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Environmental implications of decarbonising electricity supply in large economies: The case of Mexico

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ABSTRACT

Driven by the security of supply and climate change concerns, decarbonisation of energy supply has become a priority for many countries. This study focuses on Mexico, the world's 14th largest economy, and considers the environmental implications of decarbonising its electricity supply. Eleven scenarios are considered for the year 2050 with different technology mixes and GHG reduction targets, ranging from stabilisation at the year 2000 level to a reduction of 60–85%. Unlike most energy scenario analyses which focus mainly on direct CO_2 or GHG emissions, this paper presents the full life cycle impacts of electricity generation in 2050 considering ten environmental impacts which, in addition to global warming, include resource and ozone layer depletion, acidification, eutrophication, summer smog, human and eco-toxicity. The results indicate that continuing with business as usual (BAU) would double the current life cycle GHG emissions, even if annual electricity demand growth was reduced to 2.25% from the current 2.8%. Switching from the current fossil fuel mix to a higher contribution of renewables (55–86%) and nuclear power (up to 30%) would lead to a significant reduction of all ten life cycle impacts compared to the current situation and up to an 80% reduction compared to BAU.

1. Introduction

Driven by the security of supply and climate change concerns, decarbonisation of energy supply has become a priority for many countries. As global energy demand continues to grow together with dependence on fossil fuels, the need to decarbonise as well as diversify energy supply is becoming ever more pressing. For example, energy consumption in 2010 increased by 5.6% compared to 2009 and 87% of the total (primary) energy demand was met by fossil fuels [1]. Many countries, including Mexico, are seeking to develop future energy systems that would improve the self-sufficiency of supply but also contribute towards their GHG reduction targets. A signatory to the Kyoto Protocol, Mexico aims to reduce GHG emissions by 30% by 2020 (relative to business-as-usual) and by 50% by 2050 (relative to year 2000 emissions) [2]. If achieved, this would contribute to the stabilisation of CO_2 concentrations in the atmosphere below 450 ppm, required to limit the global average temperature increase between 2 and 2.4 °C [3].

Mexico is the 14th largest economy [4] and 6th largest oil producer in the world [5]. It is also rich in other natural resources including gas, coal and renewable energy sources such as hydro, geothermal, wind, solar and marine [6–10]. However, its economy and energy supply are highly dependent on fossil fuels, which together with a lack of sustainable energy planning has led to serious concerns [11–13]. One of these is that domestic production of fuels is starting to decrease owing to declining reserves [5,14] while at the same time a significant amount of crude oil continues to be exported to generate revenue [5,15]. Consequently, Mexico is becoming more dependent on imports of petrol, natural gas and other high-value secondary energy sources. In addition, little increase has been observed in the use of renewable energies despite the large potential.

Furthermore, the energy sector, and particularly electricity, is one of the most significant contributors to national GHG emissions because of its heavy reliance on fossil fuels. For instance, in 2006, 79% of electricity was generated from fossil fuels [16], contributing 27% of the total energy-related GHG emissions [2]. At the same time, electricity demand has been growing at an annual rate of 2.8% [17]. Meeting the target of 50% reduction of GHG emissions by 2050 would require cutting the emissions from electricity generation by 85% on 2000 levels (110.7 Mt CO_2 eq.), emitting only 16.2 Mt CO_2 eq. by 2050 [2]. This is a very challenging task and will necessitate significant reductions in the short and medium terms, particularly as electricity demand is projected to grow [18].

While the Mexican Government has made an effort to reduce GHG emissions in the short term by substituting heavy fuel oil

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with combined cycle gas power plants [17,19], this cannot be a long-term solution for mitigating climate change and improving the security of supply. Similarly, little consideration has been given to environmental impacts other than climate change. Therefore, more sustainable options must be identified and implemented. Given that Mexico is one of the world's largest economies, this is not only important for Mexico but also globally.

Thus far, little work has been carried out considering sustainable future electricity mixes for Mexico. A limited number of scenario analyses have been conducted [e.g. 18,20,21] but these have focused solely on direct CO_2 or GHG emissions, ignoring other impacts and life cycle stages. In order to identify environmentally sustainable options it is necessary to expand the scope of such assessments both vertically and horizontally: firstly, all life cycle stages should be accounted for to ensure that environmental burdens are not simply transferred from the point of electricity generation to another point up- or downstream; secondly, impacts other than climate change should be addressed to ensure that one environmental impact is not mitigated at the expense of another [22].

Regarding the need to address other environmental impacts for Mexican power plants, most previous work is limited to specific plants and contexts: for instance, an assessment of the cross-border health impacts induced by aerial emissions from Mexican power-exporting plants on recipients in the USA [23].

As for the need to cover all life cycle stages, life cycle assessment (LCA) studies of present-day electricity mixes are available in literature for several countries including Mexico [24] and the UK [25]. However, these only address the present day; combining LCA and scenario analysis is a novel area of research that provides a much more comprehensive information for sustainable development policy.

In the energy sector, such an approach has been partially demonstrated for four European countries by the NEEDS project (see [26]) and, independently, for Belgium [27] and Denmark [28]; however, these cannot be used for other countries with their own unique electricity mixes, resource bases and climate targets, such as Mexico. Moreover, these studies address highly developed European economies with typical carbon reduction targets of up to 80% by 2050 (compared to a 1990 baseline). These are some of the most ambitious targets in the world and therefore the analyses are not congruous with the requirements of other regions, particularly developing countries. Many developing countries have only stated a reduction target for 2020 relative to business-as-usual (BAU): Chile, for instance, targets emissions 20% lower than BAU by

Table 1
Main drivers and characteristics of different scenarios for electricity production in Mexico in 2050.

Scenario	Source	GHG reduction target for 2050 on the 2000 levels[a]	Scenario description
BAU	Based on IEA [30] and Greenpeace and EREC [18]	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	Based on Greenpeace and EREC [18]	70%	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
A-1	This study	Stabilisation (no increase)	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	This study	Stabilisation (no increase)	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	This study	Stabilisation (no increase)	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 41%; CCS and oil power plants are not considered
A-2	This study	60%	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	This study	60%	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	This study	60%	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	This study	85%	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	This study	85%	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	This study	85%	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

[a] All reduction targets refer to direct rather than life cycle emissions. GHG considered: carbon dioxide, methane and nitrous oxide.

Table 2
Assumed contribution of different electricity sources to the total electricity mix for different scenarios (current mix shown for comparison).

Source	Current (2006)[a]	BAU[b]	Green[c]	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
Electricity mix (%)												
Biomass	0.0	1.8	3.3	8.4	8.4	8.4	4.2	4.2	4.2	8.4	8.4	8.4
Coal	14.0	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	0.0	10.0	5.0	27.4	35.0	12.1	0.0	10.0	5.0
Gas	42.6	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	0.0	6.7	0.0	25.6	35.0	0.0	0.0	6.5
Geothermal	3.0	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	22.1	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro	13.5	4.4	8.9	10.0	12.5	15.0	6.3	6.3	6.3	6.3	6.3	6.3
Nuclear	4.8	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	0.0	7.2	2.5	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0
Solar thermal	0.0	0.6	18.9	6.1	8.7	11.7	3.4	3.4	8.8	4.9	7.5	9.8
Solar PV	0.0	0.4	12.6	4.1	5.8	7.8	2.3	2.3	5.9	3.3	5.0	6.5
Wind	0.0	2.8	31.1	10.2	14.4	19.5	5.7	5.7	14.7	8.2	12.5	16.4
Total	100	100	100	100	100	100	100	100	100	100	100	100
Renewable electricity	16	12	86	49	62	75	25	25	43	39	47	55
Fossil fuels	79	87	14	41	28	15	70	70	47	41	28	15
Nuclear	5	1	0	10	10	10	5	5	10	20	25	30

[a] SENER [17].
[b] IEA [30] and Greenpeace and EREC [18].
[c] Greenpeace and EREC [18].

Table 3
Installed power capacity for different scenarios (current mix shown for comparison).

Source	Current (2006)[b]	BAU[c]	Green[d]	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
Power capacity (MW)[a]												
Biomass	0	1469	2700	6674	6674	6674	3333	3333	3333	6674	6674	6674
Coal	4700	27,182	2000	13,067	0	0	6620	0	0	13,067	0	0
Coal CCS	0	0	0	0	8711	4356	23,868	30,489	10,523	0	8711	4356
Gas	18,875	42,609	9711	20,779	13,977	2657	27,882	7446	0	20,850	14,088	2800
Gas CCS	0	0	0	0	0	5338	0	20,397	27,843	0	0	5139
Geothermal	960	1249	3200	6006	6006	6006	2401	2401	2401	6006	6,006	6006
Heavy fuel oil	12,300	2204	0	0	0	0	0	0	0	0	0	0
Hydro	10,566	9550	20,000	21,594	26,993	32,392	13,561	13,561	13,561	13,561	13,561	13,561
Nuclear	1365	1029	0	7611	7611	7611	3805	3805	7611	15,222	19,027	22,833
Ocean	0	0	9100	3164	6328	6328	0	0	0	0	0	0
Solar CSP	0	441	15,473	4557	6476	8723	2561	2570	6588	3691	5597	7328
Solar PV	0	1704	54,520	17,619	25,042	33,730	9902	9937	25,475	14,272	21,643	28,337
Wind	24	6391	70,357	23,005	32,663	43,996	12,916	12,984	33,251	18,616	28,230	36,984
Total	48,790	93,829	187,060	124,075	140,481	157,809	106,851	106,922	130,587	111,959	123,537	134,017

[a] Estimated using the total generation of 598,000 GWh/yr, the electricity mix in Table 2 and capacity factors in Table 7.
[b] Adapted from SENER [17] and Santoyo-Castelazo et al. [24].
[c] Adapted from IEA [30] and Greenpeace and EREC [18].
[d] Greenpeace and EREC [18].

Table 4
Electricity generation by energy source for different scenarios.

Source	Current (2006)[a]	BAU[b]	Green[c]	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
Electricity generation (GWh/yr)												
Biomass	0	11,020	20,000	50,053	50,053	50,053	24,996	24,996	24,996	50,053	50,053	50,053
Coal	31,550	186,600	11,000	89,700	0	0	45,448	0	0	89,700	0	0
Coal CCS	0	0	0	0	59,800	29,900	163,852	209,300	72,238	0	59,800	29,900
Gas	95,885	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	0	40,126	0	153,327	209,300	0	0	38,631
Geothermal	6685	9550	24,000	45,926	45,926	45,926	18,359	18,359	18,359	45,926	45,926	45,926
Heavy fuel oil	49,743	13,224	0	0	0	0	0	0	0	0	0	0
Hydro	30,305	26,447	53,000	59,800	74,750	89,700	37,554	37,554	37,554	37,554	37,554	37,554
Nuclear	10,866	8081	0	59,800	59,800	59,800	29,900	29,900	59,800	119,600	149,500	179,400
Ocean	0	0	43,000	14,950	29,900	29,900	0	0	0	0	0	0
Solar CSP	0	3526	112,800	36,454	51,811	69,787	20,487	20,559	52,708	29,529	44,778	58,628
Solar PV	0	2351	75,200	24,303	34,540	46,524	13,658	13,706	35,138	19,686	29,852	39,085
Wind	45	16,897	186,000	60,817	86,351	116,311	34,146	34,325	87,906	49,215	74,630	97,773
Total	225,079	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000	598,000

[a] Adapted from SENER [17] and Santoyo-Castelazo et al. [24].
[b] Adapted from IEA [30] and Greenpeace and EREC [18].
[c] Greenpeace and EREC [18].

Table 5
Estimated potential for renewable electricity generation in Mexico.

Source	Potential	Potential for contribution to electricity mix[g] (%)
Biomass	50,000 GWh/yr[a]	5–10
Geothermal	12,000 MW[b]	5–10
Hydro	42,000 MW[c]	10–15
Solar	1900–2200 or more[d] (kWh/m^2/yr)	10–20
Ocean	N.A.[e]	0–5
Wind	40,000 MW[f]	15–20

[a] This is just the potential which is proven to be economically feasible, but the total potential is expected to be greater [9,18,37].
[b] Potential of high temperature resources for electricity production [37,46], from which at least 2400 MW are estimated to be economically feasible.
[c] 39,000 MW for large hydro, and 3000 MW for small hydropower plants [37].
[d] Mexico's solar potential is within the optimal regions around the world [18,37,47] for both solar thermal and solar PV technologies.
[e] Not available due to high uncertainty [18,37,47].
[f] This is mostly the estimated potential for the region of La Ventosa in Oaxaca State, but the country's potential could be greater [18,37].
[g] Estimated potential by Krewitt et al. [31] for electricity production in Mexico.

2020; for Indonesia, the target is 26%; South Africa 34%; and Brazil 36.1–38.9% [29]. Mexico lies in the middle of these with a target of 30% by 2020. However, it goes beyond that to set a 2050 target of 50% reduction on 2000 emissions [2], which brings it closer to the targets set by some developed countries.

This paper focuses on the case of Mexico and considers the life cycle environmental sustainability of different electricity options for the country up to the year 2050, using scenario analysis. The paper is structured as follows: Section 2 gives an overview of the scenarios considered, together with the assumptions and data

Table 7
Operating parameters for the power plants assumed in the scenarios [comparison with the current technologies shown in brackets as adapted from SENER [17]].

Source	Electrical efficiency [Current technologies] (%)	Capacity factor[a] [Current technologies] (%)	Lifetime[b] (yr)
Biomass	40[c]	86	30[c]
Coal	54[d] [36]	78 [78]	35[d]
Coal CCS	49[d]	78	35[d]
Gas	65[d] [45]	86 [67]	25[d]
Gas CCS	61[d]	86	25[d]
Geothermal	36[f] [36]	87 [79]	30[f]
Heavy fuel oil	35[e] [35]	68 [46]	30[c]
Hydro	36[e] [36]	32 [32]	80[g]
Nuclear	37[d] [33]	90 [90]	60[d]
Ocean	90[d]	54	80[d]
Solar thermal	19; 12; 18[d]	91	40[d]
Solar PV	22[d]	16	40[d]
Wind	36[d] [36]	30 [23]	30[d]

[a] Capacity factor is the amount of electricity produced over a period, divided by the amount of electricity that would have been produced if the power plant was running continuously at full capacity over that period; sourced from Greenpeace and EREC [18].
[b] Lifetime represents both the economic and the technical lifetime of the power plant.
[c] Gemis [45].
[d] Coal and gas with and without CCS: Bauer et al. [26]; nuclear: Lecointe et al. [48]; ocean: Sørensen and Naef [49]; solar thermal (parabolic trough, Fresnel trough and solar tower, respectively: Viebahn et al. [36]; solar PV: Frankl et al. [35]; wind: DONG Energy [50].
[e] SENER [16].
[f] MIT [51].
[g] IEA/NEA [52].

Table 6
Characteristics of power plant technologies assumed in the scenarios for the year 2050.

Electricity source	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 microgas 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: flue gas desulphurisation (FGD), selective catalytic reduction (SCR) and electrostatic precipitation (ESP) for control of SO_2, NO_X, and particulate matter (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 with CCS with a removal efficiency of 90% of CO_2 emissions from: post-combustion (for USC) and pre-combustion capture (for IGCC); includes CO_2 transport and storage in depleted gas reservoir. The USC configuration includes: FGD, SCR, and ESP for control of 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 CCS, including 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 currently
Heavy fuel oil[c]	Steam turbine (ST)	Same technology as currently
Hydro[c]	Water turbine	Large (dam-reservoir) and small (run-of-river) hydro power plants Same technology as currently
Nuclear[d]	European Pressurised Reactor (EPR)	The EPR with a capacity of 1,600 MW, using an ultra-centrifugation enrichment process
Ocean[e]	Wave energy converter	Wave Dragon energy converter of 7 MW
Solar thermal[f]	Parabolic trough, fresnel and solar tower	200 MW parabolic trough and 200 MW fresnel, both using steam as heat transfer fluid and 16 h phase changed material storage; 180 MW solar tower with salt as heat transfer fluid and 16 h of molten salt storage
Solar PV[g]	Crystalline silicon and thin film	Multi-crystalline silicon (mc-Si) and Cadmium Telluride (CdTe), with an average module efficiency of 22%
Wind[h]	Wind turbine	Average capacity: 24 MW; hub height: 160 m; rotor diameter: 250 m

[a] Ecoinvent [39,40].
[b] Bauer et al. [26].
[c] SENER [17]; Ecoinvent [39]; Gemis [45].
[d] Lecointe et al. [48].
[e] Sørensen and Naef [49].
[f] Viebahn et al. [36].
[g] Frankl et al. [35].
[h] DONG Energy [50].

sources; this is followed by discussion of the results in Section 3 and conclusions in Section 4.

2. Scenario definition, assumptions and data sources

Eleven scenarios are considered, each for the year 2050. These include two scenarios previously developed by the IEA [30] and Greenpeace and EREC [18] but adapted and extended here to consider the full life cycle impacts. In each case, the year 2050 is considered as a 'snapshot' for comparison to the present: the period between now and 2050 is not modelled.

The following scenarios are considered (see Table 1 for further details):

- Business as usual (BAU) in terms of the electricity mix and no climate change targets (adapted from IEA [30] and Greenpeace and EREC [18]);
- 'Green' scenario which considers a 70% reduction of GHG (CO_2, CH_4 and N_2O) from the electricity sector by 2050 on the 2000 levels (adapted from Greenpeace and EREC [18]); and
- Scenarios A, B and C developed in this work, based on the drivers of climate change as well as security and diversity of energy supply. Each of these three scenarios has a further three sub-scenarios considering stabilisation (no increase), 60% and 85% reduction of GHG (CO_2, CH_4 and N_2O) on the 2000 levels, respectively. As mentioned in the introduction, the latter is in line with the Government targets for the reductions of GHG emissions from the electricity sector. 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 the main energy sources but integrated with large-scale CCS. Scenario C is based mainly on nuclear power, with significant contributions from renewable energies.

To make them comparable, all the scenarios follow the assumptions in the Green scenario of the annual electricity demand growth rate of 2.25%, increasing from the current 225,079 GWh [17] to 598,000 GWh in 2050 [18]. Although this is below the current growth of 2.8% per year [17], it is assumed to be feasible owing to the projected future increase in the efficiency of electricity generation and distribution. It has also been assumed in all the scenarios that the country is self-sufficient with respect to electricity generation; this is also the case currently with less than 0.5% of electricity imported.

Scenario analysis does not attempt to predict the future, merely to consider possibilities. However, by considering 11 potential futures ranging from BAU to an 85% GHG emissions reduction, it is anticipated that a sufficiently meaningful range of possibilities is being explored and that reality will lie somewhere within that range either as one of the scenarios or as a combination of several. The scenarios are described in more detail in the following sections.

2.1. Business as usual (BAU) scenario

This scenario is based on that developed by IAE [30] for the period 2010–2030 and extrapolated to 2050 by Greenpeace and EREC [18]. However, as the assumptions for the energy growth (1.1% per annum) and technology efficiencies (same as currently) were different from the assumptions in the other scenarios considered in this work, to make it comparable, the original scenario has been adapted applying the same assumptions as in the rest of the scenarios.

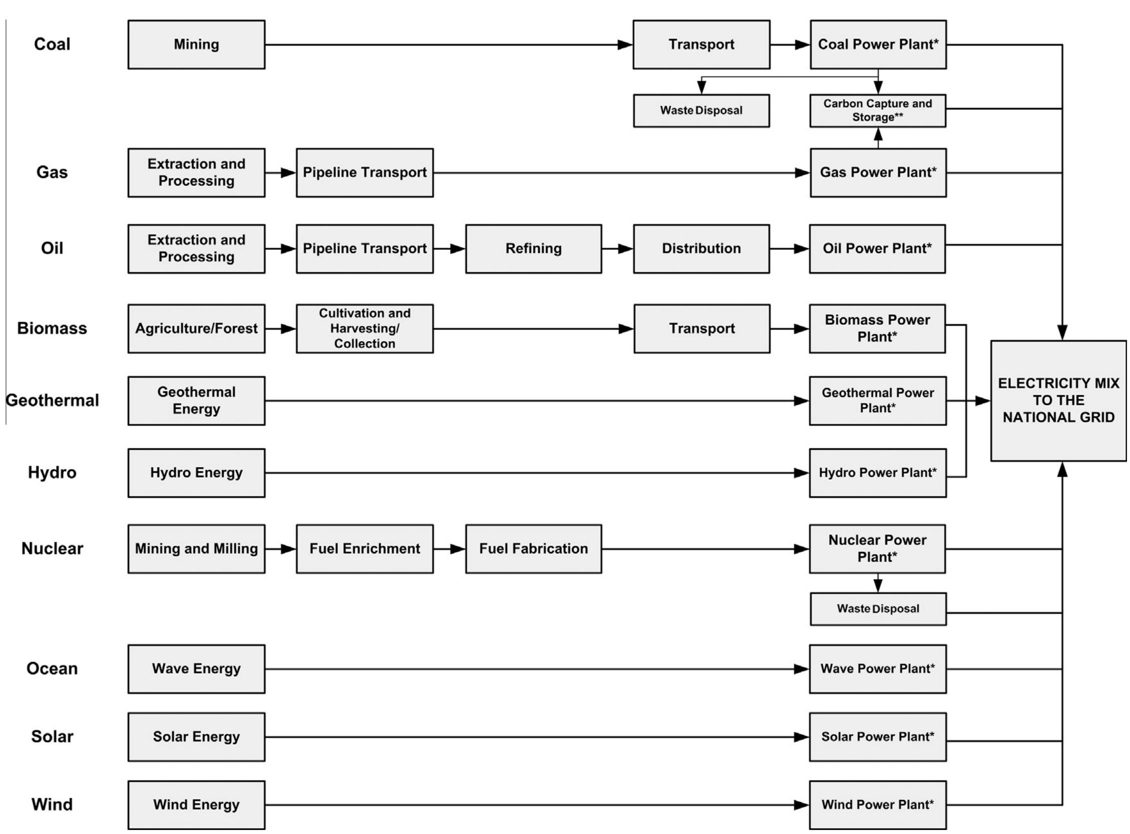


Fig. 1. The life cycle of electricity options considered in the scenarios (modified from [24]). [*Plant comprises construction and operation of power plant; **CCS is considered for coal and gas power plants only].

As the name suggests, the BAU 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 2). The contribution of oil decreases because of the depletion of the country's reserves and high uncertainty in oil prices [18]. The share of nuclear and hydropower also goes down to 1.4% and 4.4%, respectively. Even though wind power increases by 6.1% annually, it contributes only 2.8% to the total production by 2050. Biomass, geothermal and solar power also grow contributing 4.4% to the mix collectively. As shown in Table 3, the total installed capacity is 93,829 MW, double the present but still the lowest compared to the other scenarios owing to the large contribution of fossil fuel plants and their higher operating factors compared to the renewables.

2.2. Green scenario

This scenario was developed by Greenpeace and EREC [18], assuming a 72% reduction in direct CO_2 emissions from the electricity sector compared to the emissions in 2005. It has been adapted slightly by using 2000 as the base year for the CO_2 reduction target instead of 2005, to make it comparable with the other scenarios. Owing to the lower GHG emissions in 2000 compared to 2005 and slightly higher CO_2 emissions estimated for this scenario in this work (for details see Section 4.1), the reduction target for 2050 in this scenario is reduced slightly (to 70%). Furthermore, the original analysis only considered direct emissions of CO_2 (as opposed to the life cycle implications being considered in this work).

As shown in Table 4, renewables dominate in this scenario with wind and solar providing 63% of the total electricity demand in 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 development of nuclear power is planned under this scenario. The total installed capacity is 187,060 MW, being the highest compared to the other scenarios (see Table 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, notably for wind and ocean power, the assumptions exceed significantly the estimated renewable energy potential for Mexico (see Table 5). For example, this scenario assumes an installed wind capacity of 70,357 MW which exceeds by 75% its estimated potential of 40,000 MW. Similarly, the assumed potential of the ocean energy to contribute to the electricity mix exceeds some estimates [31] by 44% (see Tables 2 and 5). However, there is uncertainty in the estimated potentials (see footnotes to Table 5). For instance, the maximum potential for wind power is based on only one region (estimates for other regions were not available). Therefore the extent to which the Green scenario is technically achievable is not certain.

In addition to the above, there are also technical challenges involved in integrating variable-output technologies into the grid mix at such a large scale. Almost 70% of the Green electricity mix is composed of non-dispatchable technologies (ocean, solar thermal, solar PV and wind), therefore matching supply to demand will be difficult. This may necessitate a combination of smart grid features (such as load shifting in response to the output from renewables) and/or large-scale energy storage. This is an important area that is currently not well addressed in literature owing to a lack of data and uncertainty over technological possibilities. Therefore, this is beyond the remit of the current paper but should be borne in mind when interpreting the feasibility of the Green scenario.

2.3. Scenarios A, B and C

These 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 GHG reduction targets for 2050 relative to the 2000 levels: stabilisation of emissions (i.e. no increase); 60%; and 85% reduction. Note that all the reduction targets refer to direct emissions from the operation of power plants, but the impacts of different scenarios are estimated on a life cycle basis. The assumptions for these scenarios are summarised in Tables 1 and 4 and are discussed in more detail further below.

As shown in Table 3, the installed capacities range from 106,851–157,809 MW and are considerably lower than in the Green scenario because of a higher contribution from fossil fuels. In that respect, scenarios B-1 and B-2 are comparable to BAU, owing to the high contribution from fossil fuels to the electricity mix (70% compared to 79% for BAU; Table 2). The following other main assumptions apply for all A, B and C scenarios:

- Owing to the depletion of domestic oil reserves, continuing price increases as well as the need to mitigate climate change and other environmental impacts, 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 [17,19] and the world trends [18,32,33].
- By 2050, all coal and gas used for power generation is 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 the scenarios. The only exception are dam hydropower plants, 65% of which are still available by 2050 (based on own estimates using the CFE [34] data and assuming the lifetime of 80 years).
- Electricity from coal (with and without CCS) is shared equally between the ultra-supercritical (USC) pulverised combustion and integrated gasification combined cycle (IGCC) technologies by 2050. This assumption is made to avoid bias towards either of the technologies given that they currently both appear equally viable; until either is deployed at commercial scale, the likely split between USC and IGCC will remain unclear.
- The assumptions for the renewables are as follows [9,18,31,35–37]:
  - 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 PV;
  - solar PV technology mix: 30% multi-crystalline silicon (mc-Si) and 70% cadmium telluride (CdTe);
  - solar thermal mix: 40% parabolic trough, 40% Fresnel and 20% solar tower; and
  - biomass mix: 80% wood and forestry residues, 15% agricultural residues (sugar cane bagasse) and 5% biogas from waste.

The specific assumptions for the sub-scenarios are detailed below.

2.3.1. Scenarios A-1–A-3

For these scenarios, it has been assumed that the national policies support the development of all types of renewable energy 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 potential resource for each energy source (see Table 5) as well as the expected reduction of capital costs by 2050 [18,33].

In the case of scenario A-1 (stabilisation of emissions), the contribution from renewable energy 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 the increase in the contribution from wind, solar and hydro power (14.4%, 14.4% and 12.5%, respectively). The contribution from these sources in scenario A-3 is 19.5% from wind and solar and 15% from hydro power. The contribution from biomass and geothermal for scenarios A-2 and A-3 remains the same as for A-1 (see Table 2); the exception is ocean energy whose contribution increases from 2.5% (in scenario A-1) to 5% (in scenarios A-2 and A-3).

Although these scenarios are dominated by the renewable sources, fossil fuel plants (with and without CCS) and nuclear power have also significant contributions to the electricity supply, mainly because of the need to diversify the energy supply and meet ambitious emission targets. Gas power plays a more important role than coal owing to its lower life cycle environmental impacts (for details, see [24]). Depending on the emission reduction targets, the contribution from gas ranges from 10% in scenario A-3 to 26% in A-1. Gas power plants with CCS are only considered in scenario A-3 because of its more ambitious emission reduction target of 85% (Table 1). The contribution of coal power 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 emission targets (60% and 85%). Being low carbon, nuclear power contributes 10% to the electricity mix in all scenarios.

2.3.2. Scenarios B-1–B-3

In these scenarios, fossil fuels remain the most important electricity source, contributing 70% of the total generation. Gas power contributes 35% of the total with the amount of gas CCS varying depending on the emission targets (see Table 1): while no CCS is required in scenario B-1, it 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 B-3 (owing to the 85% emission reduction target).

The contribution from the renewable sources in scenarios B-1 and B-2 is assumed to be 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 B-3, the contribution of renewables increases to 43%, mostly owing to the increase of wind and solar power (together contributing 70% of the total renewable energy production). The share of nuclear power in scenarios B-1 and B-2 is similar to the BAU scenario (5%) while in B-3 it increases to 10%.

2.3.3. Scenarios C-1–C-3

It is assumed in these scenarios that the use of nuclear power receives political and economic support from the government (Table 1) enabling a nuclear contribution of 20%, 25% and 30% of the total electricity generation in scenarios C-1, C-2 and C-3, respectively. Renewable energy is also crucial in these scenarios, contributing 39%, 47% and 55% to the total, respectively. Similar 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

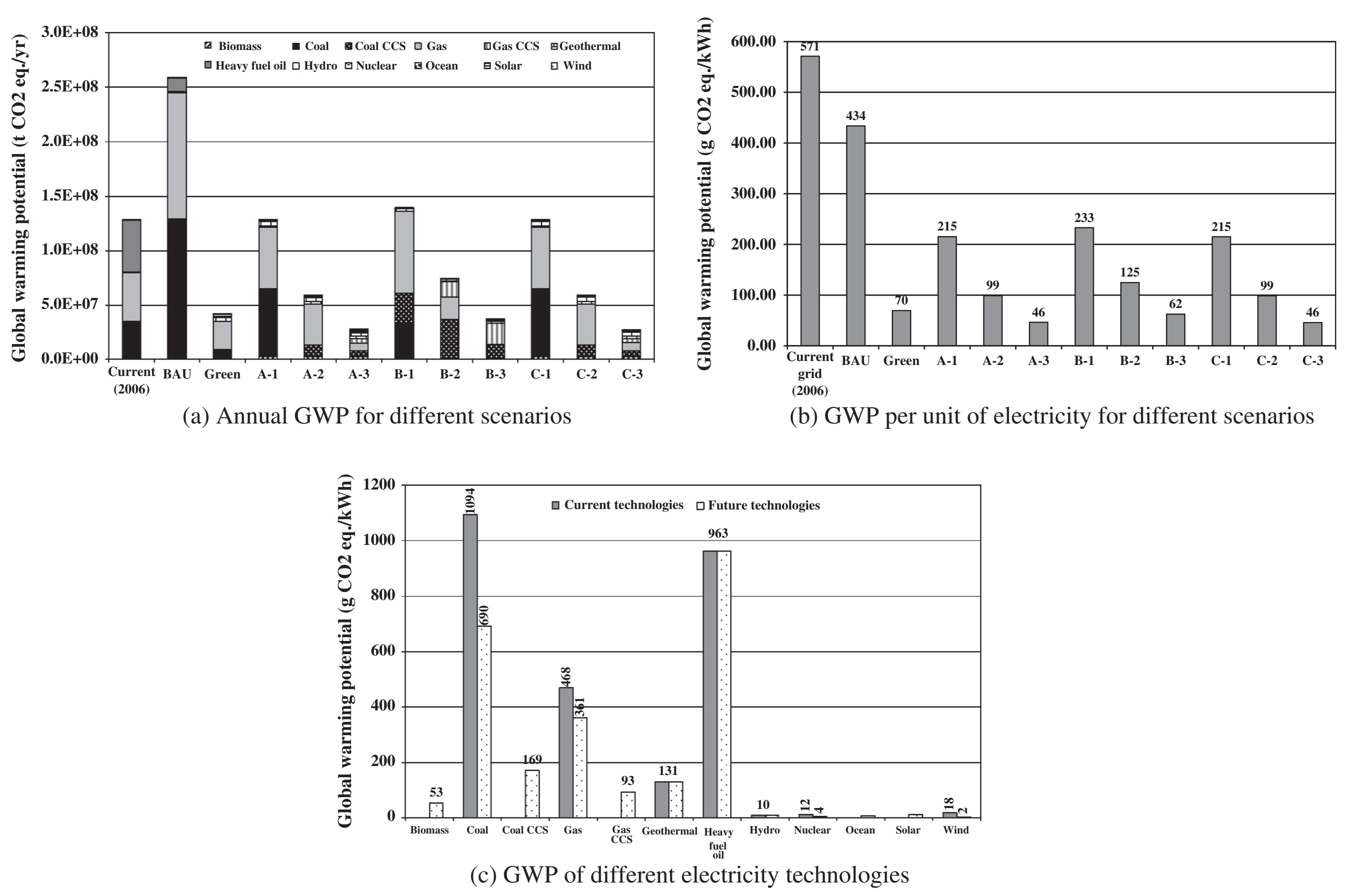


Fig. 2. Global warming potential (GWP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

power (see Table 2). The 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 2).

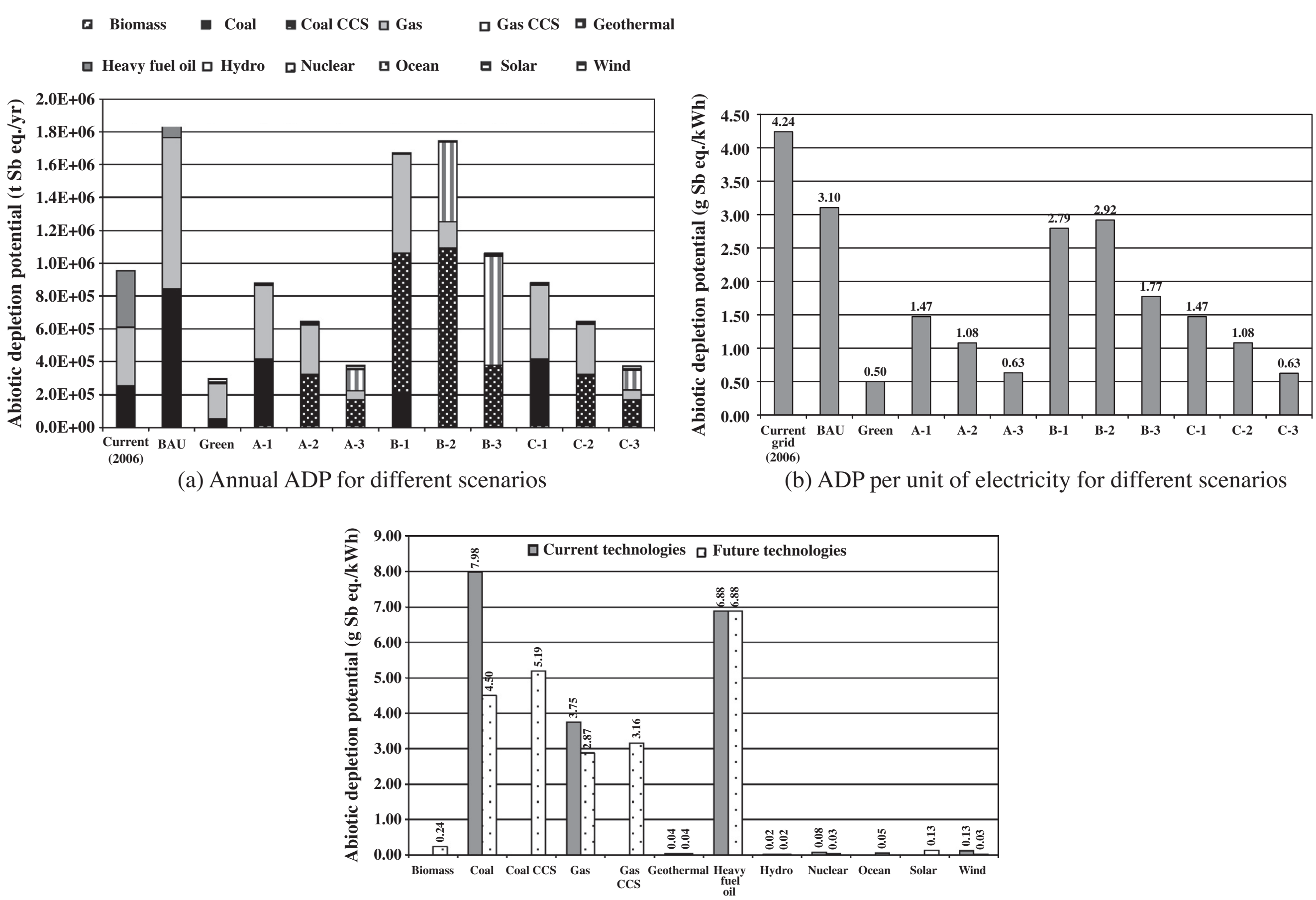
2.3.4. Power plant technologies

The characteristics of the power plants assumed in the scenarios are summarised in Tables 6 and 7. The data have been sourced mainly from the NEEDS [38] and Ecoinvent databases [39,40]. Where data for future technologies were not available (i.e. for oil, hydro, geothermal and biomass power plants), the existing power plant technologies have been assumed.

3. A life cycle approach

The scenarios are analysed on a life cycle basis, considering the full life cycle of each electricity technology as outlined in Fig. 1. The system boundary is drawn from 'cradle to grave', encompassing the following stages for each technology:

- Coal (with and without CCS): Mining, processing and cleaning of coal followed by transport to the power plant and combustion to produce electricity; construction (including extraction and production of materials) and decommissioning of the plant; offsite waste disposal. For CCS, 90% CO_2 capture is assumed followed by pipeline transport and storage in depleted gas fields.
- Gas (with and without CCS): Conventional gas extraction and processing, pipeline transport and combustion to generate electricity; construction (including extraction and production of materials) and decommissioning of the plant; offsite waste disposal. As for coal, 90% CO_2 capture is assumed for CCS installations, followed by pipeline transport and storage in depleted gas fields.
- Oil: Conventional crude oil extraction and processing, pipeline transport and combustion to produce electricity; construction (including extraction and production of materials) and decommissioning of the plant; offsite waste disposal.
- Biomass: Forestry and wood processing, sugar cane agriculture/processing or biogas extraction; transport followed by combustion and electricity generation by a steam turbine (for wood), co-generation system (for sugarcane bagasse) or micro-gas turbine (bagasse); construction (including extraction and production of materials) and decommissioning of the respective plants; offsite waste disposal.
- Geothermal: Well drilling and hot fluid extraction; flash steam power plant operation and return of fluid into the well system; construction (including extraction and production of materials) and decommissioning of the plant; offsite waste disposal.
- Hydro: Construction (including extraction and production of materials) of large reservoir and dam, or small run-of-river plant; operation; decommissioning of plant components; offsite waste disposal.



(a) Annual ADP for different scenarios

(b) ADP per unit of electricity for different scenarios

(c) ADP of different electricity technologies

Fig. 3. Abiotic depletion potential (ADP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

- Nuclear: Conventional mining and milling of U_3O_8 followed by conversion to UF_6, enrichment via centrifuge and fuel fabrication; operation in a pressurised water reactor; construction (including extraction and production of materials) and decommissioning of the plant; waste disposal in underground repository.
- Ocean: Construction (including extraction of raw materials) of a floating, overtopping-type wave energy converter ("Wave Dragon"); operation; decommissioning of plant; offsite waste disposal.
- Solar thermal: Construction (including extraction and production of materials) of parabolic troughs, Fresnel reflectors with steam turbine and molten salt tower system; operation; decommissioning of plant; offsite waste disposal.
- Solar photovoltaics (PV): Production of multi-crystalline silicon and cadmium-telluride solar modules followed by construction (including extraction and production of materials) of residential installation; operation; decommissioning of components; offsite waste disposal.
- Wind: Construction (including extraction and production of materials) of a modern onshore turbine tower, nacelle and rotors; operation; decommissioning of turbine; waste disposal.

The analysis is based on the generation of 598,000 GWh/yr electricity. It has been carried out using life cycle assessment (LCA) as a tool, following the ISO 14040/14044 methodology [41,42]. GaBi software v4.3 [43] has been used for LCA modelling and the environmental impacts have been estimated using the CML 2001 method [44]. The following ten impact categories are considered: global warming, resource depletion, acidification, eutrophication, ozone layer depletion, photochemical oxidant creation, human toxicity and freshwater, marine and terrestrial ecotoxicity.

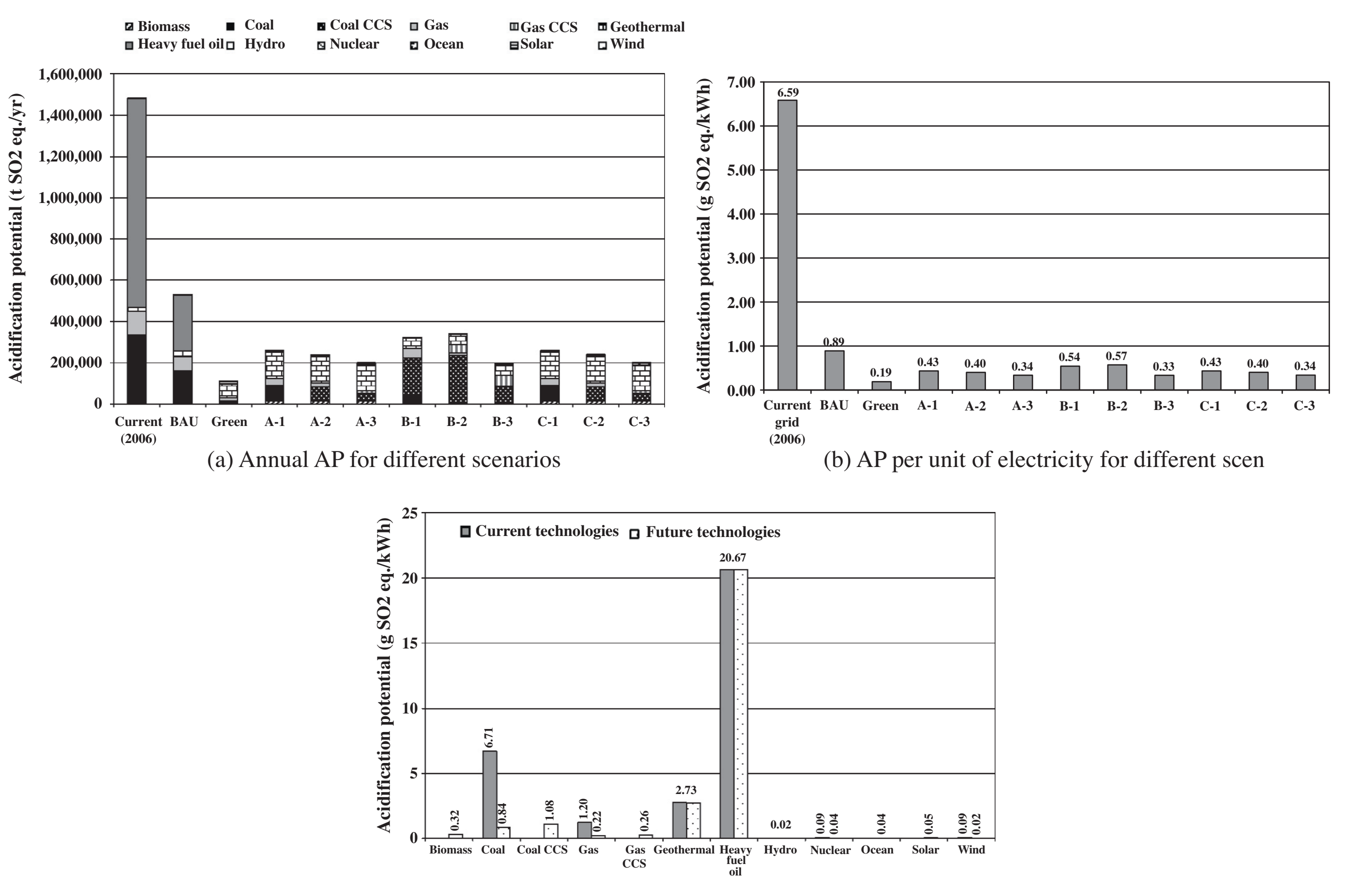
The life cycle inventory data have been sourced from the Gemis [45], Ecoinvent [39,40] and NEEDS [38] databases as well as from own original research.

4. Results and discussion

The life cycle environmental impacts for the different scenarios are presented in Figs. 2–11. Each impact is discussed in turn below, comparing the scenarios on the basis of the total electricity generation in 2050 as well as per kWh of electricity produced. The impacts from each electricity technology are also discussed. The results are considered in the context of the current electricity system. Further details on the results can be found in the Appendix.

4.1. Global warming potential (GWP)

Direct GHG emissions for different scenarios are presented in Table 8 demonstrating that the GHG targets are met as specified in Table 1. The results for the life cycle GHG emissions are given in Fig. 2a, indicating that the GWP for the BAU scenario doubles from the current 129 Mt CO_2 eq./yr [30] to 259 Mt in 2050. This is due to the high contribution from fossil fuels to the electricity



(a) Annual AP for different scenarios

(b) AP per unit of electricity for different scen

(c) AP of different electricity technologies

Fig. 4. Acidification potential (AP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

mix, mainly coal and gas, together providing 85% of generation. By comparison, if the electricity demand continued at the current rate (2.8% annually) to reach 814,000 GWh/yr in 2050 and the performance of the technologies remained the same as today, the total GWP would increase threefold.

Conversely, the scenarios with the highest contribution from renewables (and 85% GHG reduction target) have the lowest GWP. Scenarios C-3 and A-3 are the best with GWP values of 27.3 and 27.7 Mt CO_2 eq./yr, respectively. In both scenarios, the GHG emissions are split evenly between biomass, coal CCS, gas and gas CCS, and geothermal (Fig. 2a). The next best scenario is B-3 with a GWP of 37.3 Mt CO_2 eq./yr, mainly from coal and gas CCS, contributing 33% and 52% to GWP, respectively.

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. This is mainly due to direct emissions from coal and gas power plants as this scenario does not include CCS. For comparison, Greenpeace and EREC [18] estimated the direct CO_2 emissions (i.e. excluding other life cycle stages) from the same scenario at 31 Mt. If only direct emissions are included in this work, the result is 32.68 Mt CO_2 eq., which suggests good agreement between the studies given that the latter also includes GHGs other than CO_2.

Scenarios A-2, C-2 and B-2 (60% GHG reduction) emit between 59 and 75 Mt of CO_2 eq./yr, respectively, mainly owing to the emissions in the fuel supply chains for gas (with and without CCS) and coal (with CCS). The scenarios assuming stabilisation of GHG emissions (A-1, B-1, and C-1) have higher GWPs: between 129 and 139 Mt of CO_2 eq./yr. However, these are still considerably lower than the BAU scenario. Again, the main GHG sources are coal (with and without CCS), which contributes 42–48%, and gas, which contributes 44–54% of the total GWP.

It can also be noticed that the carbon intensity of the grid per kWh of electricity generated would be reduced in all the scenarios compared to the current grid, including BAU (Fig. 2b). However, with 434 g CO_2 eq./kWh, BAU is still much worse than the other scenarios. A-3 and C-3 remain the best options with 12 times lower GWP than the present grid, reducing the carbon intensity from today's 571 to just 46 g CO_2 eq./kWh.

Finally, Fig. 2c compares the GWP of future electricity technologies to those used currently. Owing to the assumed improvement in the efficiencies and capacity factors (see Table 7), GWP from coal is reduced by 60% and from gas by 30%. New wind and nuclear technologies improve most, reducing their respective GWP by 7.5 and 2.8 times. Coal and gas CCS have around four times lower GWP than the respective technologies without CCS.

4.2. Abiotic depletion potential (ADP)

This impact accounts for the depletion of both fossil fuels and elements, expressed relative to the annual depletion of the world's antimony (Sb) reserves [44]. As expected, the BAU scenario has the highest ADP with 1.86 Mt Sb eq./yr; this is twice the current ADP (see Fig. 3a). This is again due to a high share of gas and coal in the electricity mix. On the other hand, the Green scenario, because of its high contribution from renewables, has the lowest ADP value of 0.298 Mt Sb eq./yr: three times lower than currently.

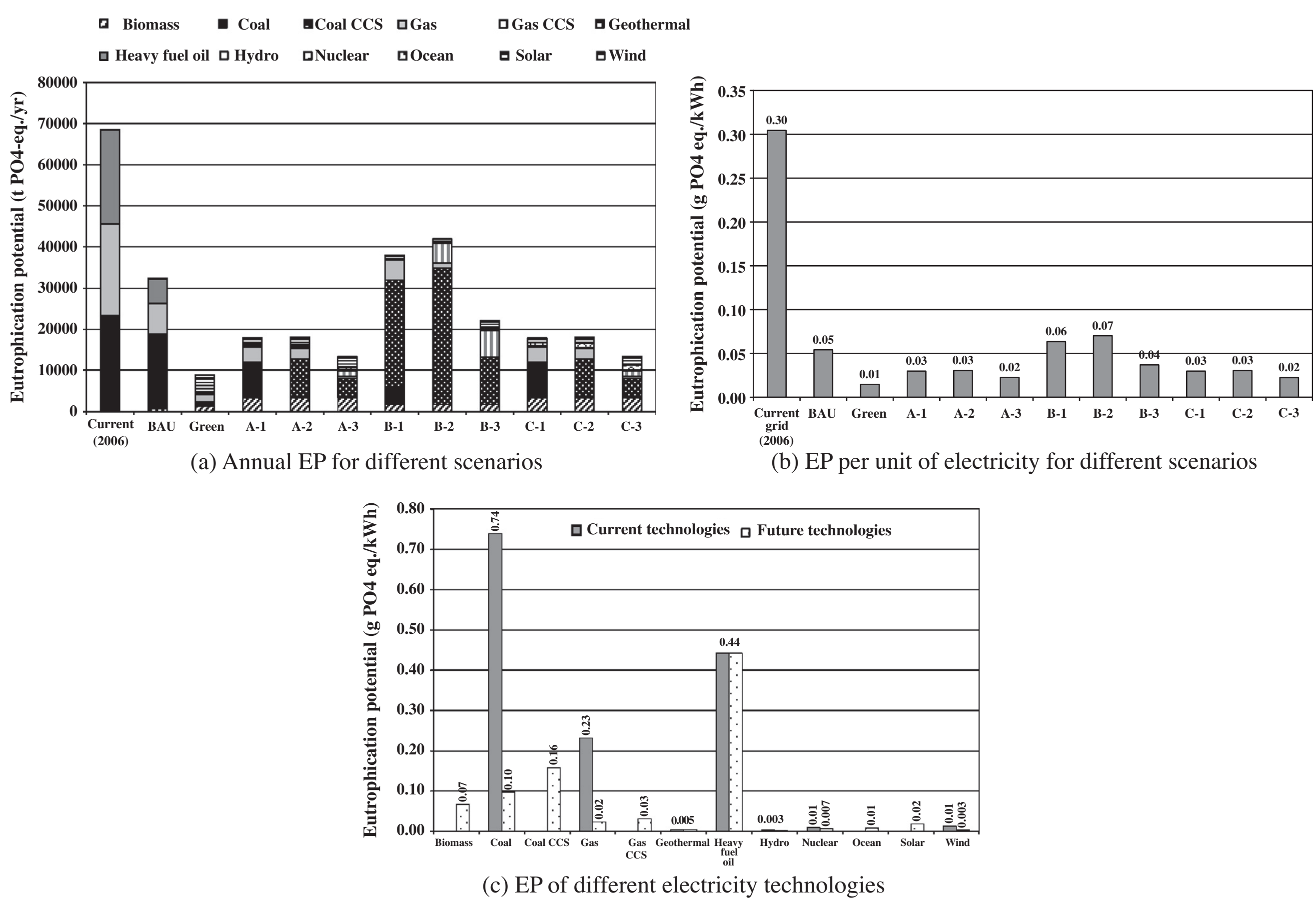


Fig. 5. Eutrophication potential (EP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

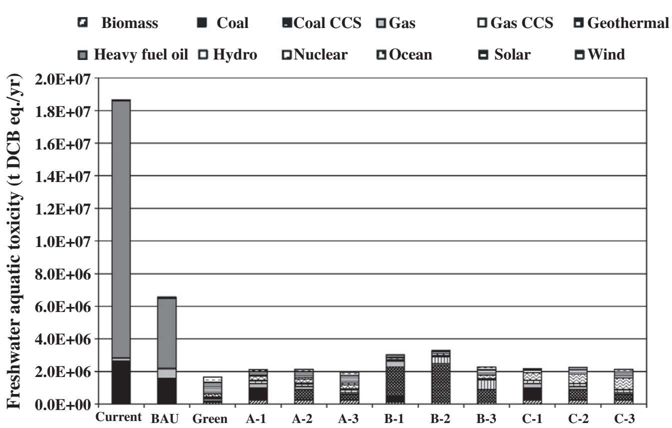
Fig. 3a also reveals that scenarios A and C have similar values owing to the similar share of fossil fuels (coal and gas), ranging from 0.373 to 1.75 Mt Sb eq./yr. A-3 and C-3 have the lowest ADP (0.377 and 0.373 Mt Sb eq./yr) while B-1 and B-2 have the highest (1.67 and 1.75 Mt Sb eq./yr); the latter is comparable to the BAU scenario. The main contributors to ADP in these scenarios are coal and gas with and without CCS. It is interesting to note that scenario B-2 has a higher ADP value than B-1, despite having the same share of fossil fuels (70%). This is mainly due to a greater use of CCS in B-2 and the related higher use of abiotic resources. The ADP from scenario B-3 is also heavily influenced by the use of coal and gas CCS, reaching an estimated 1.06 Mt Sb eq./yr, despite the considerably lower contribution of fossil fuels to the mix (47%). These results suggest that a trade off between reducing the GHG emissions and increasing the depletion of resources would be necessary.

A similar pattern can be observed per kWh of electricity generated in each scenario (Fig. 3b), except that the ADP of BAU is 36% lower than for the current grid owing to the improved efficiency of the power plants in 2050 relative to the present (see Table 7). The grid in the Green scenario has the lowest ADP per kWh, followed closely by A-3 and C-3. With respect to the electricity technologies, it is interesting to observe that coal and gas CCS have higher ADP than the respective technologies without CCS (Fig. 3c). This is due to the efficiency losses, leading to a higher consumption of resources per kWh of electricity. Therefore, while reducing GWP, these technologies increase the depletion of abiotic resources, including fossil fuels. Similar is true for all other impacts, as discussed further below.

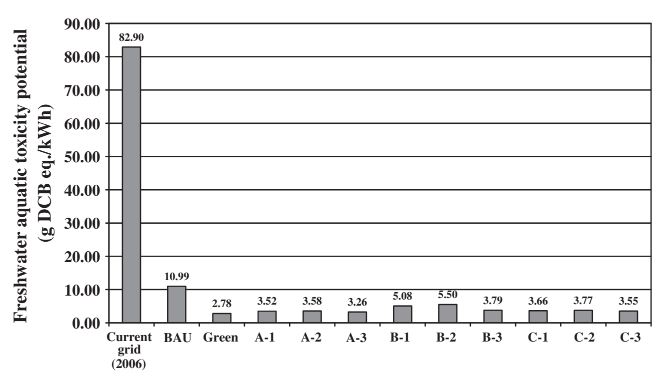
4.3. Acidification potential (AP)

The BAU scenario has the highest AP (531 kt SO_2 eq./yr), mainly owing to the SO_2 emissions from heavy fuel oil and coal (Fig. 4a). However, this is still 2.8 times lower than from the existing generation estimated at 1.48 Mt SO_2 eq./yr. With 113 kt SO_2 eq./yr, the Green scenario has the lowest AP of all the scenarios and five times lower than BAU. The AP from the Green scenario 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, emitting 200–202 kt SO_2 eq./yr. The remaining scenarios have APs between 240 and 340 kt SO_2 eq./yr. For the A and C sub-scenarios, AP is mainly due to geothermal energy and for B it is due to coal with CCS.

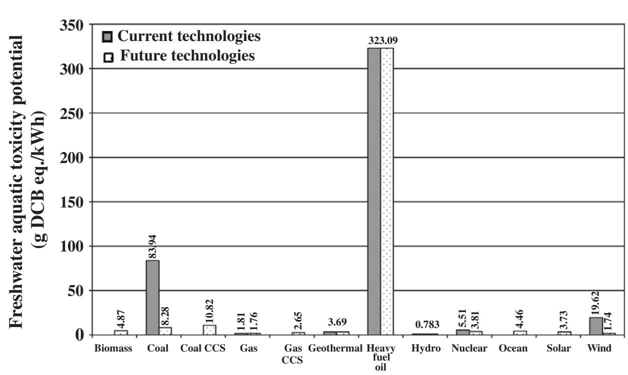
Similarly, if the technology mix in the Green scenario was deployed in the future, the AP per kWh generated would be reduced by 35 times compared to today's grid (Fig. 4b). If the other scenarios were realised instead, the reduction in AP per kWh would range from 7.5 times for BAU to 19.5 times for A-3 and C-3. This is partly due to the larger contribution of renewables but also because of technological improvements. The latter provide coal power plants with the greatest reduction compared to the present: a decrease of a factor of eight (Fig. 4c). However, the AP for coal CCS as well as gas CCS are higher than the options without



(a) Annual FAETP for different scenarios

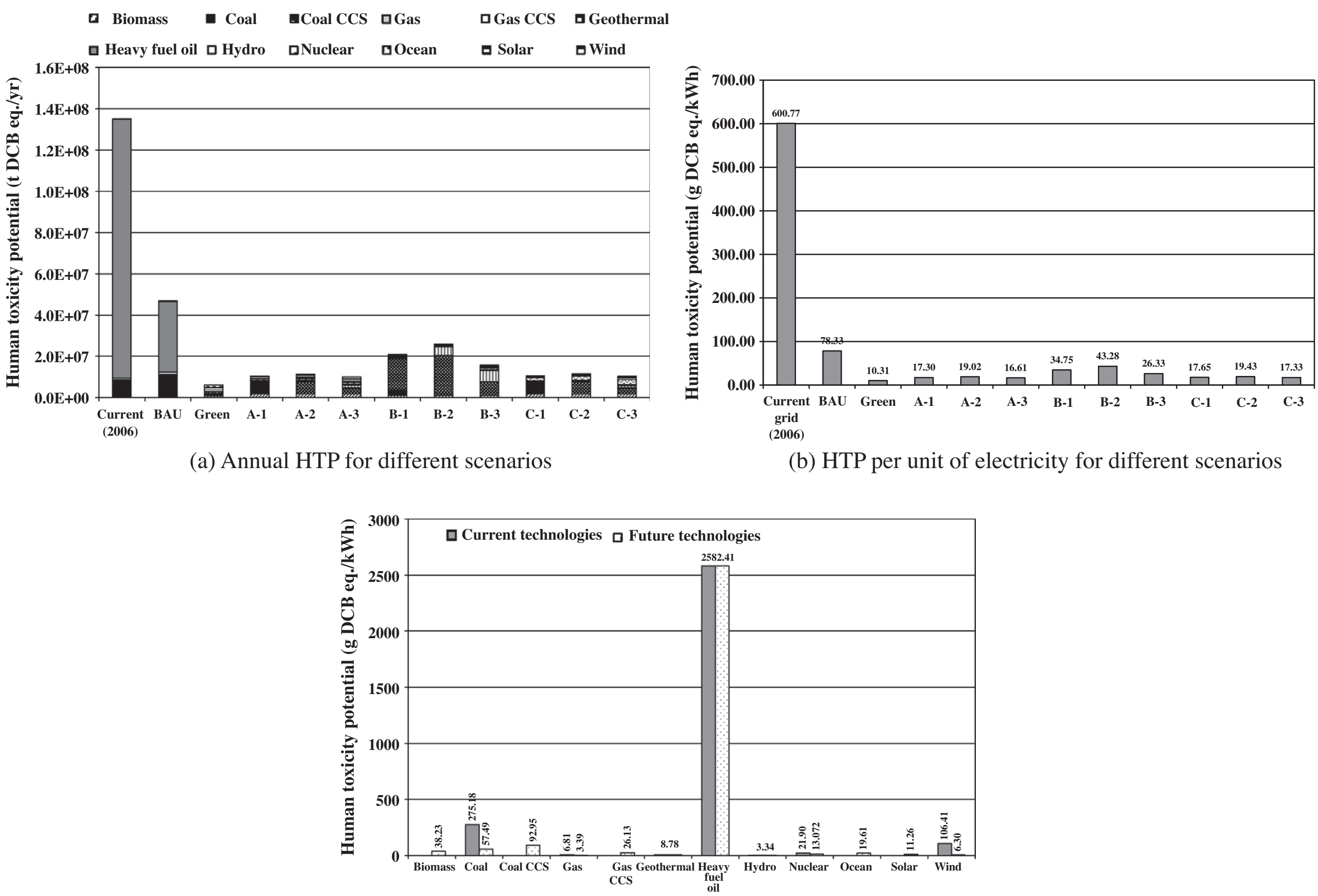


(b) FAETP per unit of electricity for different scenarios



(c) FAETP of different electricity technologies

Fig. 6. Freshwater aquatic ecotoxicity potential (FAETP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]



(a) Annual HTP for different scenarios

(b) HTP per unit of electricity for different scenarios

(c) HTP of different electricity technologies

Fig. 7. Human toxicity potential (HTP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

CCS. It can be noticed that the acidification potential of biomass is higher than that from gas, mainly owing to the impacts of agriculture.

4.4. Eutrophication potential (EP)

All the scenarios lead to a much lower EP than currently, with reductions of between 1.5 and 7.7 times. The highest values of 42 and 38 kt PO_4 eq./yr are found in scenarios B-2 and B-1 (see Fig. 5a). The reason for this is NOx and NH_3 emissions from coal with CCS in B-2 and B-1, which contributes 79% and 68% of the total EP, respectively. These outstrip the EP-related emissions from the BAU scenario (32 kt PO_4 eq./yr) despite the high contribution of fossil fuels in its mix. B-3, on the other hand, has a lower EP than the other B scenarios because of lower contribution of coal CCS to the total mix (12% compared to 27% and 35% in scenarios B-1 and B-2, respectively; see Table 2).

The lowest EP is found in the Green scenario – 8.8 kt PO_4 eq./yr – mainly related to emissions from the construction of infrastructure for solar power plants. The next best options are A-3 and C-3 with around 13 kt PO_4 eq./yr, caused mainly by emissions from coal CCS and biomass. A similar trend can be observed for the impact per kWh electricity generated in different scenarios (Fig. 5b).

With respect to the electricity technologies, as for AP, the best 'improver' is coal with a future EP 7.4 times lower than that of present-day coal power plants (Fig. 5c). Again, similar to AP, biomass is a worse option for this impact than gas.

4.5. Freshwater aquatic ecotoxicity potential (FAETP)

As shown in Fig. 6a, the BAU scenario has the highest FAETP emitting 6.57 Mt of dichlorobenzene (DCB) eq./yr, mainly owing to heavy metals from oil (contributing 65%) and coal power plants (24%). Nevertheless, this is still 2.8 times lower than the current impact. The Green scenario has the lowest FAETP, estimated at 1.66 Mt DCB eq./yr, or four times lower than BAU. Heavy metal emissions to water from the life cycle of solar energy are the main contributor to FAETP in the Green scenario (42%), followed by the wind (19%) and ocean energy (12%).

The second best option is A-3 with FAETP of 1.95 Mt DCB eq./yr, closely followed by A-1, A-2, B-3 and all C scenarios, emitting between 2.1 and 2.3 Mt DCB eq./yr. FAETP for scenarios B-1 and B-2 is higher, ranging between 3 and 3.3 Mt, mainly owing to the life cycle of coal power plants with CCS.

Consequently, replacing the current grid with any of the scenarios would lead to significant reductions per kWh electricity generated for this impact, ranging from a decrease of 7.9 times for the BAU scenario to 30 times for the Green electricity mix (Fig. 6b). The impact of the individual technologies also goes down significantly, particularly for coal (Fig. 6c).

4.6. Human toxicity potential (HTP)

The BAU scenario again has the highest impact, estimated at 46.8 Mt DCB eq./yr (Fig. 7a), mainly from the emissions of heavy metals to air from oil and coal power plants. However, this is still 2.9 times lower than the current impact of 135 Mt. 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 for the 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 and C, with HTP values ranging between 9.9 and 11.4 Mt DCB eq./yr. Finally, the values for the B scenarios are between 15.7 Mt (for B-3) and 25.9 Mt DCB eq./yr (B-2), predominantly from coal and gas CCS.

As indicated in Fig. 7b, the impact of the grid per kWh is reduced by at least 7.7 times (for BAU) and at best 58 times (for Green) compared to today's grid. The toxicity of future technologies also goes down with coal improving the most (4.8 times; see Fig. 7c). Like the AP and EP, the HTP for biomass is higher than for gas (by a factor of 10) owing to the use of fertilisers and pesticides.

4.7. Marine aquatic ecotoxicity potential (MAETP)

With nearly 85 Gt DCB eq./yr, the BAU scenario is also the worst option for this impact, mainly because of the contribution from coal and oil (Fig. 8a). However, this is still half the current impact. The values for B-1 and B-2 are close to the BAU scenario, estimated at 74 and 77 Gt DCB eq./yr, respectively, with coal CCS being the main source of MAETP. The Green scenario is again the best option with 5.9 Gt DCB eq./yr, largely owing to HF emissions from the operation of coal power plants. The next best options are A-3 and C-3 with around 13 Gt DCB eq./yr. All other A and C scenarios as well as B-3 also perform well in comparison with BAU, ranging from 25–30 Gt DCB eq./yr.

A similar pattern is replicated for MAETP per kWh of electricity (Fig. 8b), with the reductions compared to the current grid ranging from five to 70 times for B-2 and Green, respectively. Among the future technologies, the highest MAETP is from coal CCS (359 kg DCB eq./kWh), although this is five times lower than today's coal without CCS (1909 kg DCB eq./kWh) (Fig. 8c). By comparison, all other future technologies have low marine ecotoxicity, ranging from 8.8 kg DCB eq./kWh for biomass to 1.4 kg DCB eq./kWh for hydro power.

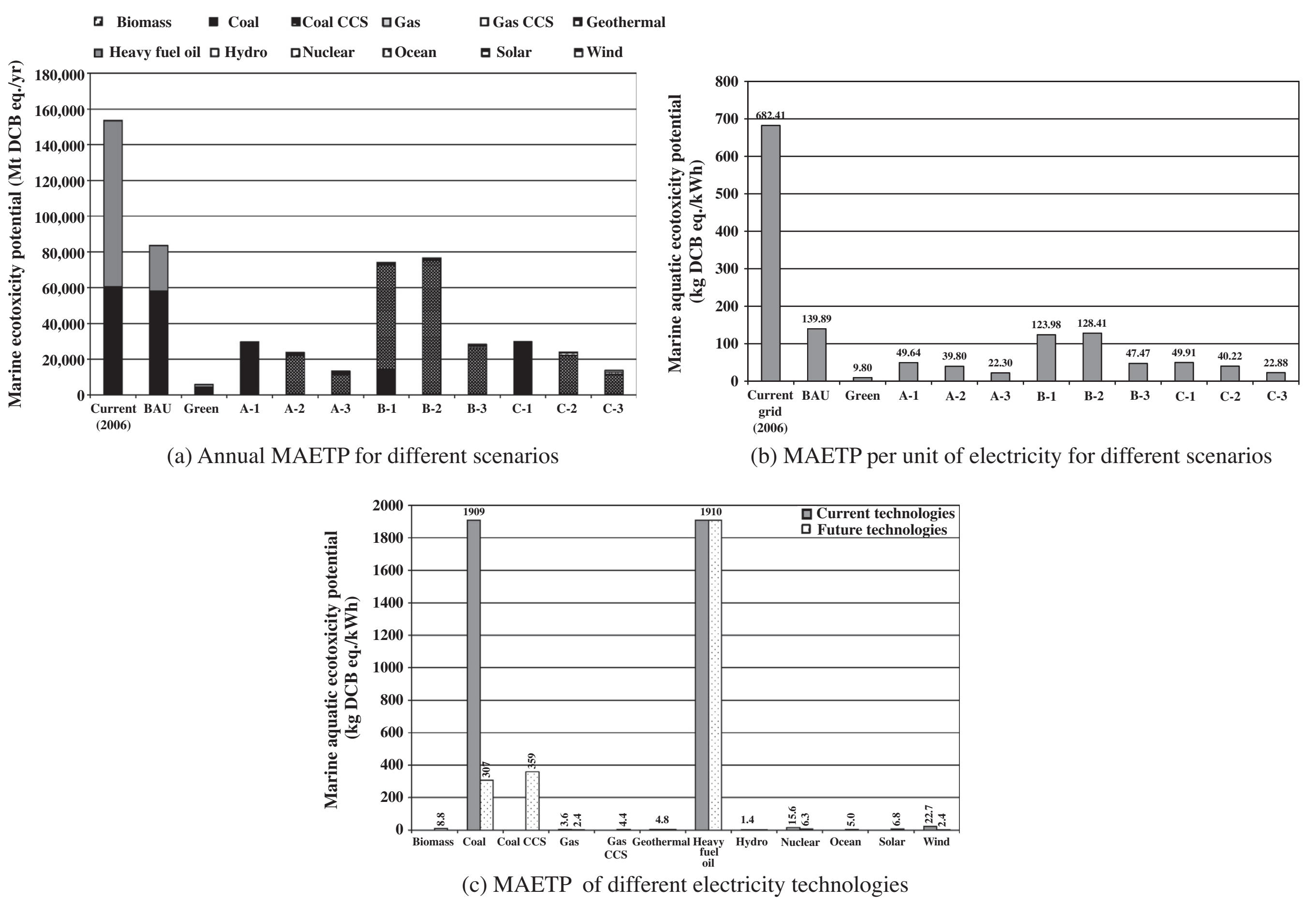
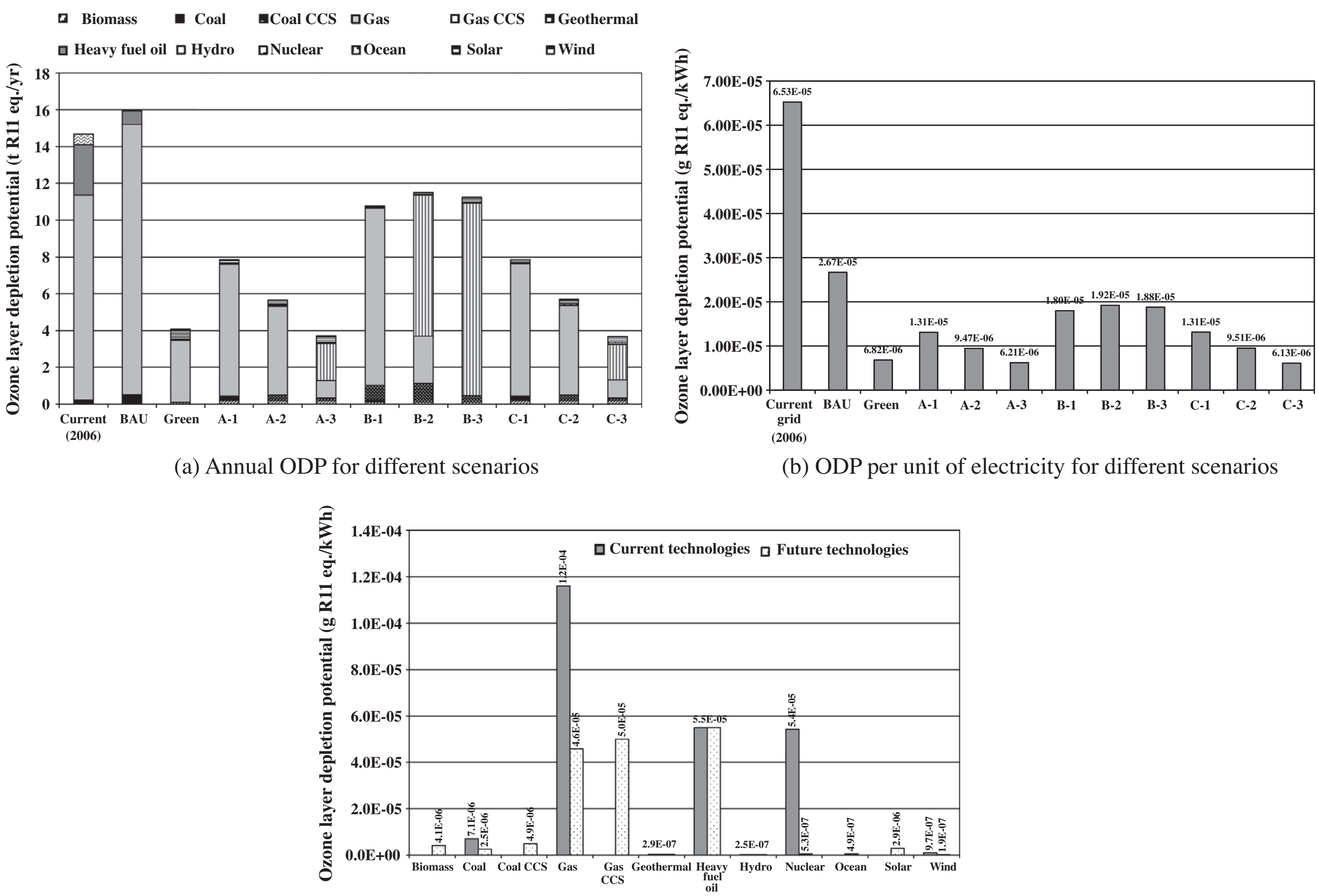


Fig. 8. Marine aquatic ecotoxicity (MAETP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]



(a) Annual ODP for different scenarios

(b) ODP per unit of electricity for different scenarios

(c) ODP of different electricity technologies

Fig. 9. Ozone layer depletion potential (ODP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

4.8. Ozone depletion potential (ODP)

In all the scenarios, the main contributor to the ODP is the leakage of halons that are used as fire retardants in the life cycle of natural gas (with and without CCS); therefore the scenarios with the most gas and gas CCS have the highest ODP. Scenarios C-3 and A-3 are the best options, each emitting 3.5 t trichlorofluoromethane (R11) eq./yr (Fig. 9a). This is 10 times lower than currently. The Green scenario follows closely with 4.1 t R11 eq./yr: slightly worse than C-3 and A-3 owing to its greater use of natural gas. This is in contrast with the BAU scenario which is the worst option with 16 t R11 eq./yr, or 40% higher than at present.

The values for the other A and C scenarios are between 6 and 8 t R11 eq./yr, again with the gas power plants being the primary source. The ODP for B scenarios ranges from 10.8 to 11.5 t R11 eq./yr, largely owing to the higher share of fossil fuels with and without CCS. Nevertheless, these values are still 28–33% lower than for the BAU scenario.

The picture is slightly different for this impact per kWh, whereby the BAU scenario is 2.4 times better than the current situation (Fig. 9b). The ODP for the other scenarios is between 3.4 and 10.5 times lower than for the current grid. Currently, in addition to gas, oil makes a significant contribution to the ODP. In the future, electricity generation from oil is expected to go down significantly (Fig. 9c).

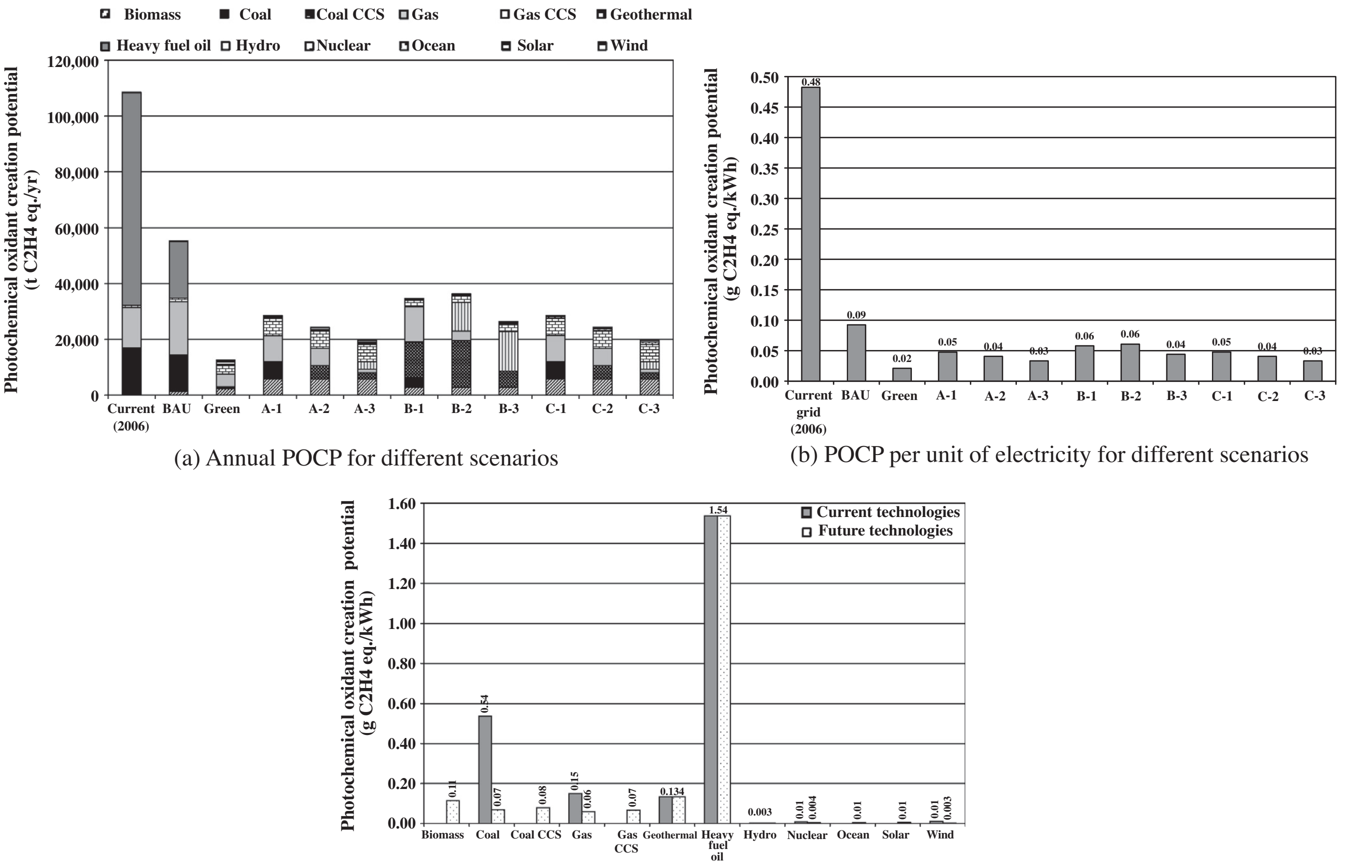
4.9. Photochemical ozone creation potential (POCP)

As for most other impacts, the BAU scenario has the highest POCP with approximately 55 kt C_2H_4 eq./yr, related to the emissions from combustion of fossil fuels (Fig. 10a). Nevertheless, this is still around a half of the current impact. The Green scenario is again the best option with 12.6 kt C_2H_4 eq./yr mainly owing to the operation of geothermal, gas, and biomass power plants. Scenarios A-3 and C-3 follow with around 20 kt C_2H_4 eq./yr. The major contributors here are biomass and geothermal power, collectively contributing around 50% to the total impact. The POCP values for the other options range from 24 (scenario C-2) to 36 kt C_2H_4 eq./yr (for B-2).

As indicated in Fig. 10b, the impact per kWh ranges from 0.02 for Green to 0.09 g C_2H_4 eq. for BAU, compared to the current value of 0.48 g C_2H_4 eq./kWh. Currently, by far the greatest POCP is from oil (1.54 g C_2H_4 eq./kWh), followed by coal (0.54 g C_2H_4 eq./kWh). The latter is expected to reduce in the future by about eight times and is comparable to gas CCS (Fig. 10c).

4.10. Terrestrial ecotoxicity potential (TETP)

At 1.5 million t DCB eq./yr, the BAU scenario is the worst option for TETP (Fig. 11a); 82% of this impact is due to the emissions of heavy metals from the operation of oil power plants. Compared



(c) POCP of different electricity technologies

Fig. 10. Photochemical ozone creation potential (POCP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

to the current situation, however, the impact is three times lower. The lowest TETP (175 kt DCB eq./yr) is that of the Green scenario; this is 8.5 times lower than BAU. The main contributors are heavy metals from the life cycle of solar PV (36%). The next best options are scenarios A-3 and C-3 with TETP values of 250 and 253 kt DCB eq./yr, respectively. The impact for the rest of the scenarios varies between 281 (scenario A-2) and 449 kt DCB eq./yr (scenario B-2).

Relative to the current grid, the future scenarios represent a reduction in TETP per kWh of between eight and 50 times (for BAU and A-3 and C-3, respectively) (Fig. 10b). Currently, power from oil has the highest impact (94.4 g DCB eq./kWh) owing to the emission of heavy metals (Fig. 10c). The TETP of future technologies is small by comparison, ranging from 0.12 g DCB eq./kWh for hydro to 1.55 g DCB eq./kWh for biomass.

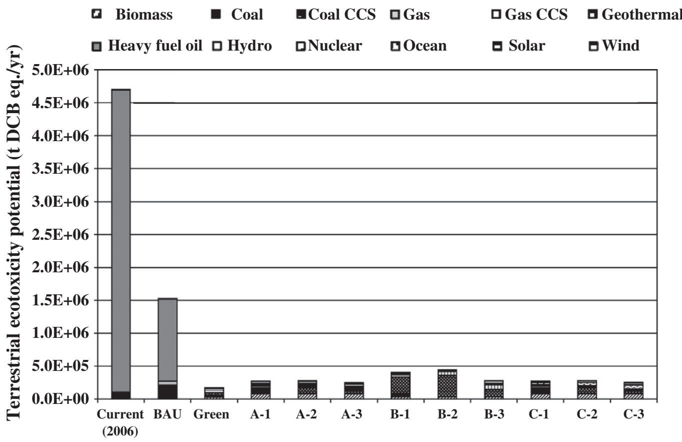
5. Conclusions

This study has demonstrated how scenario analysis can be combined with life cycle assessment to help improve environmental performance of electricity generation in the future. Eleven scenarios and ten environmental impacts have been considered, focusing on Mexico. The results show that assuming a slight reduction in electricity demand growth (from current 2.8% to 2.25%) and expected future technological improvements, a considerable reduction in environmental impacts could be achieved across all the scenarios compared to the current situation. The exception to this is global warming which is two times higher in the BAU scenario than at present. If on the other hand the current demand growth rate is maintained and no future technological improvements are assumed, the global warming impact of BAU would be three times higher than current levels. Given that decarbonisation of electricity is one of the main policy drivers, then arguably, continuing business as usual is not sustainable. This is exacerbated by the fact that resource and ozone layer depletion would also increase under BAU.

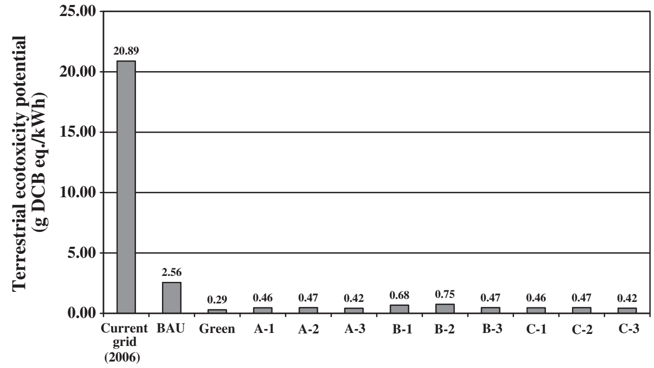
The Green, A-3 and C-3 scenarios are environmentally the most sustainable options for most impacts (ADP, EP, FAETP, HTP, MAETP, ODP, POCP and TETP), leading to an average reduction in annual impacts of 81% (Green) and 74% (A-3 and C-3), relative to BAU. This is mainly due to the high contribution of renewable energies and nuclear power. The lowest average reduction of impacts (32%) is found in the B-2 scenario, although eutrophication potential is an exception with a value 30% higher than for BAU. The reason for this is mainly the use of gas and coal CCS.

The highest reduction in GWP (89%) is achieved in scenarios A-3 and C-3, followed by Green (84%). Therefore, if mitigation of climate change is the only priority, A-3 and C-3 would be the most environmentally sustainable options. However, the Green scenario is a better option for all other impacts except for ODP, where A-3 and C-3 are slightly better. Overall, the difference in the environmental impacts between these three scenarios is relatively small: within the uncertainties of the estimates they could be considered broadly indistinguishable in terms of environmental sustainability.

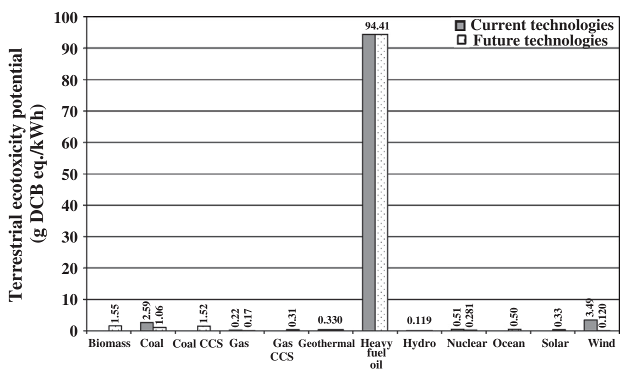
However, it should be noted that the Green scenario is hugely optimistic in its assumptions, particularly with respect to the renewable energy potential of Mexico. In some cases the estimated potential is exceeded by up to 75% (e.g. for wind). On the other



(a) Annual TETP for different scenarios



(b) TETP per unit ofelectricity for different scenarios



(c) TETP of different electricity technologies

Fig. 11. Terrestrial ecotoxicity potential (TETP). [Current situation (2006) shown for comparison (*Source:* [24]). Electricity generation in the scenarios: 598,000 GWh/yr; Current (2006) electricity generation: 225,079 GWh/yr. Owing to the lack of data for future development of geothermal, heavy fuel oil and hydro power, their impact is assumed to be equal to the current technologies.]

Table 8
Direct emissions of GHG estimated in this work for different scenarios.

Scenario	Direct GHG emissions in 2050 (Mt CO_2 eq./yr)[a]	Relative difference compared to 2000 levels[b] (%)
BAU	228.07	206
Green	32.68[c]	−70[d]
A-1	110.69	0
A-2	44.27	−60
A-3	16.60	−85
B-1	110.69	0
B-2	44.27	−60
B-3	16.60	−85
C-1	110.70	0
C-2	44.26	−60
C-3	16.60	−85

[a] The GHG considered are carbon dioxide, methane and nitrous oxide.
[b] These figures correspond to the GHG emission reduction targets specified in Table 1. Direct GHG emissions in 2000 reported as 110.7 Mt CO_2 eq./yr [2].
[c] The value estimated by Greenpeace and EREC [18] is equal to 31 Mt CO_2 (CO_2 only, no other GHG).
[d] The original CO_2 reduction target considered by Greenpeace and EREC [18] was 72% on the 2005 levels, using the CO_2 emissions in 2005 of 112 Mt CO_2. In this work, the base year for the reduction target is changed to 2000 and the GHG emissions are considered rather than CO_2 only. For that reason, the reduction target is changed to 70%.

hand, scenarios A-3 and C-3 are founded on much more realistic assumptions and could provide a feasible basis for future electricity planning. Therefore, based purely on the environmental considerations, the government should consider policy measures that would stimulate the electricity demand and supply conditions congruent with scenarios A-3 and C-3, i.e. diversification of supply to include greater contribution from renewables and nuclear power, coupled with a general aim to limit growth in demand. This would not only contribute towards meeting the 2050 target of 50% reduction in CO_2 emissions from the whole economy (via an 85% reduction in electricity emissions) but would also help to decarbonise the electricity sector.

The findings of this work indicate that per kWh of electricity generated, the electricity mixes assumed in all the scenarios are better than at present, including BAU. This implies that reducing growth rates in electricity demand would lead to a reduction in environmental impacts regardless of the electricity mix and could be achieved in a shorter time than changing the electricity mix. However, under the BAU scenario, a severe reduction in demand growth would be needed – requiring annual growth of less than 1% – just to maintain carbon emissions at their current level. This would probably be socially and politically infeasible. Therefore, diversifying future electricity supply by including more renewables and nuclear power will be necessary if climate change as well as the security of supply remain the main drivers for the country. Coal and gas CCS could also play a role although, as shown in this work, while carbon emissions would be reduced, all other impacts would be increased compared to the same technologies without CCS. Therefore, the future role of CCS should be examined carefully.

In summary, the results of this work show that switching from the current fossil fuel mix to a higher contribution of renewables (55–86%) and nuclear power (up to 30%) would lead to a considerable reduction in environmental impacts compared to the current situation and a reduction of up to 80% compared to BAU.

However, the feasibility of the scenarios considered here will also depend on various techno-economic and social factors – notably cost and public acceptance. For instance, it is likely that the most renewables-intensive scenarios, such as Green, will require some form of subsidy which may affect the overall cost of electricity to consumers. It is also likely that some of the technologies will meet public opposition, including renewable and nuclear power. Furthermore, it is important to examine the technical implications of matching supply and demand in renewables-intensive electricity mixes such as the Green scenario. The consideration of these aspects was beyond the scope of this paper but is the subject of a forthcoming publication by the authors.

Acknowledgements

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Appendix

See Tables A.1–A.10.

Table A.1
Global warming potential (GWP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
GWP (t CO_2 eq./yr)											
Biomass	5.81E+05	1.05E+06	2.64E+06	2.64E+06	2.64E+06	1.32E+06	1.32E+06	1.32E+06	2.64E+06	2.64E+06	2.64E+06
Coal	1.29E+08	7.60E+06	6.19E+07	0.00E+00	0.00E+00	3.14E+07	0.00E+00	0.00E+00	6.19E+07	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	1.01E+07	5.06E+06	2.77E+07	3.54E+07	1.22E+07	0.00E+00	1.01E+07	5.06E+06
Gas	1.15E+08	2.63E+07	5.63E+07	3.79E+07	7.20E+06	7.56E+07	2.02E+07	0.00E+00	5.65E+07	3.82E+07	7.59E+06
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.74E+06	0.00E+00	1.43E+07	1.95E+07	0.00E+00	0.00E+00	3.60E+06
Geothermal	1.25E+06	3.13E+06	6.00E+06	6.00E+06	6.00E+06	2.40E+06	2.40E+06	2.40E+06	6.00E+06	6.00E+06	6.00E+06
Heavy fuel oil	1.27E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	3.04E+05	5.42E+05	6.21E+05	7.93E+05	9.65E+05	3.64E+05	3.64E+05	3.64E+05	3.64E+05	3.64E+05	3.64E+05
Nuclear	3.43E+04	0.00E+00	2.54E+05	2.54E+05	2.54E+05	1.27E+05	1.27E+05	2.54E+05	5.08E+05	6.35E+05	7.62E+05
Ocean	0.00E+00	3.48E+05	1.21E+05	2.42E+05	2.42E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	6.74E+04	2.16E+06	6.98E+05	9.93E+05	1.34E+06	3.93E+05	3.94E+05	1.01E+06	5.66E+05	8.58E+05	1.12E+06
Wind	4.08E+04	4.49E+05	1.47E+05	2.08E+05	2.81E+05	8.24E+04	8.29E+04	2.12E+05	1.19E+05	1.80E+05	2.36E+05
Total	2.59E+08	4.16E+07	1.29E+08	5.91E+07	2.77E+07	1.39E+08	7.46E+07	3.73E+07	1.29E+08	5.90E+07	2.74E+07

Table A.2
Abiotic depletion potential (ADP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
ADP (t DCB eq./yr)											
Biomass	2.61E+03	4.73E+03	1.19E+04	1.19E+04	1.19E+04	5.92E+03	5.92E+03	5.92E+03	1.19E+04	1.19E+04	1.19E+04
Coal	8.40E+05	4.95E+04	4.04E+05	0.00E+00	0.00E+00	2.05E+05	0.00E+00	0.00E+00	4.04E+05	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	3.10E+05	1.55E+05	8.50E+05	1.09E+06	3.75E+05	0.00E+00	3.10E+05	1.55E+05
Gas	9.20E+05	2.10E+05	4.49E+05	3.02E+05	5.74E+04	6.02E+05	1.61E+05	0.00E+00	4.50E+05	3.04E+05	6.05E+04
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.27E+05	0.00E+00	4.85E+05	6.62E+05	0.00E+00	0.00E+00	1.22E+05
Geothermal	4.14E+02	1.04E+03	1.99E+03	1.99E+03	1.99E+03	7.93E+02	7.93E+02	7.93E+02	1.99E+03	1.99E+03	1.99E+03
Heavy fuel oil	9.10E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	5.10E+02	1.00E+03	1.13E+03	1.42E+03	1.71E+03	7.02E+02	7.02E+02	7.02E+02	7.02E+02	7.02E+02	7.02E+02
Nuclear	2.56E+02	0.00E+00	1.90E+03	1.90E+03	1.90E+03	9.49E+02	9.49E+02	1.90E+03	3.80E+03	4.75E+03	5.70E+03
Ocean	0.00E+00	2.11E+03	7.34E+02	1.47E+03	1.47E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	7.88E+02	2.53E+04	8.17E+03	1.16E+04	1.56E+04	4.59E+03	4.61E+03	1.18E+04	6.62E+03	1.00E+04	1.31E+04
Wind	4.57E+02	5.02E+03	1.64E+03	2.33E+03	3.14E+03	9.22E+02	9.26E+02	2.37E+03	1.33E+03	2.01E+03	2.64E+03
Total	1.86E+06	2.99E+05	8.80E+05	6.45E+05	3.77E+05	1.67E+06	1.75E+06	1.06E+06	8.81E+05	6.46E+05	3.74E+05

Table A.3
Acidification potential (AP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
AP (t SO_2 eq./yr)											
Biomass	3.52E+03	6.39E+03	1.60E+04	1.60E+04	1.60E+04	7.99E+03	7.99E+03	7.99E+03	1.60E+04	1.60E+04	1.60E+04
Coal	1.56E+05	9.21E+03	7.51E+04	0.00E+00	0.00E+00	3.80E+04	0.00E+00	0.00E+00	7.51E+04	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	6.48E+04	3.24E+04	1.78E+05	2.27E+05	7.83E+04	0.00E+00	6.48E+04	3.24E+04
Gas	7.08E+04	1.61E+04	3.45E+04	2.32E+04	4.42E+03	4.63E+04	1.24E+04	0.00E+00	3.47E+04	2.34E+04	4.65E+03
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.05E+04	0.00E+00	4.01E+04	5.47E+04	0.00E+00	0.00E+00	1.01E+04
Geothermal	2.61E+04	6.54E+04	1.25E+05	1.25E+05	1.25E+05	5.00E+04	5.00E+04	5.00E+04	1.25E+05	1.25E+05	1.25E+05
Heavy fuel oil	2.73E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	4.07E+02	8.04E+02	9.09E+02	1.14E+03	1.37E+03	5.66E+02	5.66E+02	5.66E+02	5.66E+02	5.66E+02	5.66E+02
Nuclear	2.97E+02	0.00E+00	2.20E+03	2.20E+03	2.20E+03	1.10E+03	1.10E+03	2.20E+03	4.40E+03	5.50E+03	6.60E+03
Ocean	0.00E+00	1.65E+03	5.73E+02	1.15E+03	1.15E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	2.95E+02	9.47E+03	3.06E+03	4.35E+03	5.86E+03	1.72E+03	1.73E+03	4.43E+03	2.48E+03	3.76E+03	4.92E+03
Wind	3.53E+02	3.88E+03	1.27E+03	1.80E+03	2.43E+03	7.13E+02	7.16E+02	1.83E+03	1.03E+03	1.56E+03	2.04E+03
Total	5.31E+05	1.13E+05	2.59E+05	2.40E+05	2.01E+05	3.24E+05	3.42E+05	2.00E+05	2.59E+05	2.41E+05	2.02E+05

Table A.4
Eutrophication potential (EP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
EP (t PO_4 eq./yr)											
Biomass	7.38E+02	1.34E+03	3.36E+03	3.36E+03	3.36E+03	1.68E+03	1.68E+03	1.68E+03	3.36E+03	3.36E+03	3.36E+03
Coal	1.81E+04	1.07E+03	8.70E+03	0.00E+00	0.00E+00	4.41E+03	0.00E+00	0.00E+00	8.70E+03	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	9.46E+03	4.73E+03	2.59E+04	3.31E+04	1.14E+04	0.00E+00	9.46E+03	4.73E+03
Gas	7.41E+03	1.69E+03	3.62E+03	2.43E+03	4.62E+02	4.85E+03	1.30E+03	0.00E+00	3.63E+03	2.45E+03	4.87E+02
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.25E+03	0.00E+00	4.79E+03	6.54E+03	0.00E+00	0.00E+00	1.21E+03
Geothermal	4.60E+01	1.15E+02	2.20E+02	2.20E+02	2.20E+02	8.80E+01	8.80E+01	8.80E+01	2.20E+02	2.20E+02	2.20E+02
Heavy fuel oil	5.85E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	6.60E+01	1.33E+02	1.50E+02	1.87E+02	2.24E+02	9.40E+01	9.40E+01	9.40E+01	9.40E+01	9.40E+01	9.40E+01
Nuclear	5.30E+01	0.00E+00	3.90E+02	3.90E+02	3.90E+02	1.95E+02	1.95E+02	3.90E+02	7.80E+02	9.75E+02	1.17E+03
Ocean	0.00E+00	3.64E+02	1.26E+02	2.53E+02	2.53E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	1.08E+02	3.45E+03	1.12E+03	1.59E+03	2.14E+03	6.27E+02	6.30E+02	1.61E+03	9.04E+02	1.37E+03	1.80E+03
Wind	5.90E+01	6.44E+02	2.11E+02	2.99E+02	4.03E+02	1.18E+02	1.19E+02	3.05E+02	1.71E+02	2.59E+02	3.39E+02
Total	3.24E+04	8.81E+03	1.79E+04	1.82E+04	1.34E+04	3.80E+04	4.20E+04	2.21E+04	1.79E+04	1.82E+04	1.34E+04

Table A.5
Freshwater aquatic ecotoxicity potential (FAETP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
FAETP (t DCB eq./yr)											
Biomass	5.36E+04	9.73E+04	2.44E+05	2.44E+05	2.44E+05	1.22E+05	1.22E+05	1.22E+05	2.44E+05	2.44E+05	2.44E+05
Coal	1.54E+06	9.11E+04	7.43E+05	0.00E+00	0.00E+00	3.76E+05	0.00E+00	0.00E+00	7.43E+05	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	6.47E+05	3.24E+05	1.77E+06	2.26E+06	7.82E+05	0.00E+00	6.47E+05	3.24E+05
Gas	5.64E+05	1.29E+05	2.75E+05	1.85E+05	3.52E+04	3.69E+05	9.86E+04	0.00E+00	2.76E+05	1.86E+05	3.71E+04
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E+05	0.00E+00	4.07E+05	5.56E+05	0.00E+00	0.00E+00	1.03E+05
Geothermal	3.53E+04	8.85E+04	1.70E+05	1.70E+05	1.70E+05	6.78E+04	6.78E+04	6.78E+04	1.70E+05	1.70E+05	1.70E+05
Heavy fuel oil	4.27E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	2.15E+04	4.16E+04	4.71E+04	5.93E+04	7.14E+04	2.91E+04	2.91E+04	2.91E+04	2.91E+04	2.91E+04	2.91E+04
Nuclear	3.08E+04	0.00E+00	2.28E+05	2.28E+05	2.28E+05	1.14E+05	1.14E+05	2.28E+05	4.56E+05	5.70E+05	6.84E+05
Ocean	0.00E+00	1.92E+05	6.66E+04	1.33E+05	1.33E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	2.19E+04	7.02E+05	2.27E+05	3.22E+05	4.34E+05	1.27E+05	1.28E+05	3.28E+05	1.84E+05	2.78E+05	3.65E+05
Wind	2.94E+04	3.24E+05	1.06E+05	1.50E+05	2.02E+05	5.94E+04	5.97E+04	1.53E+05	8.56E+04	1.30E+05	1.70E+05
Total	6.57E+06	1.66E+06	2.11E+06	2.14E+06	1.95E+06	3.04E+06	3.29E+06	2.26E+06	2.19E+06	2.25E+06	2.12E+06

Table A.6
Human toxicity potential (HTP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
HTP (t DCB eq./yr)											
Biomass	4.21E+05	7.64E+05	1.91E+06	1.91E+06	1.91E+06	9.56E+05	9.56E+05	9.56E+05	1.91E+06	1.91E+06	1.91E+06
Coal	1.07E+07	6.33E+05	5.16E+06	0.00E+00	0.00E+00	2.61E+06	0.00E+00	0.00E+00	5.16E+06	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	5.56E+06	2.78E+06	1.52E+07	1.95E+07	6.71E+06	0.00E+00	5.56E+06	2.78E+06
Gas	1.09E+06	2.47E+05	5.29E+05	3.56E+05	6.77E+04	7.10E+05	1.90E+05	0.00E+00	5.31E+05	3.59E+05	7.13E+04
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.05E+06	0.00E+00	4.01E+06	5.47E+06	0.00E+00	0.00E+00	1.01E+06
Geothermal	8.40E+04	2.11E+05	4.03E+05	4.03E+05	4.03E+05	1.61E+05	1.61E+05	1.61E+05	4.03E+05	4.03E+05	4.03E+05
Heavy fuel oil	3.41E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	9.47E+04	1.78E+05	2.02E+05	2.56E+05	3.09E+05	1.22E+05	1.22E+05	1.22E+05	1.22E+05	1.22E+05	1.22E+05
Nuclear	1.06E+05	0.00E+00	7.82E+05	7.82E+05	7.82E+05	3.91E+05	3.91E+05	7.82E+05	1.56E+06	1.95E+06	2.35E+06
Ocean	0.00E+00	8.43E+05	2.93E+05	5.86E+05	5.86E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	6.60E+04	2.12E+06	6.84E+05	9.72E+05	1.31E+06	3.84E+05	3.86E+05	9.89E+05	5.54E+05	8.40E+05	1.10E+06
Wind	1.07E+05	1.17E+06	3.83E+05	5.44E+05	7.33E+05	2.15E+05	2.16E+05	5.54E+05	3.10E+05	4.70E+05	6.16E+05
Total	4.68E+07	6.16E+06	1.03E+07	1.14E+07	9.93E+06	2.08E+07	2.59E+07	1.57E+07	1.06E+07	1.16E+07	1.04E+07

Table A.7
Marine aquatic ecotoxicity potential (MAETP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
MAETP (Mt DCB eq./yr)											
Biomass	9.70E+01	1.75E+02	4.39E+02	4.39E+02	4.39E+02	2.19E+02	2.19E+02	2.19E+02	4.39E+02	4.39E+02	4.39E+02
Coal	5.73E+04	3.38E+03	2.76E+04	0.00E+00	0.00E+00	1.40E+04	0.00E+00	0.00E+00	2.76E+04	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	2.15E+04	1.07E+04	5.88E+04	7.51E+04	2.59E+04	0.00E+00	2.15E+04	1.07E+04
Gas	7.80E+02	1.78E+02	3.81E+02	2.56E+02	4.90E+01	5.11E+02	1.36E+02	0.00E+00	3.82E+02	2.58E+02	5.10E+01
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.76E+02	0.00E+00	6.73E+02	9.18E+02	0.00E+00	0.00E+00	1.69E+02
Geothermal	4.60E+01	1.16E+02	2.22E+02	2.22E+02	2.22E+02	8.90E+01	8.90E+01	8.90E+01	2.22E+02	2.22E+02	2.22E+02
Heavy fuel oil	2.53E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	3.80E+01	7.20E+01	8.20E+01	1.04E+02	1.25E+02	5.00E+01	5.00E+01	5.00E+01	5.00E+01	5.00E+01	5.00E+01
Nuclear	5.00E+01	0.00E+00	3.74E+02	3.74E+02	3.74E+02	1.87E+02	1.87E+02	3.74E+02	7.48E+02	9.35E+02	1.12E+03
Ocean	0.00E+00	2.17E+02	7.50E+01	1.51E+02	1.51E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	4.00E+01	1.27E+03	4.10E+02	5.83E+02	7.85E+02	2.31E+02	2.31E+02	5.93E+02	3.32E+02	5.04E+02	6.60E+02
Wind	4.10E+01	4.52E+02	1.48E+02	2.10E+02	2.82E+02	8.30E+01	8.30E+01	2.13E+02	1.20E+02	1.81E+02	2.37E+02
Total	8.37E+04	5.86E+03	2.97E+04	2.38E+04	1.33E+04	7.41E+04	7.68E+04	2.84E+04	2.98E+04	2.41E+04	1.37E+04

Table A.8
Ozone layer depletion potential (ODP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
ODP (t R11 eq./yr)											
Biomass	5.00E−02	8.00E−02	2.10E−01	2.10E−01	2.10E−01	1.00E−01	1.00E−01	1.00E−01	2.10E−01	2.10E−01	2.10E−01
Coal	4.60E−01	3.00E−02	2.20E−01	0.00E+00	0.00E+00	1.10E−01	0.00E+00	0.00E+00	2.20E−01	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	2.90E−01	1.50E−01	8.00E−01	1.02E+00	3.50E−01	0.00E+00	2.90E−01	1.50E−01
Gas	1.47E+01	3.35E+00	7.17E+00	4.82E+00	9.20E−01	9.62E+00	2.57E+00	0.00E+00	7.19E+00	4.86E+00	9.70E−01
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.01E+00	0.00E+00	7.67E+00	1.05E+01	0.00E+00	0.00E+00	1.93E+00
Geothermal	0.00E+00	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02
Heavy fuel oil	7.30E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	1.00E−02	1.00E−02	1.00E−02	2.00E−02	2.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02	1.00E−02
Nuclear	0.00E+00	0.00E+00	3.00E−02	3.00E−02	3.00E−02	2.00E−02	2.00E−02	3.00E−02	6.00E−02	8.00E−02	9.00E−02
Ocean	0.00E+00	2.00E−02	1.00E−02	1.00E−02	1.00E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	2.00E−02	5.50E−01	1.80E−01	2.50E−01	3.40E−01	1.00E−01	1.00E−01	2.50E−01	1.40E−01	2.20E−01	2.80E−01
Wind	0.00E+00	3.00E−02	1.00E−02	2.00E−02	2.00E−02	1.00E−02	1.00E−02	2.00E−02	1.00E−02	1.00E−02	2.00E−02
Total	1.60E+01	4.08E+00	7.85E+00	5.66E+00	3.72E+00	1.08E+01	1.15E+01	1.12E+01	7.86E+00	5.69E+00	3.67E+00

Table A.9
Photochemical oxidant creation potential (POCP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
POCP (t Ethene eq./yr)											
Biomass	1.26E+03	2.29E+03	5.74E+03	5.74E+03	5.74E+03	2.87E+03	2.87E+03	2.87E+03	5.74E+03	5.74E+03	5.74E+03
Coal	1.31E+04	7.71E+02	6.28E+03	0.00E+00	0.00E+00	3.18E+03	0.00E+00	0.00E+00	6.28E+03	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	4.78E+03	2.39E+03	1.31E+04	1.67E+04	5.78E+03	0.00E+00	4.78E+03	2.39E+03
Gas	1.91E+04	4.36E+03	9.33E+03	6.28E+03	1.19E+03	1.25E+04	3.34E+03	0.00E+00	9.36E+03	6.33E+03	1.26E+03
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.71E+03	0.00E+00	1.04E+04	1.41E+04	0.00E+00	0.00E+00	2.61E+03
Geothermal	1.28E+03	3.21E+03	6.14E+03	6.14E+03	6.14E+03	2.45E+03	2.45E+03	2.45E+03	6.14E+03	6.14E+03	6.14E+03
Heavy fuel oil	2.03E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	9.30E+01	1.72E+02	1.96E+02	2.48E+02	3.01E+02	1.18E+02	1.18E+02	1.18E+02	1.18E+02	1.18E+02	1.18E+02
Nuclear	3.50E+01	0.00E+00	2.62E+02	2.62E+02	2.62E+02	1.31E+02	1.31E+02	2.62E+02	5.23E+02	6.54E+02	7.85E+02
Ocean	0.00E+00	2.27E+02	7.90E+01	1.58E+02	1.58E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	3.50E+01	1.11E+03	3.60E+02	5.11E+02	6.89E+02	2.02E+02	2.03E+02	5.20E+02	2.92E+02	4.42E+02	5.79E+02
Wind	4.30E+01	4.68E+02	1.53E+02	2.17E+02	2.93E+02	8.60E+01	8.60E+01	2.21E+02	1.24E+02	1.88E+02	2.46E+02
Total	5.53E+04	1.26E+04	2.85E+04	2.43E+04	1.99E+04	3.47E+04	3.63E+04	2.63E+04	2.86E+04	2.44E+04	1.99E+04

Table A.10
Terrestrial ecotoxicity potential (TETP) for different scenarios.

Electricity option	BAU	Green	A-1	A-2	A-3	B-1	B-2	B-3	C-1	C-2	C-3
TETP (t DCB eq./yr)											
Biomass	1.70E+04	3.09E+04	7.74E+04	7.74E+04	7.74E+04	3.86E+04	3.86E+04	3.86E+04	7.74E+04	7.74E+04	7.74E+04
Coal	1.98E+05	1.17E+04	9.51E+04	0.00E+00	0.00E+00	4.82E+04	0.00E+00	0.00E+00	9.51E+04	0.00E+00	0.00E+00
Coal CCS	0.00E+00	0.00E+00	0.00E+00	9.09E+04	4.55E+04	2.49E+05	3.18E+05	1.10E+05	0.00E+00	9.09E+04	4.55E+04
Gas	5.30E+04	1.21E+04	2.58E+04	1.74E+04	3.30E+03	3.47E+04	9.26E+03	0.00E+00	2.59E+04	1.75E+04	3.48E+03
Gas CCS	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E+04	0.00E+00	4.81E+04	6.57E+04	0.00E+00	0.00E+00	1.21E+04
Geothermal	3.16E+03	7.93E+03	1.52E+04	1.52E+04	1.52E+04	6.07E+03	6.07E+03	6.07E+03	1.52E+04	1.52E+04	1.52E+04
Heavy fuel oil	1.25E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hydro	3.36E+03	6.32E+03	7.18E+03	9.08E+03	1.10E+04	4.36E+03	4.36E+03	4.36E+03	4.36E+03	4.36E+03	4.36E+03
Nuclear	2.27E+03	0.00E+00	1.68E+04	1.68E+04	1.68E+04	8.39E+03	8.39E+03	1.68E+04	3.36E+04	4.20E+04	5.04E+04
Ocean	0.00E+00	2.14E+04	7.44E+03	1.49E+04	1.49E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Solar	1.95E+03	6.27E+04	2.03E+04	2.88E+04	3.88E+04	1.14E+04	1.14E+04	2.93E+04	1.64E+04	2.49E+04	3.26E+04
Wind	2.03E+03	2.23E+04	7.29E+03	1.04E+04	1.39E+04	4.10E+03	4.12E+03	1.05E+04	5.90E+03	8.95E+03	1.17E+04
Total	1.53E+06	1.75E+05	2.72E+05	2.81E+05	2.49E+05	4.05E+05	4.49E+05	2.81E+05	2.74E+05	2.81E+05	2.53E+05

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