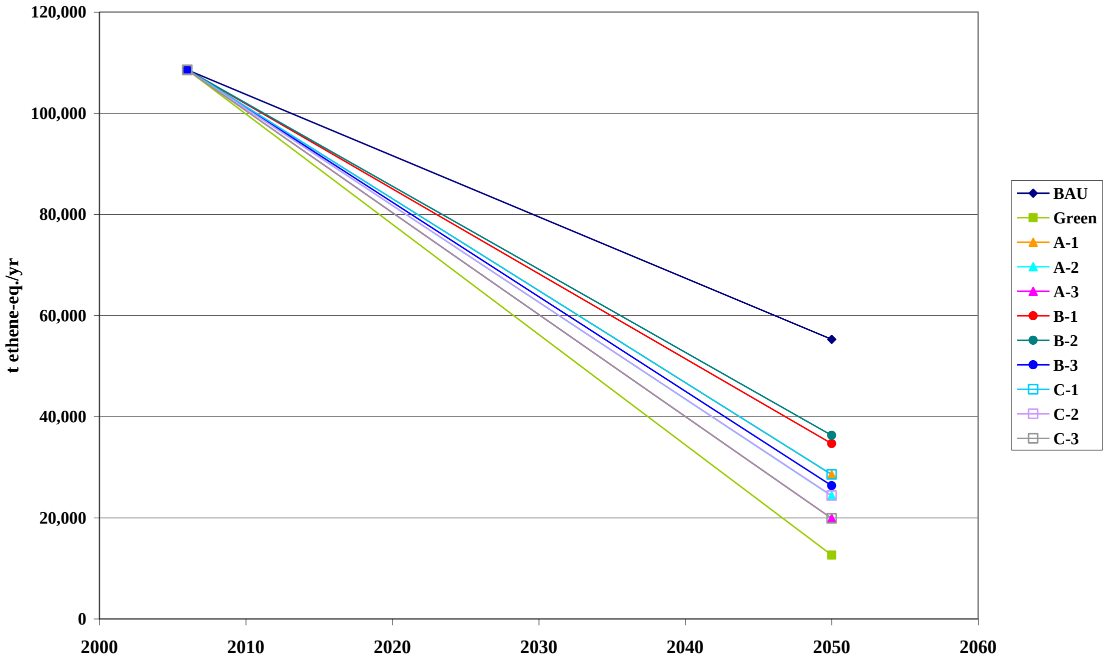

Figure 7-22 POCP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

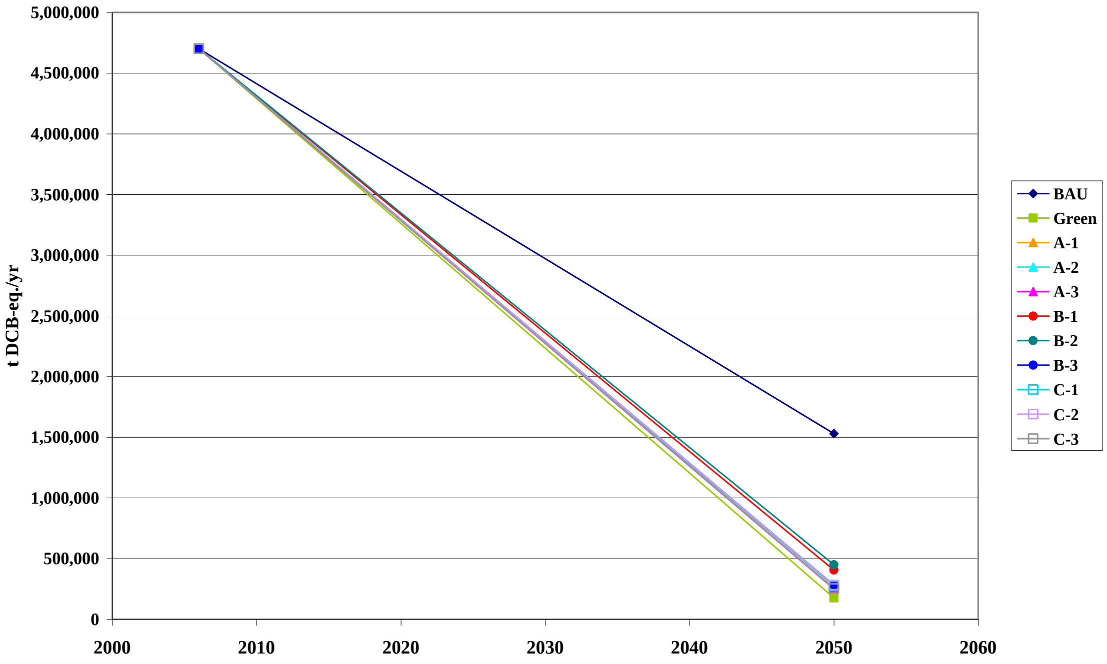

Figure 7-23 TETP trend from 2006-2050 for all scenarios assuming low electricity demand in 2050

Table 7-2 Comparison of the LCA impacts of future electricity scenarios with the base year 2006

	%										
	BAU	**Green**	**A-1**	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
GWP	102	-68	0	-54	-78	8	-42	-71	0	-54	-79
ADP	94	-69	-8	-32	-61	75	83	11	-8	-32	-61
AP	-64	-92	-83	-84	-86	-78	-77	-87	-83	-84	-86
EP	-53	-87	-74	-73	-80	-45	-39	-68	-74	-73	-80
FAETP	-65	-91	-89	-89	-90	-84	-82	-88	-88	-88	-89
HTP	-65	-95	-92	-92	-93	-85	-81	-88	-92	-91	-92
MAETP	-46	-96	-81	-85	-91	-52	-50	-82	-81	-84	-91
ODP	9	-72	-47	-61	-75	-27	-22	-23	-47	-61	-75
POCP	-49	-88	-74	-78	-82	-68	-67	-76	-74	-78	-82
TETP	-67	-96	-94	-94	-95	-91	-90	-94	-94	-94	-95
Average	**-20**	**-86**	**-64**	**-74**	**-83**	**-45**	**-47**	**-67**	**-64**	**-74**	**-83**

As can be seen from Figure 7-14 to Figure 7-23 and Table 7-2, reducing electricity demand (and generation) and implementing improved as well as renewable power plant technologies by 2050 could lead to a significant reduction of environmental impacts of the electricity sector in Mexico, compared to the current situation. On average, the greatest reduction relative to the base year is achieved for the Green (86%), A-3 and C-3 (83%) scenarios. This is mainly due to the high contribution of renewable energies. The lowest average reduction of 20% is noticed for the BAU scenario, with some impacts doubling (GWP and ADP; see Figure 7-14 and Figure 7-15), mainly due to the use of gas and coal.

The highest improvements in GWP (78% and 79%) are achieved in scenarios A-3 and C-3. The GREEN scenario is the preferred option for all other impacts; however, the difference in the environmental impacts compared to the A-3 and C-3 scenarios is relatively small.

The worst performing scenarios for GWP, apart from BAU, are scenarios A-1 and C-1, with no reduction in this impact compared to the base year due to their GWP stabilisation target in 2050. These scenarios, along with B-3, also show comparatively little improvement in ADP (-8% and 11%, respectively) because of high consumption of fossil fuels (gas and coal).

The average reductions in AP and EP among all scenarios range from -92% (Green) to -64% (BAU) and from -87% (Green) to -39% (B-2), respectively (see Figure 7-16 and Figure 7-17). These reductions are mostly because of increasing contribution of renewable energies, reducing or no contribution from oil, and implementing improved coal power plants compared to the base year.

FAETP and HTP highest average reductions are for scenarios Green, A and C ranging from -91% to -88% for FAETP and between -95% to -91% for HTP (Figure 7-18 and Figure 7-19). These reductions are also due to increasing contribution of renewable energies and reducing electricity from oil and coal. The highest improvement in

MAETP for scenarios Green (-96%), A-3 (-91%) and C-3 (-91%) is also because of increasing renewable energies (Figure 7-20).

On average, the greatest reduction in ODP relative to the base year is for scenarios A-3 (-75%), C-3 (-75%) and Green (-72%) mostly because of less electricity from gas (Figure 7-21). The highest average reductions in POCP and TETP are also for scenarios Green, A-3 and C-3 ranging from -88% to -82% and from -96% to -95%, respectively (see Figure 7-22 and Figure 7-23). These reductions are mainly because of reducing electricity from coal and increasing contribution of renewable energies.

7.4 Summary

This chapter has presented the LCA impacts of different future electricity scenarios for two functional units: ‘high electricity demand’ (814,000 GWh/yr) and ‘low electricity demand’ (598,000 GWh/yr).

The results for the former indicate that following business as usual leads to a significant increase of all environmental impacts by 2050. GWP and ADP increase by 3 times with most other impacts also going up by 2-3 times. The only exceptions are HTP and TETP which reduce by 22% to 3%, respectively, because of the assumed reduction of oil use.

If the electricity demand is low as assumed in the second functional unit, significant reductions of environmental impacts can be achieved across all the scenarios. Notably, the Green, A-3 and C-3 scenarios are the most sustainable options for most environmental impacts, achieving an average reduction of up to 85%, relative to the base year. This is mainly due to the high contribution of renewable energies. The BAU scenario remains the least sustainable, despite the reduced electricity generation, achieving only a 20% overall reduction in environmental impacts. In this scenario, GWP and ADP double on the base year, mainly due to the use of gas and coal.

Therefore, these results would indicate, that among the scenarios considered, the choice is between Green, A-3 and C-3 scenarios. Although this is the case for the environmental impacts, it is unclear at this stage how they compare for the other two dimensions of sustainability: economic costs and social impacts. These aspects are evaluated in the next chapter, followed by multi-criteria decision analysis (MCDA) of electricity scenarios in the subsequent chapter.

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8. Socio-economic assessment of future scenarios for electricity production in Mexico

This chapter presents the economic and social assessment of scenarios for electricity production in Mexico in 2050. The methodology for the assessment has been discussed in Chapter 4. The economic analysis is discussed first, followed by the social assessment.

8.1 Economic assessment of future scenarios

Similar to the economic assessment of the base case presented in Chapter 5, the economic analysis carried out for the future scenarios involves the estimation of capital and total annualised costs (capital, fixed, variable and fuel) as well as levelised costs. The analysis is based on electricity generation of 598,000 GWh and a 10% discount rate has also assumed. The operating parameters of power plants have been summarised in Table 6-3 and Table 6-9, in Chapter 6. The following section outlines further assumptions and data sources.

8.1.1 Assumptions and data sources

Fuel costs

The fuel cost projections for the scenarios have been sourced from the BAU (IEA, 2004) and Green (Greenpeace & EREC, 2008a) scenarios. For the fossil fuels, two options have been defined: a) the ‘low cost’ and ii) a ‘high cost’ scenarios (see Figure 8-1).

The ‘low fossil fuel (FF) cost’ scenario is based on the BAU (IEA, 2004) scenario describing a business-as-usual approach until 2030 (based on the oil and natural gas prices before the recent price increases); this has been linearly extrapolated to year 2050 by Greenpeace & EREC (2008a). The ‘high fossil fuel (FF) cost’ scenario is based on the Greenpeace & EREC (2008a) projection from today to 2050, assuming a considerable increase in energy demand and fast depletion of fossil fuel reserves for the future.

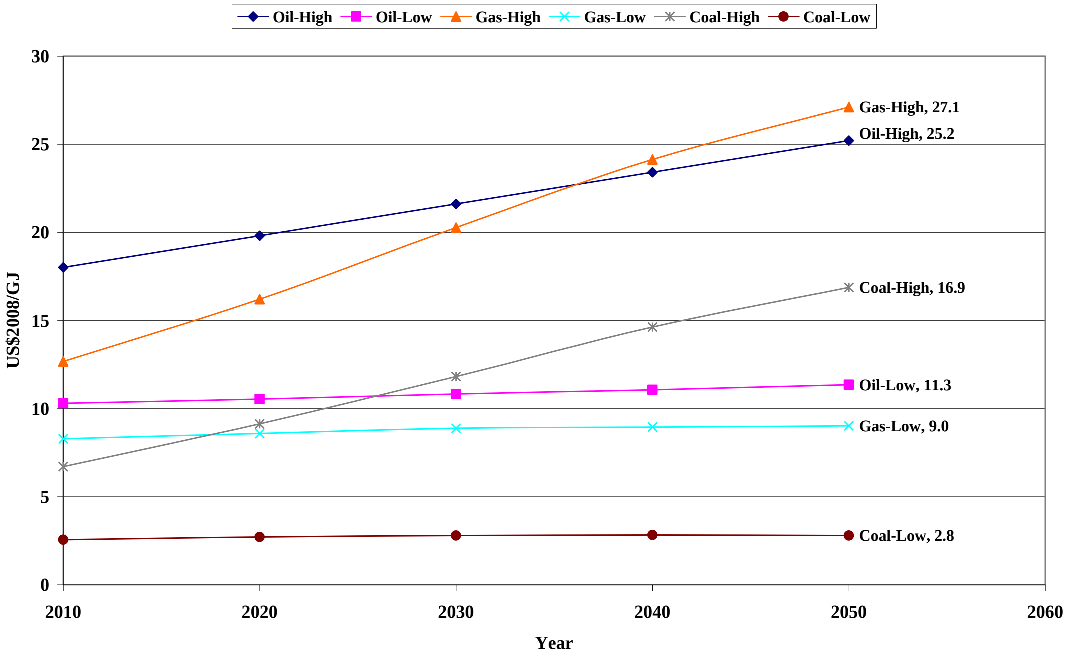

Figure 8-1 Oil, gas, and coal costs projections to 2050 for 'low' (BAU) and 'high' (Green) scenarios (IEA, 2004; Greenpeace & EREC, 2008a)

As shown in Figure 8-1, the 'low FF costs scenario' assumes an almost constant fuel price development from 2010 costs to year 2050, expecting the oil price to be at $11.3/GJ (69 US$2008/bbl) in 2050 (IEA, 2006a). This assumption may be unrealistic giving the fact that current oil prices (like in 2008) are already close or over this value (according to the IEA (2008, 2010)) being 15.88 and 9.58 US$2008/GJ for international and Mexican oil costs, respectively (see Chapter 5).

Considering the IEA's (2004) underestimation of fossil fuel prices (see Figure 8-1) and the increasing growing energy demand (especially for oil, gas and coal), together with the depletion of these fuel reserves, Greenpeace & EREC (2008a) have assumed a price development path in which the price of oil reserves reaches 25.2 US$2008/GJ (154 US$2008/bbl) by year 2050. Similar assumption for gas and coal costs have been made, increasing up to 27.1 and 16.9 US$2008/GJ by 2050, respectively (Greenpeace &

EREC, 2008a). These costs projections are in agreement with Krewitt et al. (2009) (for oil, coal and gas costs up to year 2050), and the IEA-WEO 2009 (for oil prices up to year 2030; IEA/NEA, 2010).

Moreover, higher fuel prices lead to a greater competitiveness, development of other low-carbon technologies such as renewable energy technologies and nuclear power, and the advancement along their learning curves (Neij, 2008; del Rio, 2011). Hence, the economic analysis of the current work assumes a 'high FF cost' scenario for the electricity production in Mexico by year 2050.

Capital costs

Energy policy goals frequently depend upon investment in particular power generation technologies (Gross et al., 2010). While fossil fuel based energy technologies are at an advanced phase of market development, there is a considerable further potential for costs reduction for low carbon generation technologies (especially for renewable energies; Greenpeace & EREC, 2008a; Bauer et al., 2008; Lecointe et al., 2007).

Fossil fuel power plants without CCS are technically mature (or expected to be mature in 2020 in case of an IGCC) so that only minor improvements are expected from 2020. In contrast, CCS technologies will be only at the beginning of their experience curve (Viebahn et al., 2007). Despite the fact that some of the renewable energy technologies currently available are not yet fully competitive (e.g., biomass, geothermal, ocean and solar), a large potential for cost reductions is expected to year 2050 due to further technical learning (Neij, 2008; Krewitt et al., 2009).

According to Lecointe et al. (2007), deployment of generation III nuclear reactors is likely to begin around 2020. As the EPR is a good representative of the Generation III evolutionary systems, it has been assumed that the EPR nuclear rector would be the "best available" technology for new plants in 2025. In fact, two first EPRs are already under construction in Finland and France.

Table 8-1 shows the expected development of specific capital costs for key selected electricity generation technologies.

Table 8-1 Assumptions for overnight capital cost development for selected power plant technologies in year 2050; (Greenpeace & EREC, 2008a; NEEDS project, 2009); EIA, 2009)

Energy	Overnight capital costs ($2008/kW)
Biomass	2661[a]
Coal (USC)	1234[b]
Coal (IGCC)	1516[b]
Coal CCS (USC)	1957[b]
Coal CCS (IGCC)	1889[b]
Gas	551[b]
Gas CCS	772[b]
Geothermal	3620[c]
Heavy fuel oil	1817[d]
Hydro	2130[c]
Nuclear	1731[e]
Ocean	1840[a]
Solar CSP	4761[a,f]
Solar PV	1190[a]
Wind onshore	1201[a]
Wind offshore	2083[a]

[a] Greenpeace & EREC (2008a)
[b] Bauer et al. (2008)
[c] EIA (2009) extrapolated value from year 2030 to year 2050, using Greenpeace & EREC (2008a) costs trends
[d] Same as for the base case scenario (for year 2006)
[e] Lecointe et al. (2007)
[f] Capital costs for concentrating solar thermal power plants include thermal storage systems which facilitate high capacity factors
USC: Ultra-supercritical
IGCC: Integrated gasification combined cycle

Fuel and technologies costs

As mentioned previously, the ‘high FF cost’ scenario by Greenpeace & EREC (2008a, 2008b) has been assumed for the current analysis. Besides fossil fuels, the costs of other fuels assumed for future power generation in Mexico (such as uranium and biomass) are presented in Table 8-2.

Table 8-2 Fuel costs assumed for scenarios for electricity production in Mexico by year 2050

Fuel	Cost (US$2008/GJ)	Source
Biomass	5.73	Greenpeace & EREC, 2008a
Coal	16.87	Greenpeace & EREC, 2008a
Gas	27.11	Greenpeace & EREC, 2008a
Heavy fuel oil	25.21	Greenpeace & EREC, 2008a
Uranium	4.40	NEEDS project (Lecointe et al., 2007)

The O&M costs (variable and fixed) of power plant technologies for the future scenarios are presented in Table 8-3. The main data sources are as follows:

i. variable and fixed costs for fossil fuels based power plants with and w/o CCS and EPR nuclear power plants were sourced from NEEDS project (Lecointe et al., 2007; Bauer et al., 2008);

ii. variable and fixed costs for renewable energy technologies were assumed the same as for the base case scenario and sourced from EIA (2009); this assumption is mainly based on two aspects: a) the fact that operating costs are very dependent on the location or climate region (as discussed in Chapter 3 and 5); and for this reason the Electricity Market Module (2009) reported for North American (U.S.) conditions are considered as more appropriate selection than for example operating costs in Europe (see for example IEA/NEA, 2010), b) the main costs variations for renewable energy technologies for the future are expected on reduction of overnight capital costs as indicated in section 8.2.3. (See for example IEA/OECD, 2008; Gujba et al., 2010, 2011).

The overnight capital costs assumed for the current economic analysis are presented in Table 8-1, mainly sourced from NEEDS project (2009) and Greenpeace & EREC (2008a).

Table 8-3 Operating & maintenance costs (variable and fixed) assumed for power plant technologies in Mexico by year 2050

Energy/Technology	Variable ($2008/GJ)	Fixed ($2008/kW)
Biomass[a]	1.93	66.90
Coal (USC)[b]	1.00	56.57
Coal (IGCC)[b]	1.19	73.06
Coal CCS (USC)[b]	1.15	86.96
Coal CCS (IGCC)[b]	1.38	89.60
Gas[b]	0.84	9.93
Gas CCS[b]	1.68	19.85
Geothermal[a]	0.00	172.97
Heavy fuel oil[c]	1.53	12.12
Hydro[a]	0.70	14.15
Nuclear[d]	0.23	69.06
Ocean[e]	0.00	72.73
Solar CSP[a]	0.00	58.94
Solar PV[a]	0.00	12.12
Wind onshore[a]	0.00	31.45
Wind offshore[a]	0.00	92.88

[a] EIA (2009)
[b] Bauer et al. (2008)
[c] Gujba et al. (2010)
[d] Lecointe et al. (2007)
[e] Greenpeace & EREC (2008a)

8.1.2 Results of the economic assessment

The capital, annualised costs and levelised costs of all electricity scenarios are presented and discussed in the following sections. Detailed results can be found in Appendix 4.

Capital investment costs

Figure 8-2 shows the capital costs required for all future scenarios. The results indicate that the BAU scenario is the most attractive option costing US$ 92.6 billion in 2050. This is mainly because of the lowest required power capacity (as shown in Table 6-3), which in turn is due to a high contribution of fossil fuels based power plants with considerable higher capacity factors if compared with renewable energies (Table 6-9). In contrast, the Green scenario is by far the most expensive option, requiring a capital investment of US$ 321.4 billion from today to year 2050 (see Figure 8-2). This is mainly due to the highest contribution from renewable energies to the total electricity mix (86% of total) and thus their generally higher overnight capital costs compared to the conventional technologies (as shown in Table 8-1).

Scenarios A, B and C are more expensive than the BAU but cheaper than the Green, with the capital costs ranging from US$ 148.2 to 270.6 billion. Among these, the most economical options are scenarios B-1 and B-2, also because of their high contribution from fossil fuels (70%; see Table 6-2). Their costs are US$ 148.2 and 156.5 billion, representing a 60% and 69% increase on the BAU scenario, respectively. Scenarios C are also in general more economical than their A counterparts, mainly due to a lower contribution from renewable energies and higher contribution from nuclear power; scenario C-1 is the best option among C scenarios (see Figure 8-2) Scenario A-1 is the most economical option among scenarios A, requiring an investment of US$ 189.5 billion, followed by scenario A-2 with US$ 231.5 billion. Even though scenario A-3 has a 75% contribution from renewable energies (Table 6-2), it is still US$ 50.7 billion cheaper than the Green scenario (as shown in Figure 8-2).

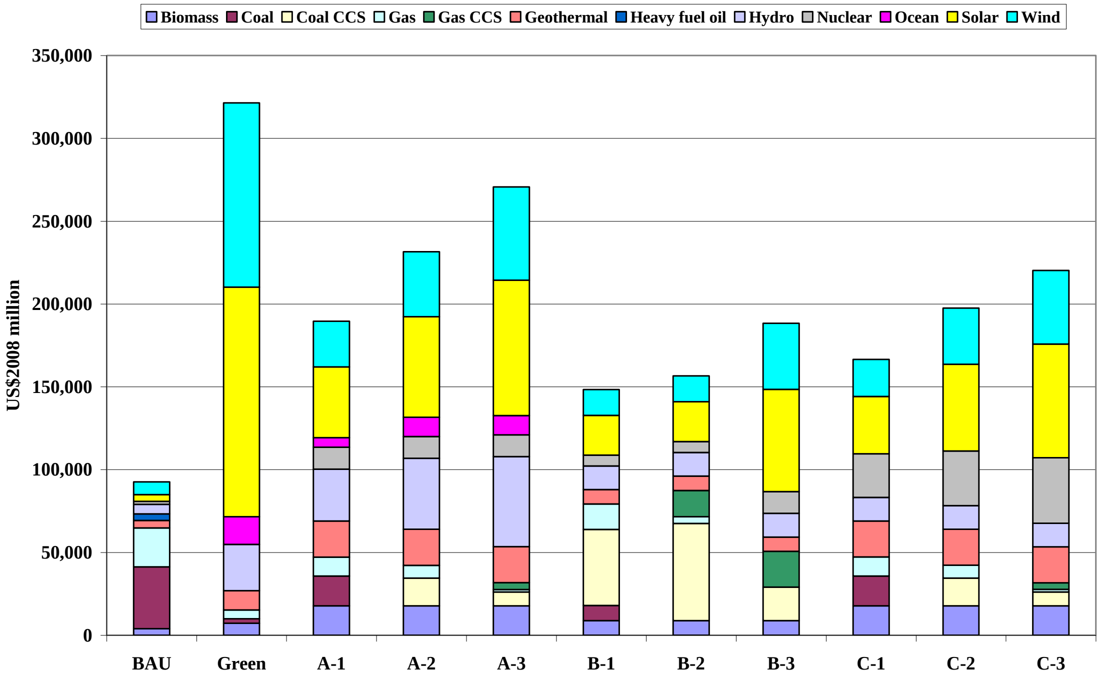

Figure 8-2 Capital investment costs for all electricity scenarios to year 2050; and energy source contribution to each scenario

Total annualised costs

Figure 8-3 presents the estimated total annualised costs (including discounted capital, fuel, variable and fixed costs). In contrast with the capital costs, herein the most expensive are the scenarios based on fossil fuels (BAU, B-2, B-1, and B-3), mainly due to the assumed high future fossil fuel costs (see Figure 8-1). The most expensive option is the BAU scenario with the annualised costs of US$ 87.9 billion, followed by B-2, B-1 and B-3 with values of US$ 85.1, 81.4 and 72.4 billion/yr, respectively.

On the other hand, scenarios with a high contribution from renewable energies (Green and scenarios A) together with scenarios C have considerably lower total annualised costs compared to the BAU and scenarios B, ranging from US$ 52.8 to 64.6 billion/yr (see Figure 8-3). Scenarios C-3 and A-3 are the most attractive options among all scenarios, followed by the Green scenario, costing US$ 52.8, 53.2, and 54.6 billion per year, respectively.

Figure 8-4 shows the breakdown of total annualised costs for each electricity scenario. It can be seen that fuel costs (especially due to fossil fuels) and discounted capital costs (mainly related to renewable energies based scenarios) dominate the total annualised costs in all scenarios.

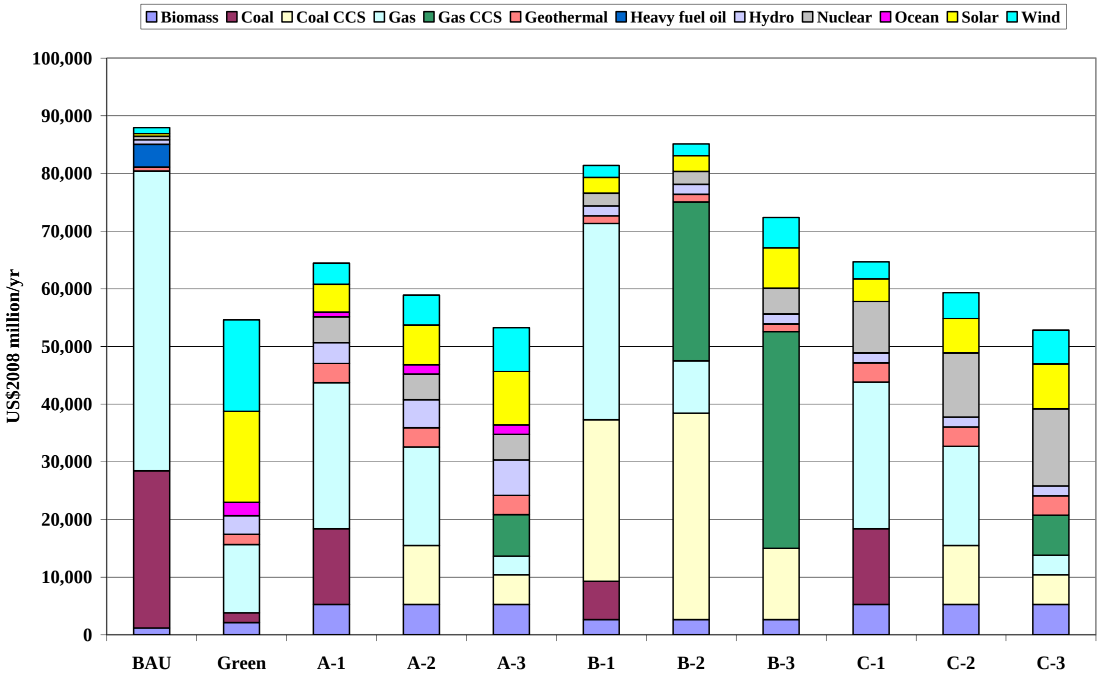

Figure 8-3 Total annualised costs of all scenarios in year 2050 and the fuel contribution to the total cost of each scenario

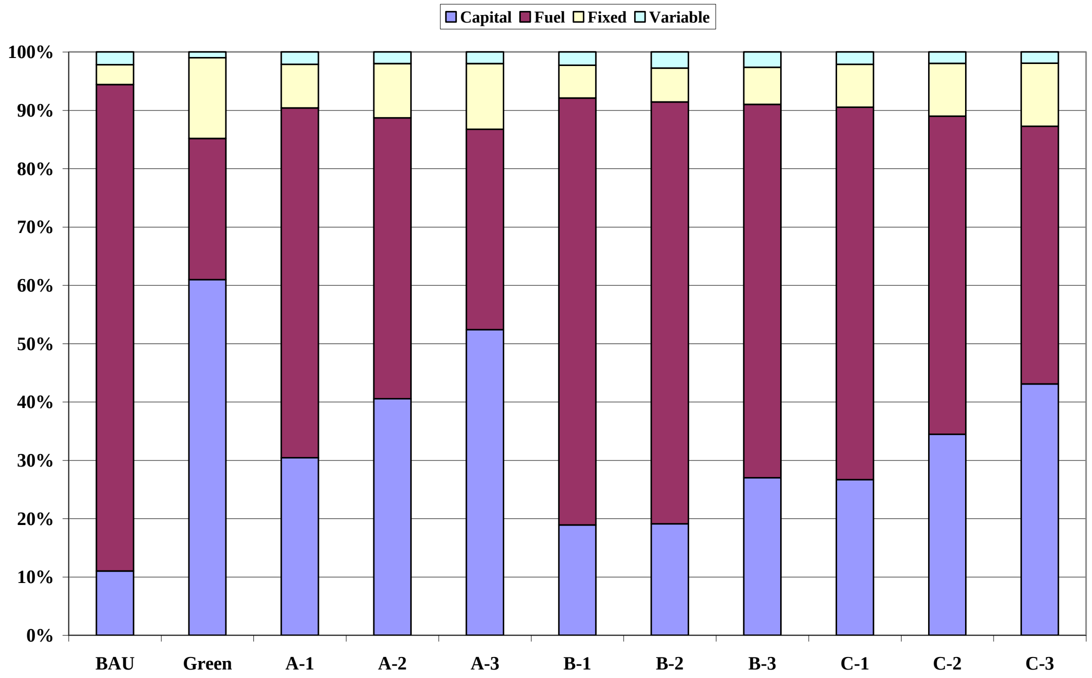

Figure 8-4 Contribution of capital, fuel and variable costs to the total annualised costs in 2050

Levelised costs

The estimated unit or levelised costs per MWh of electricity generated from each of the future electricity scenarios are presented in Figure 8-5. These costs show the same trends as the annualised costs presented in Figure 8-4, where the highest costs are for fossil fuels based scenarios ranging between 121 (for scenario B-1) and 147 (BAU scenario) US$/MWh. In contrast, the lowest unit costs are for scenarios C-3, A-3 (88 US$/MWh) and Green (91 US$/MWh). Other scenarios show unit costs ranging from 98 (scenario A-3) to 108 US$/MWh (for scenarios A-1 and C-1) (see Figure 8-5).

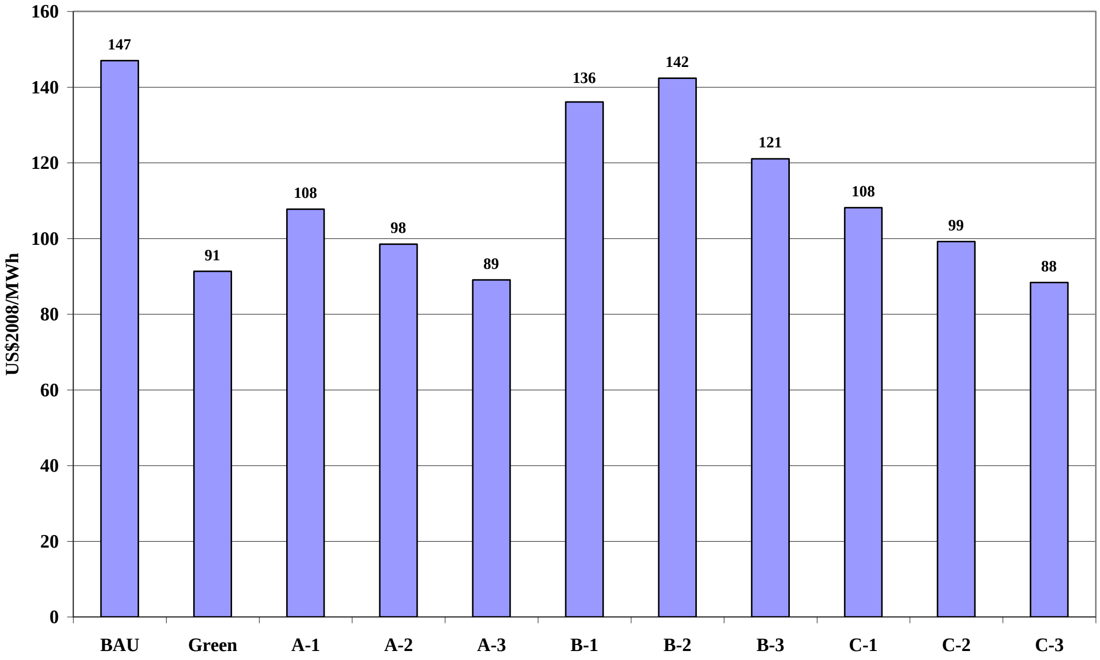

Figure 8-5 Levelised costs of electricity generation for all electricity scenarios in 2050

8.2 Social assessment of electricity scenarios for Mexico

As presented in Chapter 4, the social aspects considered in this analysis comprise:

- security and diversity of supply;
- public acceptability;
- health and safety; and
- intergenerational issues.

These are discussed below.

8.2.1 Security and diversity of supply

Aspects considered for the assessment of security supply of future scenarios for Mexico comprise, import dependency, fossil fuels depletion, diversity of electricity supply, availability of energy resource and reliability of electricity supply.

The BAU scenario can be considered the least sustainable option with respect of security and diversity of supply due to high dependence on fossil fuels (contributing 87% to the electricity mix in 2050; see Table 6-2). It has a high risk for the future due to high uncertainty of fossil fuels prices, increasing fuel demand and fast depletion of fossil fuel reserves in Mexico (Greenpeace and EREC, 2008b). Consequently, the BAU scenario has the highest ADP compared to other scenarios (see Figure 7-5 in Chapter 7).

On the other hand, the Green scenario seems to be a more secure scenario for electricity supply than the BAU scenario due to its lower dependency on fossil fuels (contributing only 14%) exhibiting the lowest ADP value among the scenarios; see Figure 7-5); however, its considerably higher dependence on wind and solar power (contributing 63%) opens questions in terms of diversification and reliability of supply (which is discussed further below).

Scenario A-3 and C-3 can also be considered as sustainable options in terms of security and diversity of supply due to the low dependency on fossil fuels (contributing 15%) leading to low ADP values (see Figure 7-5).

In the case of availability of energy resource, the Green scenario assumptions exceed considerably the estimated renewable energy potential for electricity production in Mexico because of the highest contribution from renewable energies (86% of total). For example, in the case of wind power, this scenario requires an installed capacity of 70,357 MW (see Table 6-3) which exceeds by 75% the availability of 40,000 MW (Table 6-6); similarly for ocean energy, the assumed capacity exceeds the availability by 44%. The required power capacity for scenarios A, B and C are well below or similar to the estimated potential for the country (see Table 6-3 and Table 6-9), which makes these scenarios preferred options over the Green scenario.

The intermittency of some renewable energy such as wind, solar and ocean will pose new challenges to the stability, reliability and operation of electricity grids. The additional costs for grid back-up and/or electricity storage for the large-scale grid integration of intermittent renewable energies are aspects that should also be taken into consideration (Gagnon et al., 2002; del Río, 2011). The Green scenario is the least reliable option because of the high contribution from intermittent sources such as wind, solar PV, and ocean energy contributing 51% to the electricity mix (see Table 6-2).

Overall, scenarios A are considered as better options for security of supply because of their high diversity of energy sources and high contribution from renewable energies to the electricity mix. Scenario A-3 is the best option with a balance between security and diversification of the electricity supply for Mexico in 2050. In this scenario, nine different energy sources are used to meet the electricity demand, compared to eight sources in the Green and C-3 scenarios (see Table 6-2). The highest contributors in scenario A-3 are wind, solar and hydro power, each contributing 19.5%, 19.5% and 15% to the electricity mix, respectively (Table 6-2).

Even though scenarios C have also a high contribution from renewable energies, the main issue to security of supply is the high dependency on the import of uranium resources to meet the contribution of 20%, 25% and 30% from nuclear power by 2050 in scenarios C-1, C-2 and C-3, respectively.

8.2.2 Public acceptability

The discussion here is related to the public acceptability issues reviewed for all electricity generating options in Chapter 3. These are summarized in the following way:

- regional or local environmental aspects (e.g. land change issues, landscape and visual impact, noise,);
- distrust or uncertainty towards the development of unknown technologies and
- health and safety issues

Public acceptability in scenarios A and Green with high contribution from renewable energies (mainly wind, solar and hydro; being the sources with the highest contributions to the electricity mix) is mainly related to local and regional impacts. Examples of these issues in Mexico are discussed below.

Main barriers for development of renewable energies in Mexico are mostly related to land and water issues as well public awareness and legal and administrative aspects (Lokey, 2009). For example, independent power producers (IPPs) in Mexico have had the experience of purchasing land from legal owner and later finding that people are living illegally on the land but claim it as their own. Relocating these people has been problematic and time-consuming. In general, project developers have found that locals and officials, who study for example the impact of wind turbines on birds and bats, often demand illegal payouts to allow the project to be completed (Lokey, 2009).

In the case of hydro electricity, main public acceptability aspects are also related to land and water irrigation issues as well as public awareness. For example, another private company (COMEXHIDRO) had to convince locals that the power plant they planned on building near farmers' fields would not electrify crops and that the dam would not affect water irrigation (Lokey, 2009). Current examples of public position to the construction of dams for large hydro projects are the recently built "El Cajon" power plant with a power capacity of 750 MW and "La Parota" power plant of 900 MW which is under construction (Cancino-Solórzano et al., 2010).

Among the scenarios with high contribution from renewable energies, the Green scenario is considered as the least public acceptable.

In the case of scenarios C, the public acceptability issues are mostly related to expansion of nuclear power. The most important issues are health and safety issues concerning nuclear accidents, nuclear proliferation, and increased risk from terrorism (Azapagic and Perdan, 2011; Goodfellow et al., 2011). The long term management and storage of radioactive waste is also a critical issue in Mexico as currently radioactive waste is temporarily stored in authorised facilities. There are neither arrangements for its disposal nor any decommissioning plan of nuclear facilities (OECD/NEA, 2005).

For scenario B and BAU with the highest contribution from fossil fuel with and without carbon capture and storage (CCS) main issues are related to health and safety impacts from operation of power plants and fuel production. These aspects have been outlined in Chapter 3. In the case of CCS, main safety aspects are related to the long-term storage and potential leaks of CO_2 (Pires et al., 2011). The literature does not reveal any future plans for CCS projects in Mexico.

With respect to public acceptability, all future scenarios present different advantages and disadvantages. Overall, scenarios A followed by Green are considered the most sustainable options.

8.2.3 Health and safety

Health and safety aspects of electricity generating options have been discussed in Chapters 3 and 4. Health issues in future scenarios have been have been accounted as human toxicity potential (HTP) (see Figure 7-9). Safety risks are mostly related to occupational accidents and public hazards (e.g. injuries and fatalities affecting direct workers and the public) and accidents risks along their life cycle (e.g. explosions, oil spills, etc.) which are also outlined in Chapter 3.

The BAU scenario has by far the highest HTP among all scenarios due to its high contribution from fossil fuels (mainly from heavy fuel oil). On the other hand, the Green scenario is the best option (with the lowest HTP value), followed by scenarios A and C (see Figure 7-9).

Furthermore, scenarios with a high contribution from fossil fuels to the electricity mix (scenarios BAU and B) have the highest number of fatalities and hazards from accidents along the life cycle (as discussed in Chapter 3; see Table 3-1).

Some of the most important health and safety aspects for scenarios C (mainly in C-3) are related to nuclear accidents, proliferation and radioactive waste management and storage. Health and safety risks exist for other energy technologies but on average are of a lower severity than fossil and nuclear power (Chapter 3).

Overall, scenarios A-3 and Green pose the least risks and therefore are considered to be more sustainable from the health and safety perspective.

8.2.4 Intergenerational issues

Some of the most important intergenerational issues have been outlined previously in Chapters 4, these include mitigation of climate change, depletion of fossil fuel reserves and aspects related to nuclear power (e.g. Krewitt et al., 2007, 2009; Greenhalgh & Azapagic, 2009; Lior, 2010; Stamford and Azapagic, 2011). Therefore, GWP and ADP from the LCA results (Figure 7-4 and Figure 7-5) have been considered for the assessment of these issues for scenarios in Mexico.

The GWP results show that the best options are scenarios A-3 and C-3, followed by scenarios B-3 and Green (see Figure 7-4) with the worst option being the BAU scenario.

As discussed in section 8.2.1, in terms of ADP, the BAU scenario has the highest impact while the Green scenario is considered the best option (see Figure 7-5). Regarding the depletion of uranium reserves and nuclear waste management and storage, C scenarios pose greater concerns due to their higher contribution from nuclear power. The Green and A scenarios represent the most sustainable options for this social aspect due to no or lower nuclear power assumed.

From the intergenerational point of view, scenarios Green and A-3 are also considered to be the most sustainable options.

8.2.5 Other socio-political aspects

A number of other socio-political aspects which affect the development of low carbon projects in Mexico are mentioned below.

For renewable energies the following issues need to be considered in the Mexican context (Lokey, 2008; Cancino-Solórzano et al., 2010, Ruiz-Mendoza & Sheinbaum-Pardo, 2010a;b; del Río, 2011):

- Legal and administrative barriers: the deployment of renewable energies faces policy barriers related to the granting of administrative authorisations or grid access procedures;
- Political factors: the promotion and application of renewable energies require specific targets and support policies as well as financial mechanisms (besides the existing: i.e., Clean Development Mechanism, Emissions Trading schemes);
- Subsidies to fossil fuels and nuclear power, which discourages the investment of renewable energies;
- Human capital factors: the need for sufficient skilful personnel for the installation and operation of new technologies.

Additionally, for fossil fuels and nuclear power, environmental externalities should be considered. These include for example the external costs of human health damages and global warming, due to as the emissions of GHG, SO_2, NO_x, particulates and other pollutants. Such damages could be monetized (i.e. measured in or converted to monetary units), but this aspect is still very uncertain today. The total costs of electricity generation including both internal (production) and external costs could be used as a measure of sustainability and energy planning for the future (NEEDS, 2009; Roth et al., 2009; SENER, 2009; IEA/NEA, 2010; IIE, 2010; PSI, 2010). While some studies have been done for the estimation of externalities in Mexico (Macías & Islas, 2010, SEMARNAT-CEPAL, 2004), these have only comprised a number of power plants and have not been estimated in a life cycle basis.

8.3 Summary

The economic and social assessment of scenarios for electricity production in Mexico with a time frame to year 2050 have been estimated and discussed in this chapter.

In terms of capital costs, overall, the BAU is the most economical option requiring an investment of US$ 92.6 billion, versus the Green scenario which requires US$ 321.4 billion, by far the highest investment costs among all scenarios, mainly due to the high contribution from renewable energies and their related high overnight capital costs. The capital costs for the other scenarios range between US$ 148.2 for B-1 to 270.6 billion for A-3.

In contrast, considering the total annualised costs in 2050, the BAU is the most expensive option among all scenarios (US$ 87.9 billion/yr). The best options are scenarios C-3 and A-3 (US$ 52.8 and 53.2 billion/yr), followed by the Green scenario (US$ 54.6 billion/yr). For the scenarios based on fossil fuels (BAU and B), the main contributor to the total annualised costs are projected high fossil fuels costs by 2050. The high capital costs of renewable energies are the main contributor to the total annualised costs of the Green scenario. Total annualised costs of scenarios A and C are also due to high fuel costs and capital costs of low-carbon technologies (renewable energies, CCS and nuclear power).

With respect to social issues, the BAU scenario has the highest risks related to security and diversity of supply, health and safety and intergenerational issues. Therefore, it is considered the least preferred option.

All other future scenarios have different advantages and disadvantages. For example, the Green scenario shows a good performance in terms of fuel import dependency and climate change issues, but with significant social barriers related to public acceptability, availability of energy resource and reliability of electricity supply due to the highest contribution from renewable energies (86% of the electricity mix).

Scenarios B have similar characteristics to the BAU scenario, with the main difference being their considerably lower GWP compared with the BAU; this is because of the assumed implementation of CCS. Scenarios A present a good balance between social aspects such as security and diversity of supply, health and safety and their low contribution to GWP (particularly for scenario A-3). The main social barriers for these scenarios may be related to public acceptability due to their high contribution from renewable energies to their total electricity mix and their related sustainability implications (mainly for wind, solar and hydro power). Health and safety, and intergenerational issues, are the most significant barriers for scenarios C due to the high contribution from nuclear power (especially in scenario C-3).

Therefore, from the social perspective, the most sustainable options are scenarios with the highest contribution from renewable energies such as A-3 and Green scenarios (contributing 75% and 86%, respectively).

Energy planning decisions are usually made by comparing different options with respect to several, often conflicting criteria. In these cases, there is generally no best overall option, as switching from one option to another is likely to result not only in an improvement in some criterion but also in the deterioration of other criteria. This is also the case with the environmental, economic and social implications of future electricity scenarios for Mexico (as discussed in Chapters 7 and 8). Multi Criteria Decision Analysis (MCDA) can be used as an additional tool for decision-making in complex sustainability assessment studies such as this. Therefore, the next chapter presents the results and conclusions from a particular MCDA approach applied to the sustainability assessment of future scenarios for electricity production in Mexico.

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9. Multi-criteria decision analysis of future electricity scenarios

As shown in the previous chapters, there is no ‘best’ scenario overall, as each option is better for some sustainability criteria but worse for others. Therefore, this chapter presents the MCDA evaluation of the electricity scenarios for Mexico in an attempt to identify the most sustainable options for the future. The MCDA methodology used in this work has been outlined in Chapter 4. In summary, it involves formulation of alternatives and their evaluation on different sustainability criteria; criteria weighting, and estimation of MCDA results and ranking of alternatives. The former has been discussed in the previous chapters so that the focus here is on the criteria weighting and discussion of the MCDA results. The environmental criteria considered comprise all the environmental impacts as estimated in LCA and the economic criteria are the capital and annualised costs. Since most social criteria are qualitative apart from human toxicity potential (HTP), also calculated as part of LCA, this is the only social criterion considered here. The evaluation has been performed assuming equal importance among the sustainability criteria and these results are presented next. This is followed by a discussion of how the choice of the most sustainable options might change if the criteria have different assumed importance or priority.

9.1 Equal weighting of sustainability criteria

This method assumes that all the sustainability criteria have equal importance. The criteria are ranked using a scale from 1 to 11. For the description of the methodology, see Section 4.8 in Chapter 4. The scenario with the lowest score is considered as the best available option, while the least suitable option is the scenario scoring the highest value among all options

As shown in Table 9-1 and Figure 9-1, the Green scenario ranks as the best option with a score of 2.4. It ranks 1st for 8 out of 12 criteria. The next best options are scenarios C-3 and A-3 scoring 2.9 and 3.0, respectively. The worst option is BAU, ranking bottom for 10 criteria. However, although the Green scenario scores as the best option overall, it has some important drawbacks. For example, it ranks 4th for GWP, 3rd for ODP and annualised costs and bottom for the capital costs. Moreover, as discussed in Chapter 8, the Green scenario has also critical social aspects to be addressed. These include low reliability of electricity supply (the worst among all scenarios) and various public acceptability issues. Perhaps most importantly, however, it exceeds considerably the estimated available renewable energy potential in the Mexico (specifically for wind and ocean energy) and is therefore highly unlikely to be realised by 2050.

Table 9-1 Overall score assuming equal preferences for each sustainability criterion (based on the results presented in Figures 7-4-7-13 and Figures 8-2-8-3)

	Weight (%)	**BAU**	**Green**	**A-1**	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
Indicators												
GWP	8.33	11	4	9	6	2	10	7	3	8	5	1
ADP	8.33	11	1	6	4	3	9	10	8	7	5	2
AP	8.33	11	1	7	5	3	9	10	2	8	6	4
EP	8.33	9	1	5	6	3	10	11	8	4	7	2
FAETP	8.33	11	1	3	5	2	9	10	8	6	7	4
HTP	8.33	11	1	3	6	2	9	10	8	5	7	4
MAETP	8.33	11	1	7	4	2	9	10	6	8	5	3
ODP	8.33	11	3	6	4	2	8	10	9	7	5	1
POCP	8.33	11	1	7	4	3	9	10	6	8	5	2
TETP	8.33	11	1	4	6	2	9	10	8	5	7	3
Capital costs	8.33	1	11	6	9	10	2	3	5	4	7	8
Annualised costs	8.33	11	3	6	4	2	9	10	8	7	5	1
Total/Score	100	10.0	2.4	5.8	5.3	3.0	8.5	9.3	6.6	6.4	5.9	2.9
Rank		**11**	**1**	**5**	**4**	**3**	**9**	**10**	**8**	**7**	**6**	**2**

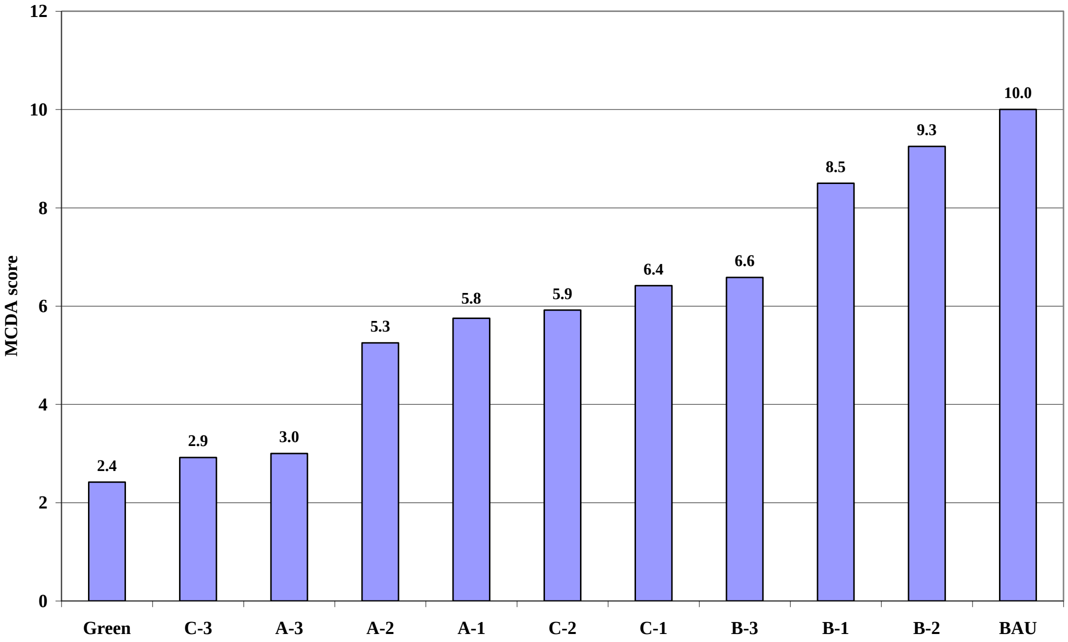

Figure 9-1 MCDA score of scenarios assuming equal weighting of criteria

9.1.1 Different preferences for different criteria

As discussed in Chapter 4, different stakeholders (i.e. government, NGO's, academia, industry) have different priorities related to electricity generation and supply. For example, GWP, HTP and levelised costs have been considered by some stakeholders as the most important indicators (see for example Roth et al., 2009; Stamford and Azapagic, 2011, Streimikiene, 2010; Wang et al., 2009). For this reason, sensitivity analysis is carried out to find out if the ranking of the scenarios changes with different weighting of the indicators. The simple multi-attribute rating technique (SMART) has been used for these purposes (Wang et al., 2009). For the description of this method, see Section 4.8 in Chapter 4.

In this work, the weighting has been carried out in two ways:

i) first, higher preference is given to one indicator at a time with all other indicators assuming equal importance; GWP, HTP and annualised costs have been chosen as the most important indicators in this part of the analysis; and
ii) higher preference is assigned to three indicators (GWP, HTP and annualised costs) at the same time.

An example calculation of the weighting of criteria can be found in Appendix 5. This appendix also shows the ranking of scenarios per criteria, the sustainability score for each scenario from the MCDA results, and the overall ranking of scenarios assuming preference on one indicator, and the priority given to three indicators (GWP, HTP, and annualised costs).

If preference is given to one indicator, an estimated weight of 48% (out of 100%, considering the sum of all criteria-weights) has been used for the MCDA, assuming that the selected indicator (GWP or HTP or annualised costs) is ten times more important than the rest of the criteria. Based on the same assumption, when given priority to three indicators (GWP, HTP and annualised costs), a weight of 25.6% was estimated for each of the selected criteria, altogether summing a total weight of 77% (with the rest of the criteria accounting for the remainder 23%).

Figure 9-2-Figure 9-4- show the MCDA results (score) with the priority assigned to GWP, HTP, and total annualised costs, respectively; the results considering preference on these three indicators are given in Figure 9-5.

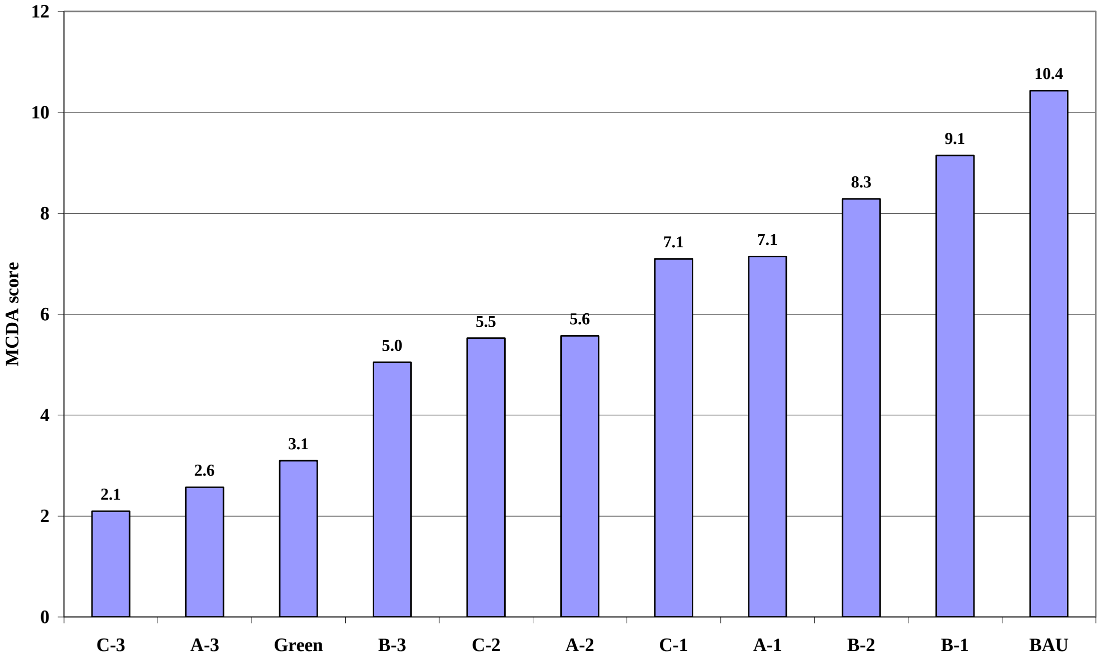

Figure 9-2 MCDA score with GWP being the most important criterion (10 times more important leading to a weight of 48%)

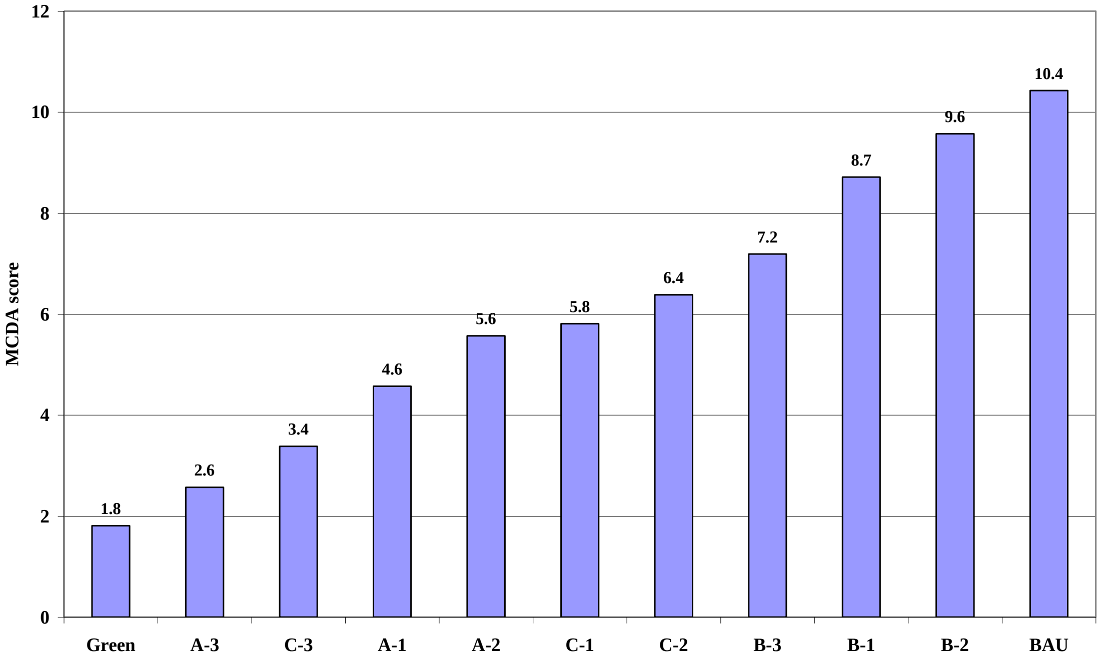

Figure 9-3 MCDA score with HTP being the most important criterion (10 times more important leading to a weight of 48%)

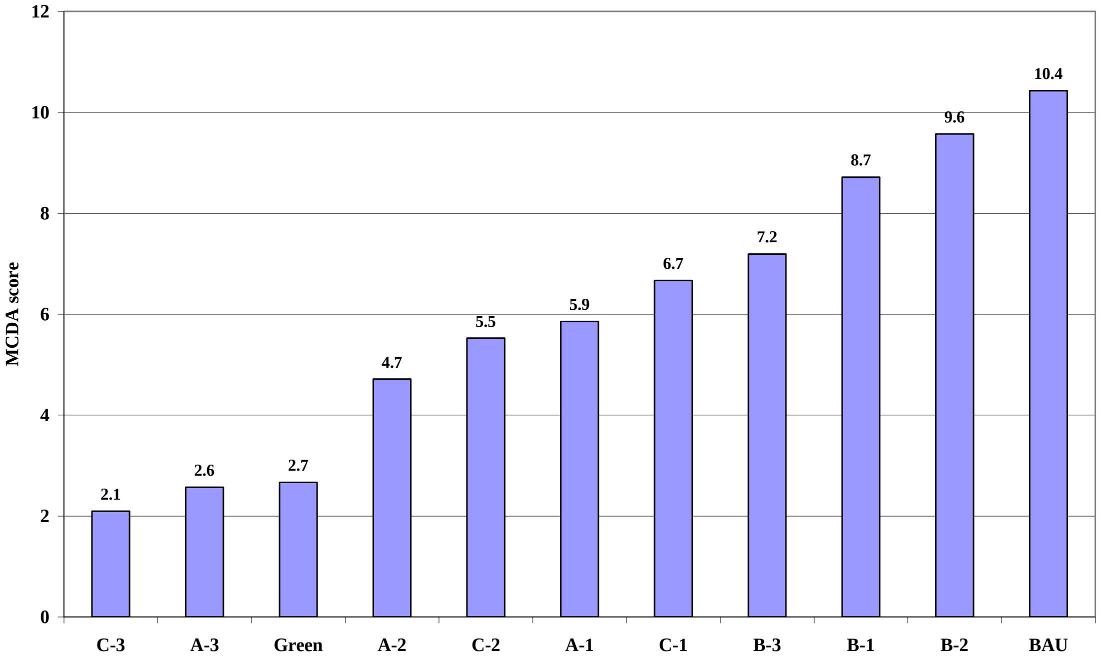

Figure 9-4 MCDA score with total annualized costs being the most important criterion (10 times more important leading to a weight of 48%)

It is clear from Figure 9-2 that, if GWP is the priority, the most attractive options are scenarios C-3, and A-3 followed by the Green scenario (ranked 1st, 2nd and 3rd and scoring 2.1; 2.6 and 3.1, respectively) due to their high GHG reduction targets (70-85%). Even though scenario B-3 also the same reduction target, it ranks 4th because of its performance on the rest of the criteria. However, this is a considerable improvement on its ranking (8th) when assuming equal weights (see Table 9.1). The BAU scenario is the worst option, scoring 10.4.

However, when giving priority to HTP, the Green scenario becomes the best option, scoring 1.8 (see Figure 9-3). It is followed by scenarios A-3 and C-3 which score 2.6 and 3.4, respectively. Interestingly, scenario A-1 improves from its previous ranking going from the 5th (Table 9-1) and 8th (Figure 9-2) place to be ranked the 4th best option due to its relatively low HTP. The BAU scenario is again the worst option scoring 10.4.

When considering the total annualised costs as the most important criterion, scenario C-3 becomes the best option scoring 2.1, closely followed by scenarios A-3 and Green (see Figure 9-4). Scenario A-2 shows a good balance among total costs and the rest of the selected criteria and it takes the 4th place. C-2 and A-1 are ranked 5th and 6th, respectively; BAU is still the least sustainable option.

Finally, Figure 9-5 shows that when priority is given to three indicators (GWP, HTP and total annualised costs), scenarios C-3 and A-3 are the best options scoring 2.3. The Green scenario follows closely, ranking as the 3rd best option with the score of 2.6. The BAU scenario is again the least sustainable option among scoring 10.7. It is followed by B-1 and B-2 which both score 9.1.

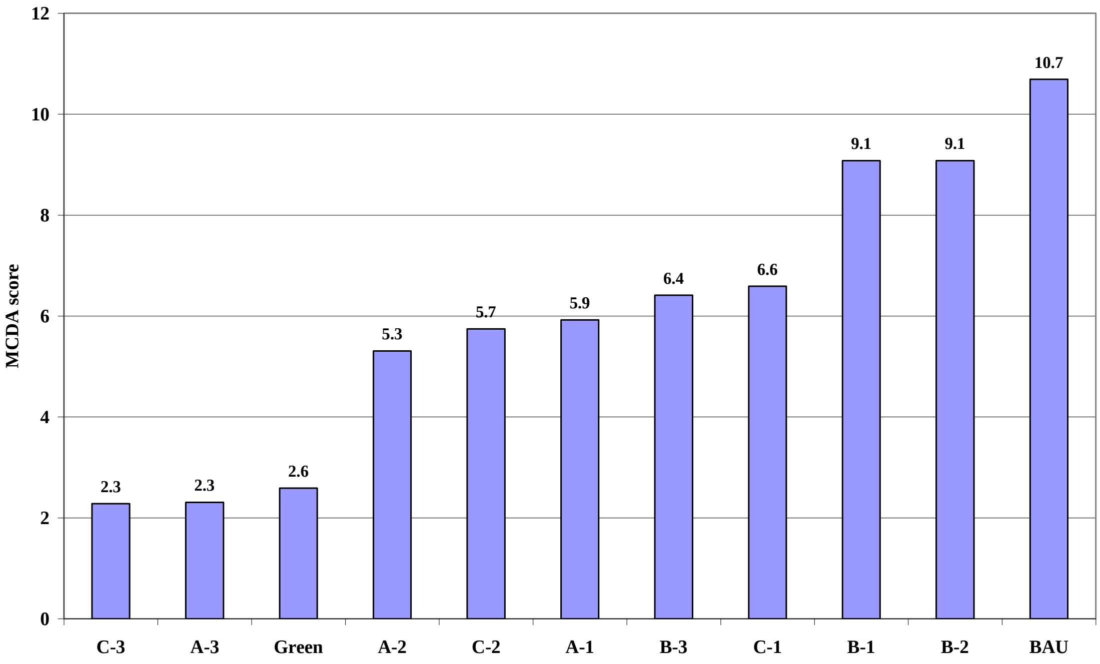

Figure 9-5 MCDA score with preference for GWP, HTP and total annualised costs (assuming an aggregated weight of 77% of the total)

9.2 Comparison of the results for different MCDA methods

Table 9-2 summarizes the rankings of the scenarios obtained using different MCDA methods. As can be seen, for all the MCDA methods the BAU scenario (with the highest contribution from fossil fuels) is the least sustainable option for future electricity supply in Mexico. Despite its lowest requirement for capital investment, its poor overall sustainability score is mainly due to its high annualised costs and LCA impacts. The BAU scenario is also considered the worst option from the social perspective (as discussed in Chapter 8).

Scenarios B, also based on a fossil fuels policy, overall perform better that the BAU scenario. This is mainly because of their higher contribution of renewable energies and the use of CCS to mitigate the GWP from the fossil fuels based power plants. Among the B scenarios, B-3 ranks as the best. This demonstrates that an 85% reduction of direct GHG emissions can be achieved with fossil fuel options - however, at the expense of other environmental impacts such as ADP, HTP, FAETP as well as the annualised costs and social aspects related to the large-scale use of CCS.

Table 9-2 Ranking of scenarios according to the MCDA scores (NB: 1 denotes the best and 11 the worst option)

			Priority given to:		
Scenario	**Equal weights**	**GWP**	**HTP**	**Annualised costs**	**GWP/HTP/A. costs**
BAU	11	10	11	11	11
Green	1	3	1	3	3
A-1	5	7	4	6	6
A-2	4	6	5	4	4
A-3	3	2	2	2	1
B-1	9	9	9	9	9
B-2	10	8	10	10	9
B-3	8	4	8	8	7
C-1	7	7	6	7	8
C-2	6	5	7	5	5
C-3	2	1	3	1	1

Overall, increasing the contribution from renewable energies and nuclear power is translated in a better sustainability performance which is the case of scenarios A-2, A-1, C-2 and C-1, generally in the middle of the ranking regardless of the MCDA method used. . These options can be considered if taking into account the stabilization of GHG from 2000 levels and 60% reduction by 2050 at a more attractive costing (if compared with scenarios B and the BAU). The main drawbacks for these options are the public acceptability of a larger scale use of renewable energies (mainly for scenarios A), as well as health and safety, and intergenerational issues for nuclear power (for scenarios C).

Generally, the Green, A-3 and C-3 top the sustainability (MCDA) rankings. If an equal weighting of sustainability criteria is considered, the Green scenario seems to be the most attractive option, which is similar when assuming a priority on HTP. However, when the focus is on climate change mitigation or on annualised costs, the more appropriate options are clearly scenarios C-3 and A-3. This is also confirmed when giving priority to GWP, HTP, and annualised costs.

9.3 Uncertainty analysis

The results obtained in this (and any similar) work are subject to uncertainty due to a number of factors, including the assumptions and data uncertainties as well as the uncertainty related to decision-makers' preferences for different sustainability criteria. While it is not possible to quantify these due to a lack of data (which in turn is one of the reasons for the uncertainty), the following sections discuss the uncertainty related to different factors and make suggestions as to how it could be reduced.

9.3.1 Assumptions and data

Due to a lack of information or specific data, a number of assumptions had to be made for the analysis of environmental and economic impacts for both the base year and the scenario analysis. The assumptions are mainly related to the operating parameters of power plants (e.g. fuel composition, emission controls) and future technological developments (technical, environmental and economic). Some of the most important assumptions and data which could affect the final results are discussed below.

Base year

For the base year, the main assumptions made are in relation to:

i) the fuel composition;
ii) emission control;
iii) background activities;
iv) costs.

The assumptions in i)-iii) affect the environmental (LCA) impacts and the assumptions in iv) affect the economic analysis.

i) Fuel composition: The data for the sulphur content for the base year are based on the real data for the previous years (sourced from Vijay et al., 2004). This assumption mainly affects the acidification potential (AP) from the operation of oil and coal power plants. The confidence in the AP results is high as it is unlikely that the sulphur content in the fuels used in Mexico has changed significantly over the past few years. The rest of the fuel composition was assumed generic and the data were sourced from the Gemis and Ecoinvent databases. This assumption affects a range of impacts such as global warming (related to the carbon content), human and eco-toxicity (e.g. heavy metals). Since the carbon content in fuels depends more on the type of the fuel rather than on where the fuel is sourced from, the confidence in the global warming results is high. However, the confidence in the results of the other environmental impacts, such as human and eco-toxicity is medium, since the content of heavy metals and other toxic compounds can differ for the same types of fuel.

ii) Emission controls: Due to a lack of information, it was assumed that no power plants in Mexico have emission controls, with the exception of coal power plants for which the electrostatic precipitators were considered. Therefore, the confidence in the results related to the emissions of particulate matter is relatively high. Since desulphurisation and denitrification of power plants are not compulsory in Mexico, the likelihood of the existence of such emission controls is small. Therefore, arguably, the confidence in the results related to the emissions of sulphur dioxide and nitrogen oxides is relatively high.

iii) Background activities: No specific information was available for the background activities such as production and transport of fuels and materials, waste disposal and construction and decommissioning of infrastructure so that generic data were used from the Ecoinvent database. This assumption does not have a major impact on the results for the base year as the majority of the impacts are related to the operation of the power plants rather than the background activities – therefore, the confidence in these results is relatively high.

Overall, it could be argued that the confidence in the environmental impacts (LCA) results for the base year is relatively high, as also confirmed in the section on the validation of the results in Chapter 5 (see section 5.1.4 and Figures 5-8 and 5-9).

iv) Costs: The main uncertainty is related to the costs of fuels in Mexico, especially for oil, as well as the capital costs. The data for these have been sourced from the IEA and EIA, respectively, but they may not reflect the Mexican conditions accurately. However, the levelised costs of the power plant technologies estimated in this study are within the ranges reported in literature (see Table 5-6) which suggests a relatively high confidence in the results.

Scenario analysis

For the scenarios analysis, the most critical assumptions were as follows:

i) electricity demand in 2050;
ii) renewable energy potentials and technology mix;
iii) characteristics of power generation technologies in 2050; and
iv) costs.

The assumption i)-iii) affect the environmental (LCA) impacts and the assumptions for costs affect the economic analysis.

i) Electricity demand: As discussed in Chapter 6, the future electricity demand depends on several parameters such as population and economic growth as well as energy intensity; for this reason, the electricity demand assumed for 2050 is uncertain and could change significantly (increase or decrease). However, the intention in this work was not to predict the future electricity demand but to identify more sustainable future power options for Mexico – the choice of the options would still be the same regardless of the electricity demand. Furthermore, this assumption is consistent across all the scenarios so that at least the relative comparisons are valid, albeit that the absolute environmental impacts for each scenario may be different. Therefore, the confidence in the ranking of the scenarios and technological options with respect to this assumption is relatively high.

ii) Renewable energy potentials: These assumptions (Table 6.6), although based on the best available estimates, are uncertain as it is not possible to verify them currently. Since the energy mix assumed in the scenarios (Table 6-7) also depends on the renewable energy potential, this brings further uncertainty to the analysis. Therefore, the level of certainty related to these assumptions could be characterised as medium.

iii) Characteristics of power plants: The assumptions made for the future power plant technologies (Table 6.8) are uncertain due to a number of factors including technological maturity, costs and energy policies, background activities etc. However, these data have been put together by a consortium of experts (as part of the EU NEEDS project) and are arguably the best data currently available. Furthermore, similar to the other assumptions in the scenario analysis, these assumptions are consistent across all the scenarios so that the confidence in the relative comparisons between the scenarios is high. Therefore, the overall level of certainty with respect to these assumptions could be characterised as medium.

iv) Costs: The future cost data, especially for fuels and capital costs for renewables, are uncertain as they depend on numerous factors (e.g. demand for fuels and discovery of new reserves, technological and market development, energy policies etc.). Different assumptions on these would affect the ranking of the scenarios. However, as for the environmental impacts, the assumptions are consistent between the scenarios so that the relative comparisons are valid. Overall, the confidence in the results could be classed as low to medium.

9.3.2 MCDA

The main assumptions in the MCDA are related to the potential decision-makers' preferences for different sustainability criteria. As the MCDA analysis carried out in this work is hypothetical, with no involvement of decision makers, a sensitivity analysis has been performed to find out how the choices of sustainable options would change with preferences. The results indicate that this is one of the most sensitive parameters in the whole analysis as it is unpredictable due to the subjective nature of the preference analysis. A further uncertainty is due to the limited number of decision criteria considered – for example, only one social indicator has been included (human toxicity potential). Therefore, the overall ranking of the scenarios could also change if a wider range of criteria are included. Nevertheless, the intention of the work was not to provide a definitive answer as to the 'best' electricity mix, but to provide an input into any future decision-making process on a range of options that are more sustainable than the current situation. It is also possible to include further criteria, depending on decision-makers' interest and preferences.

9.3.3 Overall uncertainty and recommendations for improvements

The levels of uncertainty for the different parts of analysis carried out in this work and based on the discussion in the previous sections are summarised in Table 9-3. Overall, it could be argued that the level of confidence in the results is medium to high, with the latter corresponding to the results for the base year as they show a relatively good agreement with literature. Although the medium level of confidence could be attached to the scenario analysis, arguably the best available data have been used so, unless the specific 'future' data became available, it would be difficult to improve the level of certainty at this point in time. A medium level of confidence also applies to the MCDA results due to the highly subjective nature of such analyses.

There could be different ways of minimising the uncertainty in the results. In addition to using more specific data if they became available in the future, sensitivity analyses could be carried out to determine the change in the results with the main parameters (e.g. fuels composition, emission controls, energy mix, type of technologies, capital and fuel costs, renewable energy potential, electricity demand etc.). With reference to the MCDA, further sensitivity analyses could be carried out varying the importance of the criteria significantly as well as considering all the social sustainability criteria discussed in this work (but not included in the MCDA).

Table 9-3 Summary of the levels of confidence for the different parts of analysis carried out in this work

Parameter	**Important for type of analysis**	**Importance for the overall conclusions of the study**	**Level of confidence**
<u>Base year</u>			
i) Fuel composition	Environmental	Medium	Medium-high
ii) Emission control	Environmental	Medium	High
iii) Background activities	Environmental	Low-Medium	High
iv) Costs	Economic	High	High
<u>Scenario analysis</u>			
i) Electricity demand in 2050	Env'l/Economic	Low	Low-Medium
ii) Renewable energy potentials and technology mix	Env'l/Economic	Medium	Medium
iii) Characteristics of power plants	Environmental	High	Medium
iv) Costs	Economic	High	Low-Medium
Preferences for sustainability criteria	MCDA	High	Medium
Overall			**Medium-High**

9.4 Summary

This chapter has considered the overall sustainability of different scenarios using different preferences for the sustainability criteria. The results indicate that the BAU scenario is the least sustainable regardless of the preferences for the criteria or the MCDA method used. This is mainly due to the high annualised costs (contributed largely by the costs of fuel) and high environmental impacts. On the other hand, the Green, A-3 and C-3 scenarios are the most sustainable for all the MCDA methods and preferences for the criteria. However, they have the following sustainability drawbacks which should be borne in mind:

- Green scenario: it is critical to take into consideration its ambitious renewable energy contribution target (86%), which affects its reliability of electricity supply (even if it did not exceed the renewable energy potential in Mexico), requires highest capital costs and is faced with various socio-political barriers for installation and public acceptability;

- A-3 scenario: with the high (15%) contribution from hydropower, the main issues are related to the direct environmental and social impacts of large-scale hydro-installations; this scenario is also the second most expensive option in terms of capital costs;

- C-3 scenario: with the highest contribution from nuclear power (30%), the most critical sustainability aspects for this scenario are related to health and safety, and intergenerational issues (nuclear accidents, potential for nuclear proliferation and terrorism, and long-term waste management).

The following chapter provides further conclusions of the work and proposes areas of further work.

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10.Conclusions and future work

This research has developed an integrated methodology for sustainability assessment of different electricity technologies and scenarios, taking into account environmental, economic and social aspects. The methodology has been applied to Mexican conditions for the assessment of both current and future electricity production. A range of future scenarios has been developed in an attempt to find out the most sustainable options for providing electricity in Mexico. The development of the scenarios has been driven and informed by the national GHG emission reduction target of 50% by 2050 on the 2000 levels, translating to an 85% reduction from the power sector. Additional GHG reduction targets have been also considered: stabilization of GHG emissions on the 2000 levels and 60% reduction of GHG emissions from the power sector.

The developed methodology, described in Chapter 4, involves selection of sustainability indicators for the power sector, scenario development, life cycle assessment, economic and social analysis of the scenarios, and multi-criteria decision analysis (MCDA) to help identify most sustainable scenarios and electricity options.

The objectives of this research have been met in that:

- an integrated methodology has been developed to enable identification of most sustainable electricity options and scenarios for Mexico (Chapter 4);
- a life-cycle model of the current electricity sector in Mexico has been developed (as a base case scenario) and evaluated through life cycle assessment and economic analysis (Chapter 5);
- low carbon power generation technologies have been identified for electricity production in Mexico for the future. These include renewable energies, improved fossil fuels-based power plants with and without CCS, and nuclear power (Chapters 3 and 6);

- future scenarios (BAU, Green, A, B and C) for electricity production in Mexico with an outlook to 2050 (Chapter 6), have been proposed and evaluated through life cycle assessment, and socio-economic analysis (Chapters 7 and 8);
- The most sustainable electricity scenarios for the future have been identified through a multi-criteria assessment from selected sustainability indicators (Chapter 9).

Thus, the main research outcomes of this work are:

- a new integrated sustainability assessment methodology to evaluate different energy scenarios for electricity generation (applied to Mexican conditions; Chapter 4);
- first life cycle assessment (LCA) and economic analysis of current Mexican power sector (Chapter 5; see also Santoyo-Castelazo et al., 2011);
- life cycle GHG projections to the year 2050 using the IEA's BAU scenario (Chapter 7);
- scenario development to reduce GHG emissions from the Mexican power sector by 2050 for different reduction targets (Chapter 6); and
- environmental (Chapter 7) and socio-economic evaluation (Chapter 8) of different scenarios and MCDA to help identify most sustainable electricity options for the future (Chapter 9).

The main conclusions from this work are summarised below. This is followed by policy recommendations and finally by suggestions for future work.

10.1 Conclusions

The conclusions that can be drawn from this work are related to the environmental and socio-economic implications of the scenario analysis (base-case and future options), as well as from the MCDA and sensitivity analysis of future scenarios for electricity production in Mexico.

10.1.1 Base case scenario

The base case scenario refers to the current situation of electricity production in Mexico in 2006. The main conclusions from the environmental and economic analysis are as follows (see Chapter 5 for details).

1. The LCA results show that 129 million tonnes of CO_2 eq. are generated annually from 225 TWh of electricity generated in Mexico. CO_2 emissions account for about 94% of the total CO_2 eq. emissions; CH_4 contribute further 4.2% and N_2O 1.2%.

2. As expected, the main source of the greenhouse gas emissions is the operation (combustion) of the fossil-fuelled power plants, contributing in total 87% to the GWP. The majority of other environmental impacts are caused by the combustion of fossil fuels in the power plants, with heavy fuel oil contributing the most (59-97%) to the impacts from electricity generation.

3. Total capital costs of the current electricity sector of Mexico are estimated at US$ 82.6 billion, with hydro power, heavy fuel oil and gas power plants representing the majority of the total investment costs (30%, 28% and 22%, respectively).

4. Total annualised costs are equal to US$ 22.4 billion/yr. Fuel annual costs contribute 54% (US$ 12.1 billion) to the total mainly due to the operation of gas and heavy fuel oil power plants.

5. Reducing the share of heavy fuel oil in the electricity mix would not only reduce the environmental impacts but also lessen the economic costs of electricity production in Mexico. While its contribution has gradually reduced over time with the introduction of the combined-cycle power plants, there is still a significant scope for improvement.

10.1.2 Future scenarios

Eleven future scenarios have been developed for the year 2050 and the results of the findings are summarised below (see Chapters 7-8).

6. The LCA results for the BAU scenario based on the 'high electricity production' (814,000 GWh/yr), indicate that Mexico's life cycle GWP would increase by 300% on the 2006 levels. Other related environmental impacts would also increase (Chapter 7). For this reason, it is important to consider other alternative scenarios besides the IEA projection, as well as reducing the electricity demand (and thus the electricity production) for the future.

Based on the 'low electricity production' assumption (598,000 GWh/yr), the following conclusions can be drawn:

7. The Green, A-3 and C-3 scenarios are arguably the most sustainable and the BAU scenario the least sustainable options with respect to most of the environmental impacts considered in this analysis.

8. The BAU is the most economical option requiring US$ 92.6 billion of capital investment, compared to the GREEN scenario which requires by far the highest investment of US$ 321.4 billion (mainly due to high contribution from renewable energies and their related high overnight capital costs). The capital investment costs for alternative scenarios range between US$ 148.2 and 270.6 billion; with the best scenarios being B-1, followed by B-2 and C-1.

9. In contrast, considering the total annualised costs, the BAU is the most expensive option (US$ 87.9 billion/yr), with the best options being scenarios C-3 and A-3 (US$ 52.8 and 53.2 billion/yr), followed by the Green scenario (US$ 54.6 billion/yr). For scenarios based on fossil fuels (BAU and scenarios B), the main contributor to the total annualised costs are projected high fossil fuels costs in 2050.

10. With respect to social issues, the BAU scenario has the highest risks related to security and diversity of supply, health and safety and climate change. Therefore, it is considered the least preferred option.

11. The Green scenario shows a good performance in terms of fuel import dependency and climate change issues, but with significant social barriers related to public acceptability, availability of energy resource and reliability of electricity supply due to the highest contribution from renewable energies (86%).

12. Scenarios B, although with similar characteristics as the BAU scenario, have considerably lower GWP (-86% to -46%) because of their high assumed use of CCS (27-61%).

13. Scenarios A present a good balance between social aspects such as security and diversity of supply, health and safety and their low contribution to GWP (particularly for scenario A-3). The main social barriers for these scenarios may be related to public acceptability due to their high contribution from renewable energies to their total electricity mix and their related sustainability implications (mainly for wind, solar and hydro power).

14. Health and safety, and intergenerational issues are the most significant barriers for scenarios C due to the high contribution from nuclear power (especially in scenario C-3).

15. Therefore, from the social perspective, the most sustainable options are scenarios with the highest contribution from renewable energies such as A-3 and Green scenarios.

10.1.3 MCDA of future scenarios

Different scenarios and technologies have different advantages and disadvantages so that the choice among them is not easy. To aid identification of the most sustainable options, MCDA has been used and the following conclusions apply (Chapter 9):

16. The BAU scenario (with the highest contribution from fossil fuels) is the least sustainable option to meet Mexico's electricity supply in the future. Despite the fact this scenario has the lowest capital costs, its poor environmental performance and the highest annualised costs make it the least preferred option.

17. Scenarios B, also heavily based on fossil fuels, overall perform better that the BAU scenario, mainly because of the higher contribution of renewable energies and the use of CCS. B-3 (with an 85% GHG reduction target by 2050) ranks as the most suitable B option.

18. Increasing the contribution from renewable energies and nuclear power leads to a better sustainability performance which is the case of scenarios A-2, A-1, C-2 and C-1. These options can be considered if taking into account the stabilization and 60% reduction of GHG emissions by 2050 at more attractive operating costs (compared to B and BAU).

19. Overall, the Green, A-3 and C-3 scenarios are the most sustainable options for the future electricity supply in Mexico.

20. Specifically, if an equal weighting of sustainability criteria is considered, the Green scenario seems to be the most attractive option. The same applies when assuming that human toxicity potential (HTP) is the most important sustainability criterion.

21. However, when the focus is on climate change mitigation or on total annualised costs, the more sustainable options are scenarios C-3 and A-3. This is also true

when assuming that GWP, HTP, and total annualised costs are the most important criteria.

10.2 Policy recommendations

On the basis of this research, a number of policy recommendations can be made aimed at promoting sustainable development of the electricity sector in Mexico.

The high fossil fuels dependence for electricity production in Mexico has brought significant environmental and economic concerns for the country. As shown from the LCA results for the current situation in Mexico, the GHG emissions together with SO_2, NO_x, NMVOC, PM and heavy metals are the environmental burdens of major concern which in turn contribute to a number of environmental impacts (i.e. GWP, AP, POCP, EP, FAET, MAETP and HTP). Heavy fuel oil, gas and coal power plants contribute together to 87% of GWP (Chapter 5). Heavy fuel oil also contributes to most (59-97%) of the life cycle environmental impacts.

While the Mexican Government has made an effort on improving the environmental implications arising from heavy fuel oil-based power, by introducing new gas combined cycle power plants, yet this is not a long-term solution for the mitigation of climate change. As shown from the LCA results of Chapter 5, gas power plants have considerable GWP emission factors per unit of electricity produced (468 g CO_2 eq/kWh) than for example low-carbon technologies such as hydro, wind and nuclear power (12, 18 and 12 g CO_2 eq/kWh). Furthermore, the BAU projection to year 2050 (mainly based on gas and coal power representing 55% and 30% of total electricity mix) shows that GWP will increase by almost 300% from today emissions (considering an electricity production of 814, 000 GWh in year 2050; Chapter 7). Therefore, if the main energy driver is mitigation of climate change, electricity policies in the country should be oriented towards increasing and diversifying the contribution from low-carbon technologies (mainly renewable energies and nuclear power) and improving energy efficiency.

Moreover, by increasing the contribution of renewable energies, the total annualised operating costs from the Mexican electricity sector will be reduced considerably (Chapter 5), due to low or no fuel costs. Consequently, the high uncertainty of fossil fuel costs for electricity production in Mexico would be minimised.

Because of the great potential of renewable energies in Mexico, main sustainability drivers and barriers must be taken into consideration when assessing the implementation of these energy sources (Chapters 3 and 8). Hydro and geothermal power are already well established energy sources in Mexico, yet with a significant potential for development and proven to be high reliable sources for electricity supply (for both the base and peak loads). In addition, hydro power (together with wind power) is the option with the lowest GWP among all renewable energies, and it also contributes to agricultural productivity through irrigation, and local economic development by means of work opportunities to local residents. However, the main barrier for large hydro power plants is public acceptability mainly due to environmental and social impacts related to dam constructions (e.g. ecosystem impacts, relocation of communities).

From the emerging technologies, wind power presents the fastest market and technological development than for example solar and ocean based power. The main barrier for implementation of large-scale solar projects for electricity production in Mexico is their high capital costs. On the other hand, ocean energy is at an early stage of development, still requiring significant work for the estimation of its energy potential and financial support for R&D projects. While Mexico has large and diverse biomass energy resources (forestry, energy crops and wastes), the implementation of these resources has been limited mostly to the use of sugar cane bagasse for electricity production, due to the lack of appropriate supporting policies and sufficient financial incentives. Therefore, main efforts from the Mexican Government should aim to strengthen the current renewable energy policies within the country.

Another critical aspect from the scenario analysis of this work is the importance of reducing future electricity demand (and thus the electricity production). Instead of the

2.9% average annual growth rate (AAGR) projected by the BAU scenario from today to 2050, the electricity production from the Mexican power sector should adopt an AAGR of just 2.2% for the same period. This recommendation would limit the electricity production to 598,000 GWh by 2050 or 166% increase on the 2006 levels.

Additionally, the decarbonisation of the Mexican power sector for the future should implement a more diverse electricity supply combining large-scale use of renewable energies, nuclear power and to a lesser extent the use of CCS for future fossil fuel-based power plants.

In the event of a fossil fuel based policy, scenario B-3 represents the most suitable option allowing for an 85% GHG reduction target by 2050. However, other environmental impacts such as ADP, HTP, FAETP increase, mainly due to the use of CCS; the annualised costs also go up due to the expected high fossil fuel costs .

On the other hand, by introducing more renewable energies and nuclear power into the electricity mix, as in scenarios Green, A-3 and C-3, most of the life cycle environmental impacts are reduced considerably compared to the BAU scenario. Although renewable energy based scenarios require high capital costs, the total annualised costs will even out over time (as evidenced with scenarios A-3, C-3 and Green) due to lower fuel costs involved.

While the current sustainability assessment of electricity options for Mexico proposes the scenarios Green, A-3 and C-3 as the most sustainable options for 2050, the selection among these options will depend highly on decision makers' preferences. If the focus is on mitigation of climate change impacts, scenarios A-3 and C-3 are the most sustainable options due to the high contribution from renewable energies (mainly hydro, wind and solar) and nuclear power, respectively. Scenarios A-3 and C-3 are also favoured when considering GWP, HTP, and total annualised costs as most important sustainability criteria.

Furthermore, the following policy recommendations for the Mexican Government should be considered for both the current situation and future scenarios for the Mexican power sector:

- the Mexican Government should adopt life cycle assessment as a tool for evaluation of environmental sustainability;

- the life cycle emissions inventory from electricity generation in Mexico should be regularly updated (e.g. on a two-year or five-year basis) to keep track on emission reduction targets;

- public access to environmental and economic data related to the Mexican electricity sector should be improved;

- more stringent emission standards should be introduced and implemented to regulate the operation of fossil fuel based power plants (mainly oil and coal).

- an economic feasibility assessment of emission control technologies (e.g. FGD, SCR) for SO_2 and NO_x emissions should be carried out and mechanisms introduced to stimulate their implementation;

- techno-economical potential for all renewable energies available in Mexico (especially for ocean energy) should be assessed for the sustainable implementation of these energy sources for power generation;

- the Government should also support the development and training of personnel for the large-scale adoption of renewable energy technologies;

- a feasibility assessment should be carried out regarding the implementation of CCS (e.g. infrastructure requirements for carbon transport, and the potential for carbon storage in Mexico);

- a potential for the expansion of nuclear power should be assessed considering the social aspects outlined in the current work such as public acceptability, health and safety and intergenerational issues;

- Specific pathways for mitigation of climate change (e.g. based on scenarios A-3 and C-3) should be considered by the Mexican Government;

- suitable energy policies and financial support mechanisms for the promotion of low-carbon power generation technologies in Mexico should be considered and introduced, as existing national energy policy lacks of an explicit statement about any incentive mechanisms to promote renewable energies;

- besides the existing international incentive mechanisms, such as the Kyoto Protocol (e.g., Clean Development Mechanism, and Emissions Trading), the Government should strengthen the collaboration between the public and private sectors to promote investment and implementation of low-carbon technologies for electricity generation for the future.

10.3 Recommendations for future work

The following are suggestions for future work:

1. Integration of a carbon price to the levelised costs of electricity generation, to estimate the GHG externalities from fossil fuel based power plants in Mexico; this may support low-carbon energy technologies, such as renewable energies to become more economically attractive for their investment.

2. Besides GHG emissions, external costs from power generation should consider other impacts to the environment and human health, for example from burdens such as SO_2, NO_x, and PM emissions.

3. Estimation of the total levelised costs of electricity generation from power plants in Mexico, including both internal costs (estimated in this work comprising capital, O&M, and fuel costs), and external costs as a measure of sustainability and energy planning for the Mexican power sector.

4. Evaluation of additional sustainability indicators besides the ones considered in this work; for example, related to water and land use from operation of power plants, human health impacts (i.e. worker fatalities, non-fatal illness due to normal operation), fatalities due to large accidents, employment (direct and indirect), and local impacts from electricity production (i.e. involvement in community projects).

5. Stakeholder survey to identify preferences for different sustainability criteria and to compare these with the results presented in the current work.

6. To assess the sustainability criteria and future scenarios proposed by the current work using different MCDA methods (e.g., pair-wise comparison, AHP or compromise programming), and to compare the ranking results with the MCDA approach used by the current research work by means of sensitivity analysis.

10.4 Concluding remarks

The integrated methodology for the sustainability assessment of electricity options for Mexico presented in this work has been successfully applied to the Mexican conditions for both the current situation and future scenarios. The most sustainable energy options for electricity production in 2050 are the Green, A-3 and C-3 scenarios, all dominated by renewable technologies.

It is hoped that both the proposed methodology and the research outcomes from this dissertation can be used as a support framework for decision makers in Mexico to plan the country's electricity supply for the future, considering the security and diversity of energy supply, climate change mitigation targets, protection to environment and human health as the key energy drivers for sustainable development.

11.Appendices

The appendices 1 to 5 are included on the CD attached.