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Life cycle assessment of electricity generation in Mexico

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ABSTRACT

This paper presents for the first time a Life Cycle Assessment (LCA) study of electricity generation in Mexico. The electricity mix in Mexico is dominated by fossil fuels, which contribute around 79% to the total primary energy; renewable energies contribute 16.5% (hydropower 13.5%, geothermal 3% and wind 0.02%) and the remaining 4.8% is from nuclear power. The LCA results show that 225 TWh of electricity generate about 129 million tonnes of CO_2 eq. per year, of which the majority (87%) is due to the combustion of fossil fuels. The renewables and nuclear contribute only 1.1% to the total CO_2 eq. Most of the other LCA impacts are also attributed to the fossil fuel options. The results have been compared with values reported for other countries with similar electricity mix, including Italy, Portugal and the UK, showing good agreement.

1. Introduction

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. However, the conversion and consumption of energy is often accompanied with environmental, social and economic concerns. Some of these include climate change, increasing energy costs and security of energy supply. Similar to other countries, Mexico is also concerned about its energy supply, particularly since it is mainly dependent on fossil fuels [1]. Moreover, the demographic explosion and economic growth have resulted in an ever increasing demand for electricity as well as an increase in energy use in the transport, industry and domestic sectors [2]. Electricity generation is one of the most polluting sources in the country, affecting the ecosystems and human health [3] and the reason for this is that fossil fuels are the primary source of electricity in Mexico. In 2006, the base year considered in this work, fossil fuels contributed 79% of the total generation. Other sources include hydro (13.5%), nuclear (4.8%), geothermal (3%) and wind power (0.02%) [1]. The electricity mix by fuel type is shown in Fig. 1.

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 7569 MW in the private sector [4]. The public sector integrates the national companies and the Independent Energy Producers. The national companies are Federal Electricity Commission (CFE, Comisión Federal de Electricidad) and Light & Power of the Centre (LFC, Luz y Fuerza del Centro). CFE owns 67% of the total SEN-installed capacity. 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 (along with LFC). The two national companies currently supply electricity to 95% of the nation [5].

Table 1 lists the different types of technologies deployed in the public electricity sector in Mexico. Since this sector contributes the majority of the generated electricity in Mexico, and due to the lack of information on the electricity provided by the private sector, the analysis in this paper focuses on the electricity from the public sector.

Fig. 2 shows how the electricity mix in Mexico changed over time, from 1996 to 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

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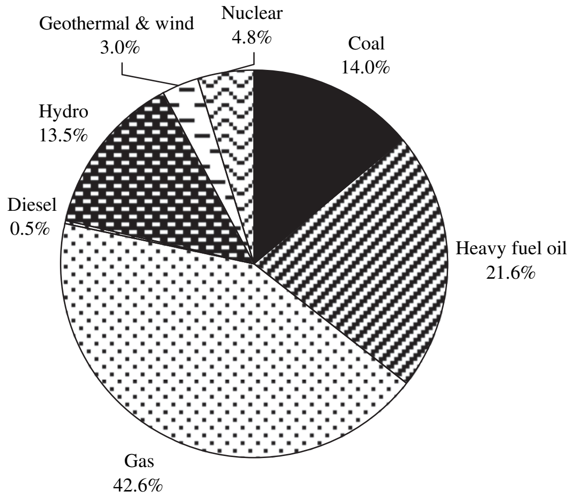

Fig. 1. Contribution of different fuels to the electricity mix in Mexico [1].

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 [4].

Therefore, this paper uses year 2006 as a base year to estimate the life cycle environmental impacts of electricity generation in Mexico. As far as the authors are aware, this is the first study of its kind for the Mexican electricity sector.

Table 1
Energy technologies used for electricity generation in Mexico by the public sector in 2006 [4].

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 [4].
[b] Approx. 94% of total OGST power generation is from heavy fuel oil and the remainder from gas.
[c] SENER [4] 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 h 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.

2. Methodology

The LCA methodology used in this study follows the ISO 14040 and 14044 guidelines [6,7]. The data sources and the approach to estimating the environmental impacts are outlined in Fig. 3 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 [8].

2.1. *Goal and scope of the study*

The goal of this study has been to estimate the life cycle environmental impacts of electricity generation from the public sector in Mexico. The functional unit is defined as the total annual amount of electricity generated by this sector, in this case 225 079 GWh generated in 2006 [1]. The impacts per 1 kWh have also been calculated, to enable comparisons with the impacts from other countries with a similar electricity mix, including Italy, Portugal and the UK.

The system boundaries are from 'cradle to grave', comprising the following life cycle stages (see Fig. 4): 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.

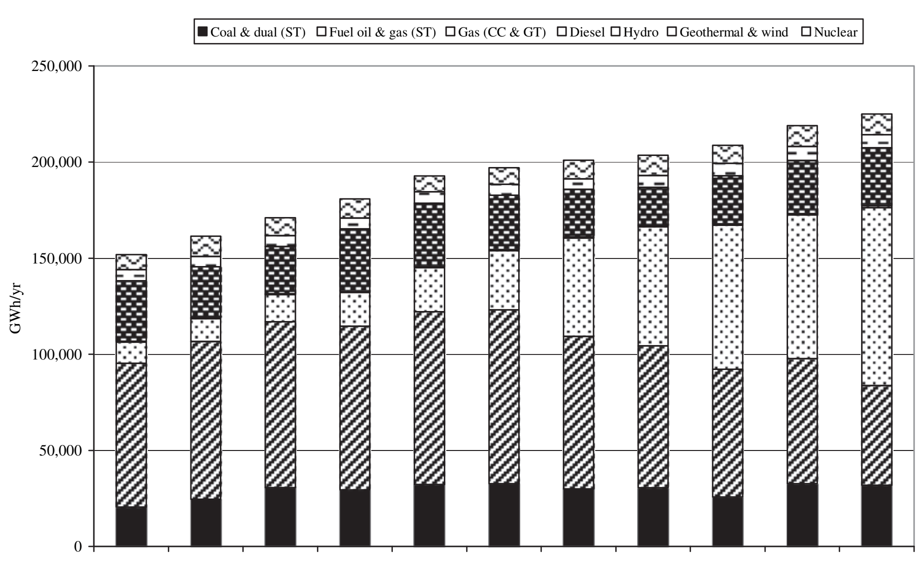

Fig. 2. Electricity generated by the Mexican public sector (1996–2006) [9].

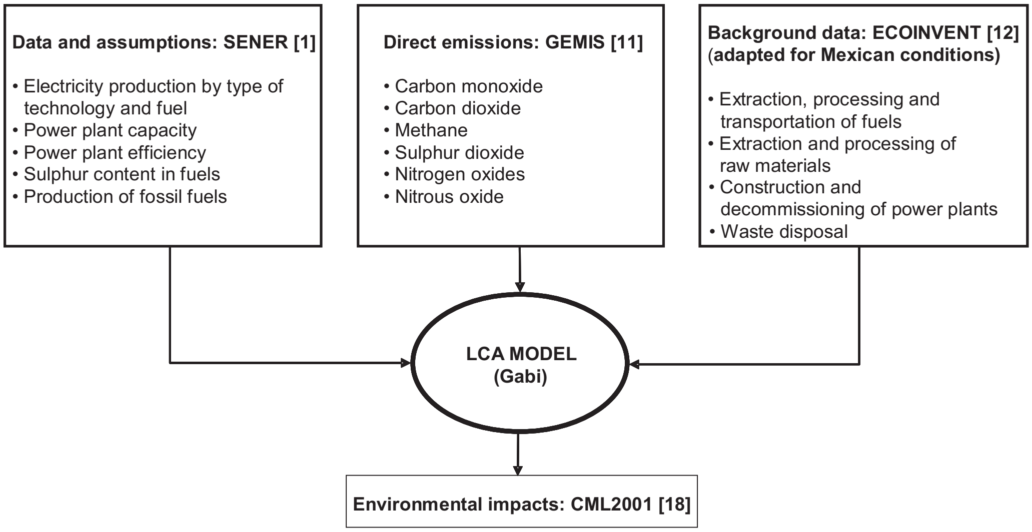

Fig. 3. The methodology and data sources used to estimate the environmental impacts from the Mexican electricity sector.

2.2. Data sources

The data for this study are based on the 2006 National Energy Balance (NEB), reported by SENER [1]. 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 1) as well as fuel composition in Mexico (Appendix A). The GEMIS database [11] has been used for these purposes (see Fig. 3).

The background data have been sourced from the Ecoinvent database [12]. These data have then been adapted to reflect Mexican conditions, e.g. using the appropriate electricity mix, fuel composition, waste disposal methods, *etc*.

2.3. Assumptions

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

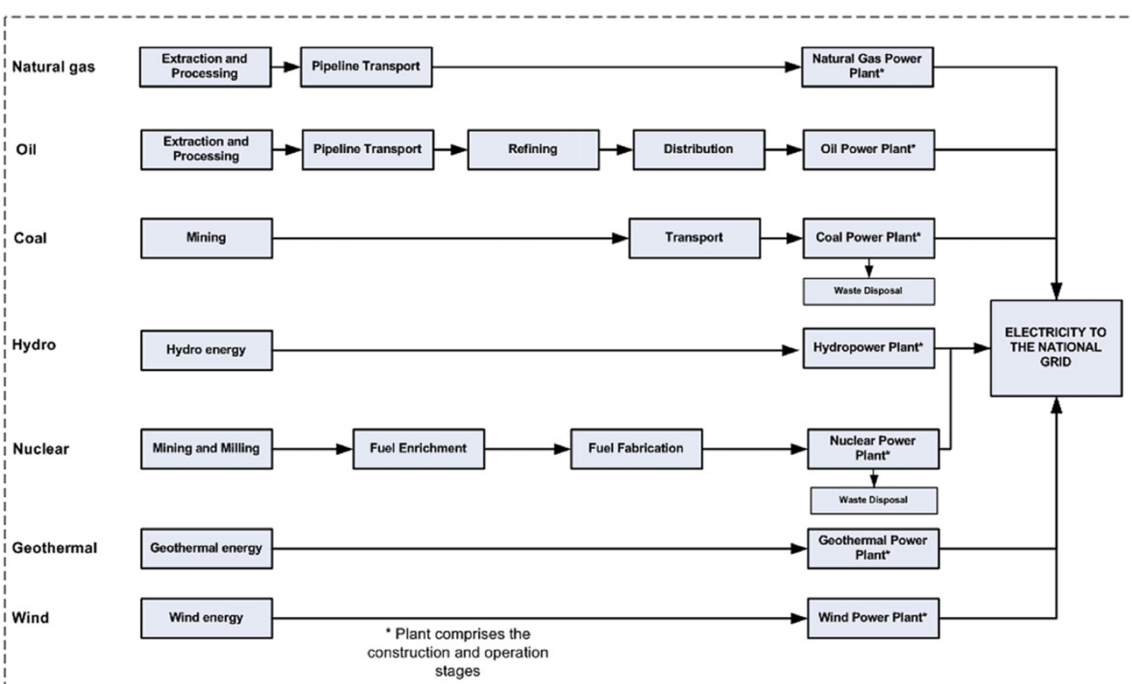

Fig. 4. The life cycle of electricity generation in Mexico (modified from Gujba et al., 2010 [10]).

- all heavy fuel oil is produced domestically, of which 20% is produced onshore and 80% offshore [13,14];
- 92% of natural gas is produced domestically and the remaining 8% is imported from the USA [15,16]; of this, 67% of gas is produced onshore and 33% offshore [13];
- 56% of coal is produced domestically and the remaining 44% is imported [4]; and
- gas venting (5%) and flaring (0.3%) during oil and gas production within the country have been taken into consideration [15].

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% [17];
- 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 [1]; 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 [17].

3. LCA results and discussion

3.1. Environmental burdens

Emissions to air from the combustion of fossil fuels contribute most to the total environmental impacts from electricity generation in Mexico. Table 2 and Fig. 5 show the life cycle emissions to air, expressed per kWh and GWh per year, respectively. As can be seen from Table 2, the life cycle emissions of CO_2, SO_2, NOx, 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 NOx emissions (8.05 g/kWh). The emissions of N_2O are similar across the fossil fuel options. The life cycle emissions from the renewables and nuclear power are mainly from the construction of infrastructure [12]; the exception to this is geothermal power, where the majority of CO_2 and SO_2 are from direct emissions [11].

Based on these results, the total life cycle emissions of CO_2 in 2006 were 121.3 Mt (Fig. 5), 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. Renewables and nuclear power contribute collectively less than 1% of the total emissions.

Table 2
Direct and life cycle emissions from different electricity-generating options in Mexico [11,12].

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	4.30	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	4.30	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	2.60
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	2.70	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	0.010	0.06

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

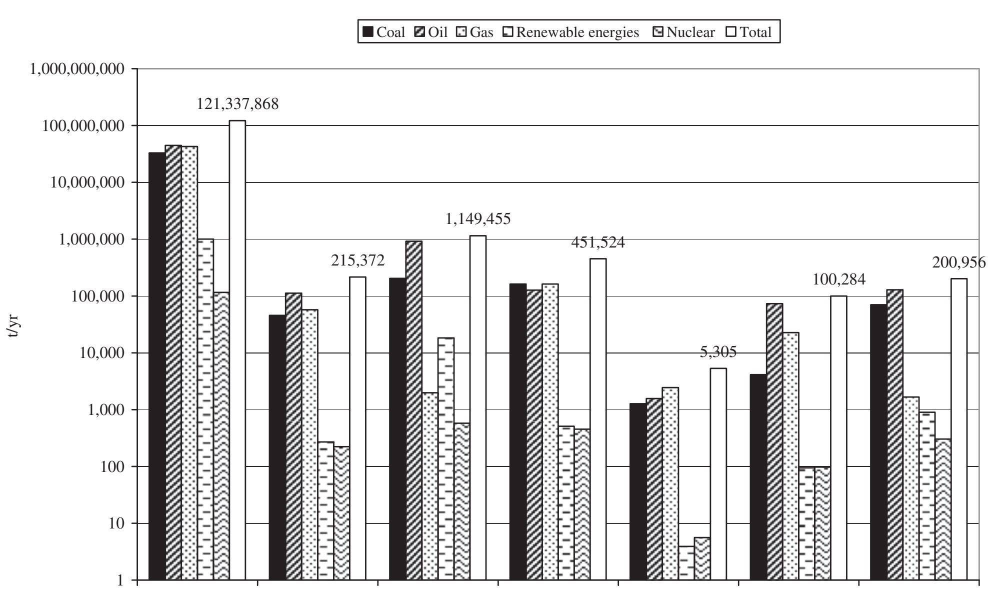

Fig. 5. Selective life cycle environmental burdens from electricity generation in Mexico in 2006 [Oil comprises heavy fuel oil and diesel].

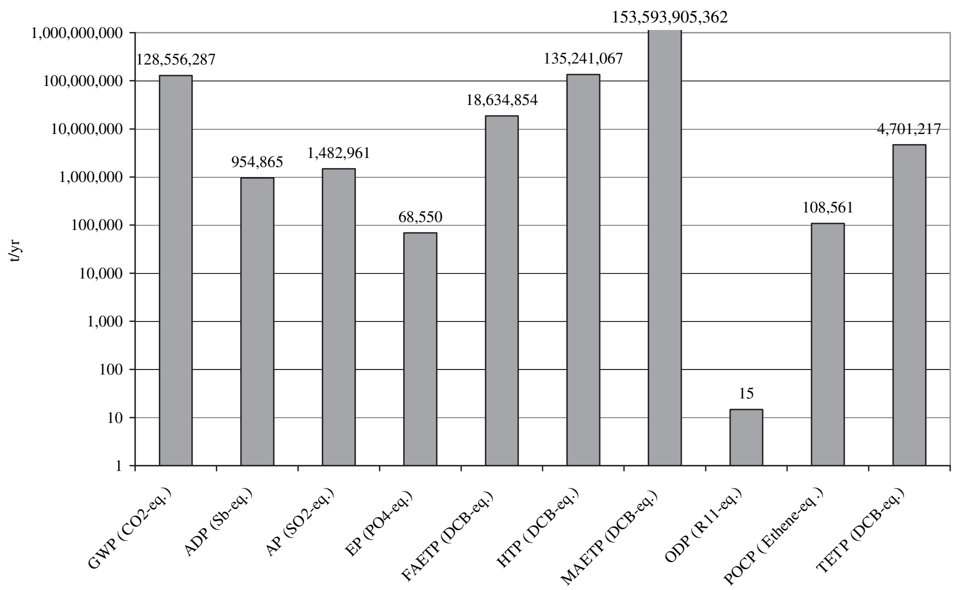

Fig. 6. Total environmental impacts per year (2006). [GWP: Global Warming Potential; ADP: Abiotic Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; FAETP: Fresh water Aquatic Ecotoxicity Potential; HTP: Human Toxicity Potential; MAETP: Marine Aquatic Ecotoxicity Potential; ODP: Ozone Depletion Potential; POCP: Photochemical Ozone Creation Potential; TETP: Terrestrial Ecotoxicity Potential].

3.2. Impact assessment and interpretation

The environmental impacts have been estimated using the CML 2001 method [18]. These results are presented in Figs. 6 and 7, showing the total annual and impacts per kWh, respectively. Fig. 8 shows the contributions to the impacts of different electricity-generating options in the integrated electricity system. 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 B.

3.2.1. 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) [19]. 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 Fig. 9). 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.

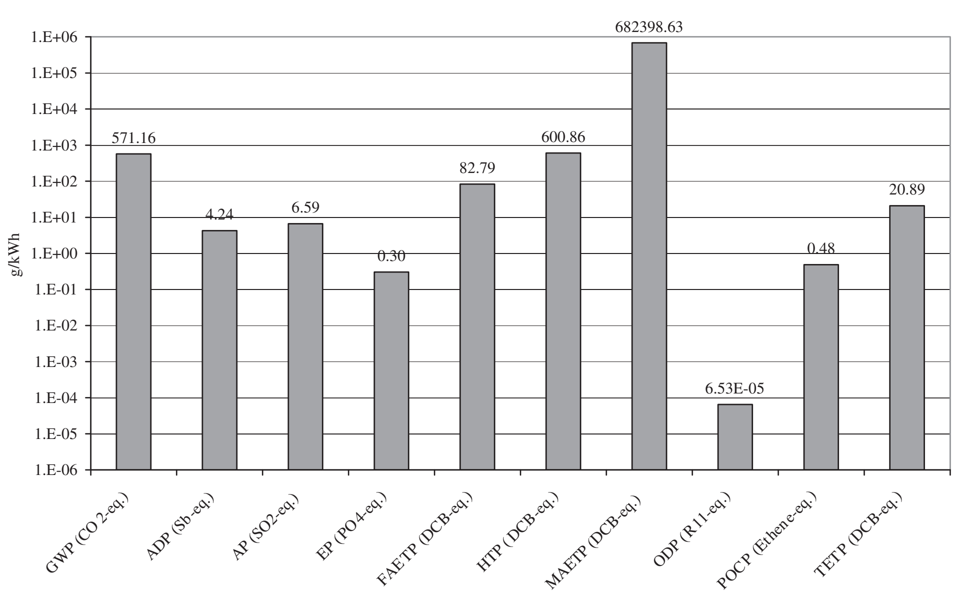

Fig. 7. Environmental impacts per kWh.

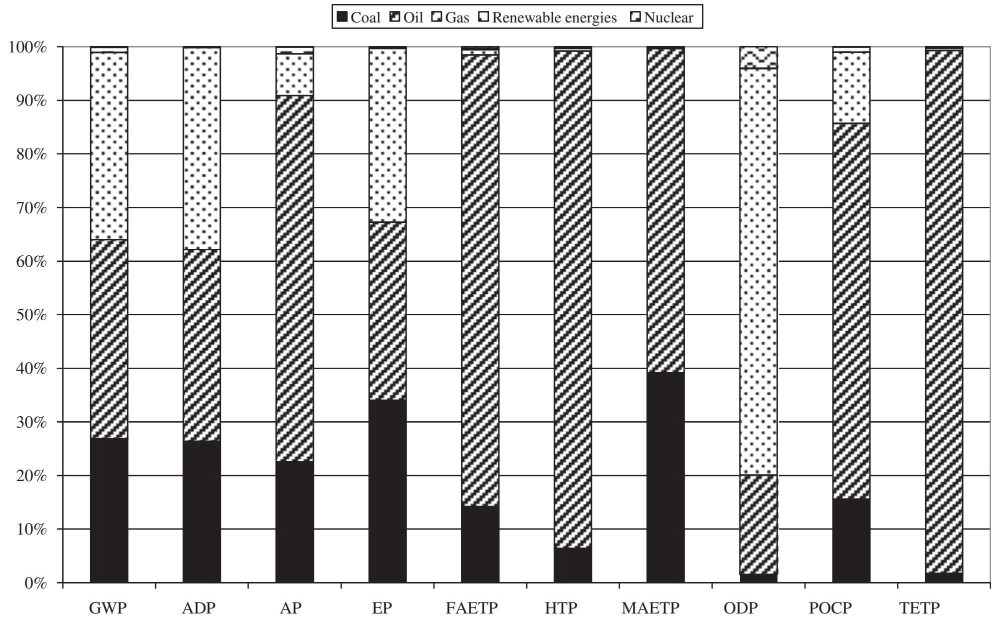

Fig. 8. Contribution of different electricity technologies to the total impacts.

3.2.2. Other impacts

Like GWP, the operation of fossil-fuel based power plants is also responsible for the majority of other environmental impacts (Fig. 8). This is discussed briefly below.

3.2.2.1. 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.

3.2.2.2. 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 B). 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. NOx 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.

3.2.2.3. 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^{2-} eq./yr, respectively. NO_X emissions from these power plants account for 86% of EP. Waterborne emissions to fresh

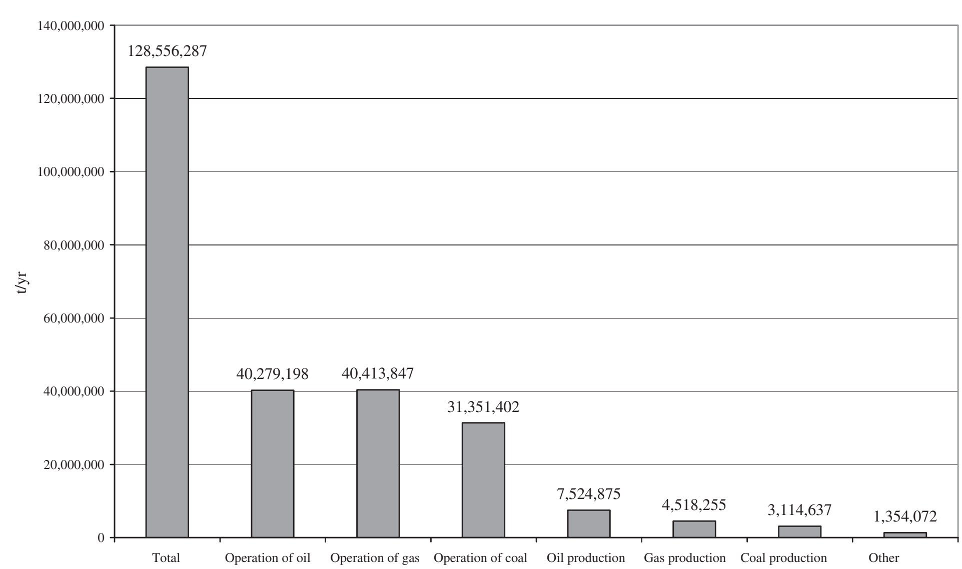

Fig. 9. Contribution to GWP100 of different electricity options in Mexico. [Gas, oil and coal production comprise the extraction, processing, transport, storage and distribution of fuels. Oil comprises heavy fuel oil and diesel. Other represents hydro, geothermal, wind and nuclear power.].

and sea water contribute further 8%, mainly due to operation of heavy fuel oil power plants and heavy fuel oil production.

3.2.2.4. 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.

3.2.2.5. 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 NOx (mainly from gas and coal power plants) account for 2.9% and 0.4% of the total HTP, respectively.

3.2.2.6. 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.

3.2.2.7. 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).

3.2.2.8. 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 NOx emissions which account for 51%, 33%, and 12%, respectively. Most of the SO_2 emissions are due to the combustion of heavy fuel oil; the NMVOC emissions are mainly from oil production while NOx emissions are mainly from the operation of gas and coal power plants.

3.2.2.9. 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.

4. Validation of 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.

4.1. Comparison with other countries

Three countries with a similar electricity mix to Mexico have been considered here: Italy, Portugal and the UK (see Appendix C 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 Fig. 10.

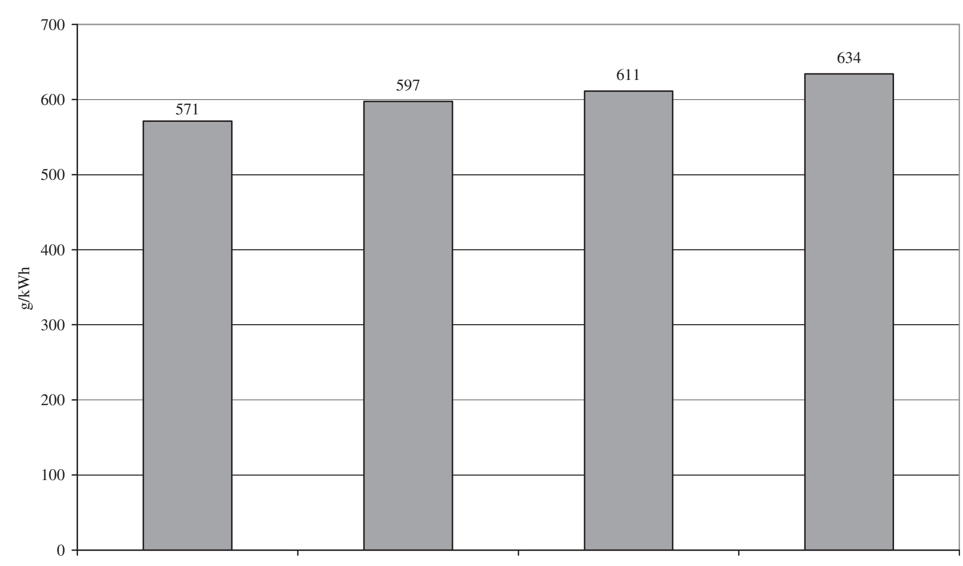

Fig. 10. Comparison of the GWP100 for the Mexican electricity mix with other countries.

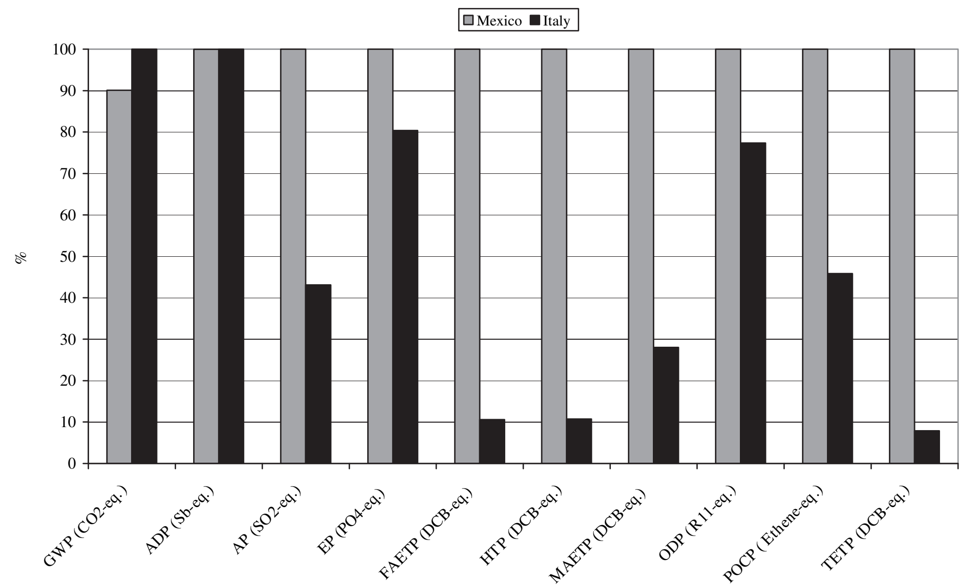

Fig. 11. Comparison of environmental impacts for Mexico and Italy.

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 [20]. 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% [1] against 37.5% reported for Italy in Ecoinvent [20].

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 C).

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 Fig. 11.

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 C) as well the lack of emission control technologies for coal power plants. According to Ecoinvent [20], 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

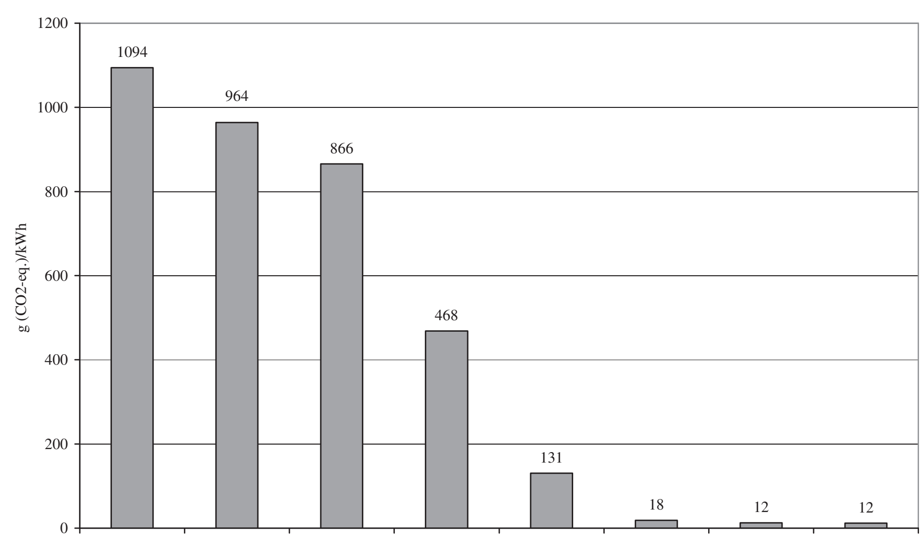

Fig. 12. GWP for power plants operated in Mexico [These results have been obtained using the data in Table 2 and applying the CML method [18] for estimation of GWP.].

Table 3
Emissions of CO_2 and GWP100 for the Mexican electricity mix compared with literature data [21–24].

Plant type	Study	Power plant specifications			Emissions			
		Carbon content (%)	Load factor (%)	Efficiency (%)	CO_2 emissions (g CO_2/kWh) Direct	Life cycle	GWP100 (g CO_2 eq./kWh) Direct	Life cycle
Coal	Current study	67[a]; 67.5[b]	79	35.8	981[d]	1046[d]	992	1094
	Odeh and Cockerill [20]	60	80	35	882	990	N/A[c]	N/A[c]
	Weisser [21]	N/A[c]	N/A[c]	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 [22]	N/A[c]	70	36.2	704	742	N/A[c]	N/A[c]
	Kannan et al. [23]	N/A[c]	80	36	N/A[c]	N/A[c]	N/A[c]	889
	Weisser [21]	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. [23]	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.

removal. Only the ESPs have been considered in the case of Mexico, to reflect the current situation in the country.

4.2. 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. 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.

4.2.1. GWP for coal-based technologies

As shown in Fig. 12, 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 CO_2 eq./kWh). The comparison of these results with some other reported values is given in Table 3.

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 [22]. 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 [21]. 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 3, a 60% carbon content was considered by Odeh and Cockerill [21], 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 [11].

4.2.2. 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 3). 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 [23] 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 3).

A similar but smaller discrepancy is noticed with the results by Kannan et al. [24] 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 3).

4.2.3. GWP for gas-based technologies

As shown in Table 3, several authors report 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. [24] 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 3), 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 [22], 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 CO_2 eq./kWh for the life cycle impacts, also compare well with this range.

5. Conclusions

The results of this LCA study show that around 129 million tonnes of CO_2 eq. are generated annually from 225 TWh of electricity generated in Mexico by the public sector (using 2006 as a base year). 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 87% to GWP. 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%).

Therefore, reducing the share of heavy fuel oil in the electricity mix would help to reduce the environmental impacts from this sector 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. The country's current plan is to reduce its greenhouse gas emissions by 50% 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 a subject of ongoing research by the authors, the results of which will be reported in a follow-up paper.

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Appendix A. Chemical composition of fuels used in Mexico

Table A.1
Chemical composition of coal, heavy fuel oil and diesel[a] [11].

Elements	Weight share (%)			
	Coal (domestic)	Coal (import)	Heavy fuel oil	Diesel
C	66.99	67.49	84.60	86
H	3	3	10.93	13.5
S	1	0.5	3.6	0.5
O	8	8	0.21	0
N	1	1	0.2	0
Cl	0.1	0.1	0	0
F	0.01	0.01	0	0
Ash	12	12	0.07	0
Water	7.9	7.9	0.4	0
Total	100	100	100	100
LHV (MJ/kg)	25.23	25.35	40.10	42.64

[a] Due to limited data availability, only the sulphur (S) content of Mexican fuels was considered in the LCA model. The rest of the chemical composition was sourced from generic fuels from Gemis [11].

Table A.2
Chemical composition of natural gas [11].

Composition	Vol. (%)
CH_4	92.07
C_2H_6	0.5
C_2H_4	0.5
C_3H_8	0.04
C_4H_{10n}	0.01
C_4H_{10i}	0.01
CO_2	0.02
N_2	6.1
H_2S	0.0005
H_2	0.75
Total	100.00
LHV (MJ/Nm^3)	33.8

Appendix B. Environmental impacts from electricity generation in Mexico

Table B.1
Environmental impacts from electricity generation in Mexico.

Life cycle stage	GWP (t CO_2 eq./yr)	Contribution to the total (%)	ADP (t Sb eq./yr)	Contribution to the total (%)	AP (t SO2 eq./yr)	Contribution to the total (%)	EP (t PO4 eq./yr)	Contribution to the total (%)
Coal mining	1.49E + 06	1.16	2.40E + 05	25.14	1.29E + 04	0.87	2.01E + 03	2.93
Transport & storage of coal	1.62E + 06	1.26	1.09E + 04	1.14	2.62E + 04	1.77	2.63E + 03	3.83
Operation of coal power plant	3.14E + 07	24.39	9.18E + 02	0.1	2.95E + 05	19.91	1.87E + 04	27.24
Diesel production	6.87E + 04	0.05	7.04E + 02	0.07	5.01E + 02	0.03	6.38E + 01	0.09
Storage & distribution of diesel	7.71E + 03	0.01	5.31E + 01	0.01	7.24E + 01	0.005	1.31E + 01	0.02
Operation of diesel power plant	8.42E + 05	0.65	3.31E + 01	0.003	9.00E + 03	0.61	1.19E + 03	1.74
Extraction & processing of gas	2.43E + 06	1.89	3.45E + 05	36.16	4.56E + 03	0.31	1.13E + 03	1.65
Long distance transport of gas	1.32E + 06	1.03	9.45E + 03	0.99	2.83E + 03	0.19	5.41E + 02	0.79
High pressure distribution of gas	7.66E + 05	0.6	4.20E + 03	0.44	1.67E + 03	0.11	2.50E + 02	0.36
Operation of gas power plant	4.04E + 07	31.44	7.28E + 02	0.08	1.06E + 05	7.17	2.03E + 04	29.62
Extraction & processing of oil	3.53E + 06	2.75	3.02E + 05	31.6	3.51E + 03	0.24	1.13E + 03	1.65
Long distance transport of oil	1.09E + 06	0.85	7.49E + 03	0.78	6.05E + 03	0.41	8.45E + 02	1.23
Heavy fuel oil production	2.47E + 06	1.92	2.79E + 04	2.93	1.89E + 04	1.27	2.52E + 03	3.68
Storage & distribution of heavy fuel oil	3.51E + 05	0.27	2.43E + 03	0.25	3.34E + 03	0.23	6.00E + 02	0.87
Operation of heavy fuel oil power plant	3.94E + 07	30.68	1.18E + 03	0.12	9.72E + 05	65.57	1.64E + 04	23.99
Wind power	8.18E + 02	0.001	5.67E + 00	0.001	3.92E + 00	0.0003	5.95E-01	0.001
Geothermal power	8.73E + 05	0.68	288.9397612	0.03	1.82E + 04	1.23	32.00388014	0.05
Hydropower	3.49E + 05	0.27	5.84E + 02	0.06	4.67E + 02	0.03	7.57E + 01	0.11
Nuclear power	1.31E + 05	0.1	8.52E + 02	0.09	9.32E + 02	0.06	1.01E + 02	0.15
Total	1.29E + 08	100	9.55E + 05	100	1.48E + 06	100	6.86E + 04	100

(*continued on next page*)

Table B.1 (*continued*)

Life cycle stage	FAETP (t DCB eq./yr)	Contribution to the total (%)	HTP (t DCB eq./yr)	Contribution to the total (%)	MAETP (t DCB eq./yr)	Contribution to the total (%)
Coal mining	5.54E + 04	0.3	2.93E + 05	0.22	3.76E + 08	0.24
Transport & storage of coal	1.03E + 05	0.55	5.99E + 05	0.44	6.56E + 08	0.43
Operation of coal power plant	2.49E + 06	13.37	7.79E + 06	5.76	5.92E + 10	38.52
Diesel production	2.02E + 03	0.01	2.00E + 04	0.01	1.45E + 07	0.01
Storage & distribution of diesel	7.91E + 02	0.004	2.79E + 03	0.002	4.13E + 06	0.003
Operation of diesel power plant	1.14E + 03	0.01	2.28E + 04	0.02	2.03E + 06	0.001
Extraction & processing of gas	5.11E + 04	0.27	8.25E + 04	0.06	1.31E + 08	0.09
Long distance transport of gas	2.12E + 04	0.11	1.90E + 04	0.01	3.42E + 07	0.02
High pressure distribution of gas	2.26E + 04	0.12	5.37E + 04	0.04	6.77E + 07	0.04
Operation of gas power plant	7.84E + 04	0.42	4.98E + 05	0.37	1.11E + 08	0.07
Extraction & processing of oil	4.91E + 04	0.26	2.21E + 05	0.16	1.63E + 08	0.11
Long distance transport of oil	1.48E + 05	0.79	2.27E + 05	0.17	6.44E + 08	0.42
Heavy fuel oil production	9.15E + 04	0.49	8.53E + 05	0.63	6.55E + 08	0.43
Storage & distribution of heavy fuel oil	3.53E + 04	0.19	1.29E + 05	0.1	1.90E + 08	0.12
Operation of heavy fuel oil power plant	1.54E + 07	82.5	1.24E + 08	91.7	9.11E + 10	59.34
Wind power	8.83E + 02	0.005	4.79E + 03	0.004	1.02E + 06	0.001
Geothermal power	24684.70938	0.13	5.87E + 04	0.04	32358169.92	0.02
Hydropower	2.46E + 04	0.13	1.09E + 05	0.08	4.33E + 07	0.03
Nuclear power	5.99E + 04	0.32	2.38E + 05	0.18	1.70E + 08	0.11
Total	1.86E + 07	100	1.35E + 08	100	1.54E + 11	100

Life cycle stage	ODP (t R11 eq./yr)	Contribution to the total (%)	POCP (t Ethene-eq./yr)	Contribution to the total (%)	TETP (t DCB eq./yr)	Contribution to the total (%)
Coal mining	3.66E-02	0.25	1.44E + 03	1.33	8.87E + 03	0.19
Transport & storage of coal	1.64E-01	1.11	1.80E + 03	1.66	1.26E + 04	0.27
Operation of coal power plant	2.37E-02	0.16	1.37E + 04	12.62	6.02E + 04	1.28
Diesel production	1.34E-02	0.09	6.99E + 01	0.06	4.43E + 02	0.01
Storage & distribution of diesel	7.60E-04	0.01	5.88E + 00	0.01	1.06E + 02	0.002
Operation of diesel power plant	5.26E-04	0.004	7.88E + 02	0.73	3.28E + 02	0.01
Extraction & processing of gas	7.71E + 00	52.52	6.74E + 03	6.21	8.04E + 03	0.17
Long distance transport of gas	2.55E + 00	17.37	3.83E + 02	0.35	9.90E + 02	0.02
High pressure distribution of gas	8.61E-01	5.86	3.06E + 02	0.28	2.00E + 03	0.04
Operation of gas power plant	1.03E-02	0.07	7.01E + 03	6.46	9.79E + 03	0.21
Extraction & processing of oil	2.07E + 00	14.07	2.37E + 04	21.83	3.41E + 03	0.07
Long distance transport of oil	6.80E-02	0.46	6.64E + 02	0.61	8.77E + 03	0.19
Heavy fuel oil production	5.29E-01	3.6	2.93E + 03	2.7	1.98E + 04	0.42
Storage & distribution of heavy fuel oil	3.46E-02	0.24	2.71E + 02	0.25	4.93E + 03	0.1
Operation of heavy fuel oil power plant	1.65E-02	0.11	4.77E + 04	43.9	4.55E + 06	96.77
Wind power	4.36E-05	0.0003	4.58E-01	0.0004	1.57E + 02	0.003
Geothermal power	0.001913455	0.01	8.94E + 02	0.82	2209.236313	0.05
Hydropower	7.64E-03	0.05	1.07E + 02	0.1	3.85E + 03	0.08
Nuclear power	5.89E-01	4.01	8.54E + 01	0.08	5.50E + 03	0.12
Total	1.47E + 01	100	1.09E + 05	100	4.70E + 06	100

Appendix C. Electricity mix by country

Table C.1
Electricity mix by country [8,20].

	Electricity mix (%)			
Energy source	Mexico (2006)	Italy (2004)	Portugal (2004)	UK (2004)
Fossil fuels	78.7	78.9	71.7	76.8
Coal	14.0	15.1	33.0	33.6
Oil	21.6	16.1	12.7	1.1
Gas	42.6	47.6	26.0	42.1
Diesel	0.5	–	–	–
Biomass	–	0.5	2.8	1.0
Nuclear	4.8	–	–	19.7
Hydro	13.5	19.9	23.5	2.0
Geothermal	3.0	–	–	–
Solar PV	–	0.001	0.001	–
Wind	0.02	0.7	1.9	0.5
Total	100	100	100	100

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