Journal of Cleaner Production 80 (2014) 119–138

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Sustainability assessment of energy systems: integrating environmental, economic and social aspects

Edgar Santoyo-Castelazo, Adisa Azapagic*

School of Chemical Engineering and Analytical Science, Room C16, The Mill, Sackville Street, The University of Manchester, Manchester M13 9PL, UK

A R T I C L E I N F O

Article history:
Received 14 February 2014
Received in revised form
20 May 2014
Accepted 20 May 2014
Available online 2 June 2014

Keywords:
Energy
Multi-criteria decision analysis
Life cycle assessment
Sustainability assessment
Scenario analysis
Mexico

A B S T R A C T

Sustainable development of energy systems requires consideration of all three sustainability dimensions: environmental, economic and social. Current work presents a new decision-support framework for facilitating this. Taking a life cycle approach, the framework integrates the three sustainability dimensions to enable assessments at both technology and systems levels. The framework comprises scenario analysis, life cycle assessment, life cycle costing, social sustainability assessment and multi-criteria decision analysis, which are used to assess and identify the most sustainable energy options. The application of the framework is illustrated on the example of future electricity supply in Mexico. Eleven scenarios up to 2050 have been developed considering different technologies, electricity mixes and climate change targets. The results show that, based on the 17 sustainability criteria used in this work, the business-as-usual scenario, mostly based on fossil fuels, is unsustainable regardless of the preferences for different sustainability criteria. This is mainly due to the high costs and environmental impacts associated with fossil fuels. Overall, the most sustainable scenarios are those with higher penetration of renewables (wind, solar, hydro, geothermal and biomass) and nuclear power. These electricity pathways would enable meeting the national greenhouse gas emission targets by 2050 in a more sustainable way than envisaged by the current policy. However, some trade-offs among the sustainability criteria are needed, particularly with respect to the social impacts. These trade-offs can be explored easily within the decision-support framework to reveal how different stakeholder preferences affect the outcomes of sustainability assessment, thus contributing to more informed decision and policy making.

1. Introduction

Sustainable development of energy systems is becoming increasingly more important for policy and decision makers worldwide. The main global policy objectives include economic growth, security of energy supply and mitigation of the effects of climate change (IPCC, 2007; IEA and OECD, 2008, 2010). Meeting these policy aims requires consideration and integration of all three sustainability aspects of energy systems: environmental, economic and social. This is progressively being recognised by decision and policy makers (Ness et al., 2007; Jeswani et al., 2010; UNEP and SETAC, 2011) and is reflected in a number of studies that have considered the sustainability of energy systems (see Table 1). Although most studies focus on electricity (rather than heat), they differ greatly in their scope and methodology (Nakata et al., 2011; Stamford and Azapagic, 2011). As shown in Table 1, they vary according to system boundaries (at the national, local, or technological level), time horizon (current, short, medium and long-term), the type and number of sustainability aspects and indicators considered (technical, environmental, economic and social), methodologies for the assessment (e.g. life cycle assessment, life cycle costing, etc.) and methods for integrating sustainability considerations (e.g. subjective approach, multi-criteria decision analysis, etc.). For example, most studies focused on electricity technologies (e.g. May and Brennan, 2006; Evans et al., 2009; Maxim, 2014) and only a few authors considered integrated electricity systems (e.g. Karger and Hennings, 2009; Kowalski et al., 2009; Gujba et al., 2011). The studies that looked into the future electricity generation typically considered the time horizons from 2020 up to 2050 with several studies using scenario analysis for these purposes (e.g. Heinrich et al., 2007; Keles et al., 2011). Although most studies considered all three dimensions of

* Corresponding author.
E-mail address: Adisa.Azapagic@manchester.ac.uk (A. Azapagic).

http://dx.doi.org/10.1016/j.jclepro.2014.05.061

Table 1
Recent studies on sustainability assessment of electricity generation.

Study	Aim and scope	Time horizon	Scenario analysis	Sustainability indicators		Integration of indicators
				Number	Life cycle approach	
May and Brennan (2006)	Sustainability assessment of power generation from Australian fossil fuels: coal and natural gas	Current	N.A.[a]	Total: 21; environmental: 12; economic: 5; social: 4	Yes	N.A.[a]
Heinrich et al. (2007)	Decision support framework for ranking and selection of power expansion alternatives for multiple objectives under uncertainty	Current and future	24 scenarios	Total: 4	No	Multi attribute value theory
Chatzimouratidis and Pivalachi (2009a; b)	Sustainability evaluation of ten types of power plants	N.S[b]	N.A.[a]	Total: 9	No	Analytical hierarchy process
Evans et al. (2009)	Assessment of sustainability indicators for renewable energy technologies (solar PV, hydro, wind and geothermal)	Current	N.A.[a]	Total: 7	Yes	Weighted sum
Jacobson (2009)	Review and ranking of power technologies that can provide solutions for global warming, air pollution, and energy security	Current and future	N.A.[a]	Total: 11	Yes	Multi attribute value theory
Karger and Hennings, (2009)	Sustainability evaluation of decentralized electricity generation in Germany	2025	Four scenarios	Total: 5	N.S.[b]	Analytic hierarchy process
Kowalski et al. (2009)	Assessment of sustainable electricity scenarios for Austria (at the national and local level)	2020	Five scenarios	Total: 17; environmental: 4; economic: 1, social: 12	No	SIMOS and PROMETHEE
Roth et al. (2009)	Sustainability assessment of electricity supply technology portfolio (best available commercial options and future technologies)	2000, 2030	N.A.[a]	Total: 75; environmental: 11; economic: 31; social: 33	Yes	Multi attribute value theory
Schenler et al. (2009) (NEEDS project)	Sustainability assessment of current and future electricity generation technologies (technology roadmap)	2050	N.A.[a]	Total: 36; environmental: 11; economic: 9; social: 16	Yes	Dominating-alternative algorithm
Gallego-Carrera and Mack (2010)	Sustainability assessment of electricity generation technologies via social indicators	Current and future	N.A.[a]	Social criteria: 4	Yes	N.A.[a]
Gujba et al. (2010, 2011)	Environmental and economic assessment of electricity generation in Nigeria	2003–2030	Four scenarios	Total: 13; environmental: 10; economic: 3	Yes	N.A.[a]
Onat and Bayar (2010)	Sustainability indicators of electricity generation systems	Current	N.A.[a]	Total: 8	N.S.[b]	Weighted sum
Rovere et al. (2010)	Methodology to analyse the sustainability of the expansion of electricity generation alternatives (at the power plant level)	N.S.[b]	N.A.[a]	Total: 15; environmental: 5; economic: 3; social: 3; technological: 4	No	Data envelopment analysis
Streimikiene (2010)	Comparative assessment of future power generation technologies based on carbon price development	2020, 2050	N.A.[a]	N.S.[b]	Yes	Externals costs of GHG emissions and total costs
Dorini et al. (2010)	Sustainability comparison of two options for electricity generation: coal versus biomass	N.S.[b]	N.A.[a]	Total: 22; environmental: 13; socio-economic: 9	Yes	Compromise programming
Jeswani et al. (2011)	Assessment of electricity generation options from biomass	Current	N.A.[a]	Total: 7; environmental: 5; economic: 2	Yes	N.A.[a]
Keles et al. (2011)	A critical survey of scenarios for electricity generation in Germany	2030	Four scenarios	N.S.[b]	No	N.A.[a]
Stamford and Azapagic (2011, 2012)	Sustainability assessment of electricity generation	Current	N.A.[a]	Total: 43; environmental: 11; techno-economic: 13; social: 19	Yes	N.A.[a]
Maxim (2014)	Sustainability assessment of electricity generation technologies	Current	N.A.[a]	Total: 10; environmental: 2; techno-economic: 4; Social: 4	Yes	SWING
Current study	Generic decision-support framework for integrated sustainability assessment of electricity with an application to Mexico	2050	11 scenarios	Total: 17; Environmental: 10; economic: 3; social: 4	Yes	Multi attribute value theory and SMART

[a] Not applied.
[b] Not specified.

sustainability, the number of indicators varied from four (Heinrich et al., 2007) to 75 (Roth et al., 2009). A life cycle approach was typically only considered for the environmental indicators, except in two papers (Stamford and Azapagic, 2011; 2012), where economic and social impacts were also assessed on a life cycle basis. The integration of the sustainability indicators was carried out in most studies, using methods such as multi attribute value theory, analytical hierarchy process and weighted sum (Table 1). Only a few studies though considered the influence of different preferences on the outcomes of the sustainability assessment (e.g. Schenler et al., 2009; Dorini et al., 2010).

However, despite many studies, as far as we are aware, there are no other studies which have proposed a generic methodology that can be applied to different energy systems, allowing an integrated sustainability assessment of future scenarios on a life cycle basis. Therefore, this paper goes beyond previous research to develop a decision-support framework for an integrated sustainability assessment of energy systems where environmental, economic and social aspects are considered in parallel, enabling decision makers to incorporate different preferences for sustainability criteria and identify most sustainable options. The framework takes a life cycle approach and incorporates a range of sustainability indicators which are used to assess the sustainability of different electricity scenarios, using multi-criteria decision analysis. The methodological framework is described in the next section. This is followed in Section 3 with an illustrative application of the framework. For these purposes, the electricity system in Mexico has been chosen, considering the time horizon of up to 2050. This is the first time that an integrated sustainability assessment of future electricity system in Mexico has been carried out on a life cycle basis. Following the discussion of the results, policy recommendations are outlined in Section 4 and conclusions are drawn in Section 5. It should be noted that, although the application of the framework is illustrated on a case of electricity in Mexico, the methodology is applicable to other energy systems and regions.

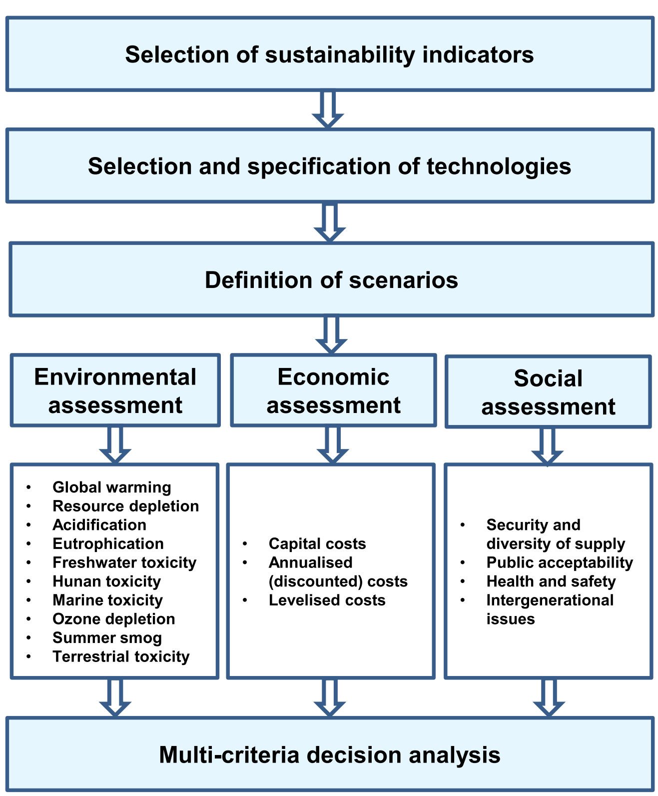

Fig. 1. Decision-support framework for integrated sustainability assessment of energy systems. [Sustainability indicators used in this work are shown as illustrative examples; they can be changed depending on the aims of the study.].

2. Decision-support framework

The proposed framework for integrated sustainability assessment of energy systems is outlined in Fig. 1. It involves the following steps:

1. selection of environmental, economic and social indicators to be used for measuring the sustainability;
2. selection and specification of energy technologies;
3. definition of scenarios and the time horizon;
4. environmental, economic and social assessment on a life cycle basis; and
5. integration of sustainability indicators via a multi-criteria decision analysis to determine the most sustainable options for the future.

The following sections describe each step in turn.

2.1. Sustainability indicators

The selection of the indicators considered here is driven by the global energy policy discussed in Introduction as well as by the findings of previous research on the sustainability of energy systems as summarised in Table 1.

2.1.1. Environmental indicators

Taking a life cycle approach, the environmental indicators included in the framework are those typically considered in life cycle assessment (LCA) studies. Here, ten impacts are assessed: global warming (GWP), abiotic depletion (ADP), acidification (AP), eutrophication (EP), freshwater aquatic ecotoxicity (FAETP), human toxicity (HTP), marine aquatic ecotoxicity (MAETP), ozone depletion (ODP), photochemical ozone creation (POCP) or summer smog, and terrestrial ecotoxicity (TETP). The indicators are estimated following the CML 2001 method (Guinée et al., 2001).

2.1.2. Economic indicators

Three economic indicators are considered for the economic sustainability assessment:

i) capital costs;
ii) total annualised costs; and
iii) levelised costs.

i) Capital costs comprise costs of construction and installation of power plants. In this work, they are calculated as 'overnight' costs, i.e. costs without paying any interest on the borrowings (IEA and NEA, 2010):

$$TC_C = \sum C_C E \quad (\$) \tag{1}$$

where :

TC_C – total capital costs ($)
C_C – overnight capital costs of electricity generating option ($/kW)
E – installed capacity of energy-generating plant (kW)

ii) The total annualised cost of an energy system is defined as (Gujba et al., 2010):

$$\mathrm{TAC} = \sum \mathrm{AC}_C + \sum F_C + \sum V_C + \sum f_C \quad (\$/\mathrm{yr}) \tag{2}$$

where:

TAC = total annualised cost of generating electricity ($/yr)
AC_C = annualised capital cost ($/yr)
F_C = annual fixed costs ($/yr)
V_C = annual variable costs (all variable costs excluding fuel costs) ($/yr)
f_C = annual fuel costs ($/yr).

The annualised capital costs (AC_C) are calculated taking into account the total capital costs (TC_c) and an annuity factor (*f*) as follows:

$$\mathrm{AC}_C = \mathrm{TC}_C f \quad (\$) \tag{3}$$

$$f = \frac{z(1+z)^t}{(1+z)^t - 1} \tag{4}$$

where:

TC_C – total capital costs ($)
z – discount rate
t – lifetime of the plant (years).

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

iii) The levelised costs or unit energy costs represent the cost of energy generated over the lifetime of a power plant, expressed per unit of energy. It is calculated by dividing the total annualised cost (*TAC* in Eq. (2)) by the total annual energy generation in the same year:

$$\mathrm{LC} = \mathrm{TAC}/\mathrm{AE} \quad (\$/\mathrm{MWh}) \tag{5}$$

where:

AE – annual energy generation (MWh/yr).

2.1.3. Social indicators

The social indicators considered within the decision-support framework are classified into four main categories:

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

The motivation for selecting these categories is discussed below, together with definitions of the individual indicators used within each category.

2.1.3.1. Security and diversity of supply. Among the most important factors affecting the security and diversity of supply are rapid depletion of energy reserves (fossil fuels and uranium), uncertainty of future fossil fuel prices together with the disruption of fuel supply because of political conflicts (especially related to oil), fuel import dependency and intermittency of electricity supply (Krewitt et al., 2007, 2009; Greenpeace and EREC, 2008a; IEA and OECD, 2009). It has been argued that in order to secure energy supply for the future it is essential to promote a diversification of the energy sector based on low-carbon technologies (Greenpeace and EREC, 2008b; IEA and OECD, 2008). For this reason, the financial support and appropriate energy policies are essential for the development of these technologies (Nakata et al., 2010).

The following indicators are selected here for assessing security and diversity of supply:

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

Depletion of fossil fuel reserves is an important indicator for the security of energy supply in many countries because of the fast depletion of their national reserves. In this work, abiotic reserve depletion, calculated as part of LCA, has been used as the indicator to assess this social impact. Import dependency, as a direct consequence of depletion of national reserves, is also becoming a critical factor for many countries. To mitigate against this, availability of renewable energy resources is an important indicator of security of supply, although that can also affect reliability of supply, particularly if the system is too reliant on intermittent sources such as wind, solar and ocean (Boyle, 2003).

2.1.3.2. Public acceptability. Public perception and acceptability is key to the implementation of any energy technology, be it fossil fuels with or without carbon capture and storage (CCS), renewables or nuclear power (Gallego-Carrera and Mack, 2010; Onat and Bayar, 2010). For example, main issues affecting the implementation of wind power are related to land requirement, visual intrusion and noise (Evans et al., 2009). For large hydro-power plants, lack of public acceptance is mainly associated with transformation of land and relocation of population (Lokey, 2009). Main social concerns for biomass are related to competition for agricultural land, water and food production (Jacobson, 2009). In the case of nuclear power, public acceptability is mainly affected by the perceptions related to health and safety issues, including nuclear accidents and terrorism, nuclear proliferation and radioactive waste management and storage (Jazayeri et al., 2008; Greenhalgh and Azapagic, 2009).

2.1.3.3. Health and safety. This social aspect is in this work measured by two indicators, covering the whole life cycle of energy technologies: human health impacts and safety risks. For instance, the main health impacts from combustion of fossil fuels in power plants arise from emissions of SO_2, NO_x, particulate matter and heavy metals. Health issues have been quantified in the current work using the human toxicity potential estimated within LCA. A similar approach has been taken in other studies (e.g. Dorini et al., 2010; Stamford and Azapagic, 2011).

Safety risks are mostly related to occupational accidents and public hazards (e.g. injuries and fatalities affecting workers and the public) and accident risks along the life cycle (e.g. explosions, oil spills, etc.) (Boyle, 2003; Jazayeri et al., 2008).

2.1.3.4. Intergenerational issues. Within the sustainable development context, intergenerational aspects refer to issues which affect current and future generations, and therefore addressing these problems today is essential (Azapagic and Perdan, 2011). Some of the most important intergenerational issues include mitigation of climate change and depletion of fossil fuel reserves (Krewitt et al., 2007; 2009; Azapagic and Perdan, 2011; Stamford and Azapagic, 2011). In this work, GWP and ADP estimated through LCA are used to reflect these two issues, with the latter being also related to security and diversity of supply discussed in Section 2.1.3.1. These indicators have also been used by other authors (e.g. May and Brennan, 2006; Gujba et al., 2010; 2011; Stamford and Azapagic, 2012).

A further intergenerational issue relevant to energy technologies is the long-lived hazardous waste, which applies to radioactive waste and CO_2 captured from fossil (and biomass) fuel technologies (Stamford and Azapagic, 2011). Both types of waste have obvious consequences for future generations if there are accidental leaks. However, the risk of accidental leaks cannot be quantified at this stage owing to the lack of experience in operating a repository as well as site-specific information; nevertheless, this should be flagged and discussed as an important issue in sustainability assessments of energy systems. Therefore, this aspect is included within this decision-support framework.

2.2. Selection and specification of technologies

This step of the decision-support framework is aimed at identifying energy technologies that are available currently or may become available in the future, taking into account the specific conditions of the country or region where the sustainability assessment is being carried out. Once the technologies have been selected, they need to be characterised with respect to their capacities, efficiencies, capacity factors, lifetimes, emissions to the environment, emission controls, etc. Future development of technologies also needs to be taken into account as part of scenario analysis (see the next section). As the sustainability assessment is carried out on a life cycle basis, the life cycles of the technologies then need to be mapped from ‘cradle to grave’, considering extraction of fuels and materials, construction and operation of the plants and their eventual decommissioning.

2.3. Definition of scenarios

This framework uses scenario analysis to explore alternative energy futures and assess the sustainability implications. Unlike forecasting or backcasting, scenario analysis does not aim to predict the future but instead looks at possible futures which may or may not happen, providing answers to ‘what if’ types of question. The development of scenarios for consideration in any study will depend on many different factors, including policy and socio-economic drivers such as economic growth, security of supply and mitigation of climate change as well as the anticipated technological development in the future. These will also determine the time horizon to be considered in scenario analysis; typically, this covers the period from 2020 up to 2050 (see Table 1). The technologies identified in the previous step are then integrated to form an energy system and, depending on the scenario, their configuration or mix may differ. For example, if an electricity system is being assessed on sustainability, the scenarios may consider a different penetration level or mix of technologies.

2.4. Sustainability assessment

The scenarios are then assessed on the environmental, economic and social sustainability using the indicators outlined in Section 2.1. As mentioned earlier, within this framework, LCA is used for assessing the environmental sustainability, life cycle costing for the economic and various social indicators for the social sustainability. In total, there are 17 sustainability indicators and each scenario is assessed on each indicator. To help analyse the results and identify sustainable options, the outputs of the assessment are fed into multi-criteria decision analysis, as described in the next section.

2.5. Multi-criteria decision analysis (MCDA)

MCDA methods are useful as they help deal with multiple – often conflicting – criteria in a structured way, allowing consideration of different preferences for the criteria. This is particularly important in energy debates, where there are many sustainability criteria and even more different – and usually opposing – views of different stakeholders.

Numerous MCDA methods exist (for an overview, see e.g. Azapagic and Perdan, 2005a, b) and any of these could be used within this decision-support framework. For illustration, multi-attribute value theory (MAVT) has been selected in this work as one of the most widely used methods (Wang et al., 2009). MAVT involves determination of partial value functions and establishing weights for each criterion to calculate a global value function *V(s)* as follows (Azapagic and Perdan, 2005b; Løken, 2007):

$$V(s) = \sum_{i=1}^{I} w_i u(s) \quad (6)$$

where:

$V(s)$ – global value function, representing the total sustainability score for scenario s
w_i – weight of importance for criterion (sustainability indicator) i
$u(s)$ – value function reflecting the performance of scenario s on indicator i
I – total number of sustainability indicators

First, a value function *u(s)* is estimated, reflecting the performance of scenario *s* on indicator *i*. In this case, value functions *u(s)* represent values of sustainability indicators estimated for each scenario. The scenarios are then ranked according to each criterion, using a scale from 1 to N, where N represents the total number of scenarios and 1 is the best and N the worst option. Then, the sustainability score *V(a)* is estimated for each scenario according to Eq. (6). The scenarios are then ranked again, this time according to the total sustainability scores, again using the scale from 1 to N (for a similar approach, see e.g. Jacobson, 2009).

To test the robustness of the MCDA results, sensitivity analysis should be carried out to find out if and how the ranking of the scenarios changes with different weighting of the indicators. For example, the simple multi-attribute rating technique (SMART) can be used for these purposes (Wang et al., 2009). In SMART, the criteria are ranked according to their relative importance from the lowest to the highest levels. A value of 10 points is assigned to the least important criterion and increasing number of points (without an explicit upper limit) are assigned to the other criteria to express their importance relative to the least important criteria; the weights are calculated as follows:

$$w_i = \frac{v_i}{\sum_{i=1}^{I} v_i} \times 100 \quad (7)$$

where:

v_i – value of points assigned to indicate the importance of sustainability indicator i relative to other indicators.

Once the weights have been estimated for each indicator, the MAVT method is applied again using Eq. (6) to estimate the sustainability scores for the scenarios and to rank them from 1 to N. The results are then compared to those obtained using the original weighting for the indicators to find out if and how the ranking of the scenarios may have changed owing to the change in the weights.

The application of the decision-support framework is demonstrated in the next section, using electricity supply in Mexico as an illustrative example.

3. Application of the decision-support framework

Like many other countries, Mexico is seeking to develop a more sustainable future energy system that would improve the self-sufficiency of supply but also contribute towards the country's GHG reduction targets. A signatory to the Kyoto Protocol, Mexico aims to reduce GHG emissions by 50% by 2050 relative to 2000 (PECC, 2009). If achieved, this would contribute to the stabilisation of CO_2 concentration in the atmosphere at the level required to limit the global average temperature increase to around 2.0 °C (IPCC, 2013). Meeting the GHG target would require cutting the emissions from electricity generation by 85% on the 2000 levels (from 110.7 Mt CO_2 eq.), emitting only 16.2 Mt CO_2 eq. by 2050 (PECC, 2009). This is a very challenging task and will require significant reductions in the short and medium terms, particularly as the electricity demand is projected to grow (Greenpeace and EREC, 2008a). While the Mexican Government has made an effort to reduce the GHG emissions in the short term by substituting heavy fuel oil with combined cycle gas power plants (SENER, 2006a, 2007) and increasing wind and hydro-power capacity (SENER, 2012), these options alone cannot be a long-term solution for mitigating climate change and improving the security of supply. Therefore, more sustainable options for future electricity supply must be identified and implemented. The following sections consider how this may be achieved using the integrated sustainability assessment framework developed in this work.

3.1. Sustainability indicators

As discussed in Section 2.1, ten environmental, three economic and four social sustainability indicators are integrated within the sustainability assessment framework; therefore, the electricity supply in Mexico is assessed on these indicators.

3.2. Choice of technologies

The chosen electricity technologies are listed in Table 2 and their life cycles are outlined in Fig. 2. As indicated, all electricity sources are considered, including fossil fuels with and without CCS, biomass, geothermal, hydro and nuclear power, solar, wind and ocean energy. Further details on the technologies are provided in

Table 2
Characteristics of power plant technologies assumed in the scenarios.

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 micro gas turbine)
Coal[b]	Ultra-supercritical (USC) pulverized combustion, and integrated gasification combined cycle (IGCC)	600 MW ultra-supercritical and 450 MW IGCC coal power plants. The USC configuration includes: 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 Pressurized Reactor (EPR)	The EPR with a capacity of 1600 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 (Dones et al., 2007; Jungbluth et al., 2007).
[b] Bauer et al., 2008.
[c] SENER (2006b); Ecoinvent (Dones et al., 2007); GEMIS (Öko Institute, 2005).
[d] Lecointe et al. (2007).
[e] Sørensen and Naef (2008).
[f] Viebahn et al. (2007).
[g] Frankl et al. (2005).
[h] DONG Energy (2008).

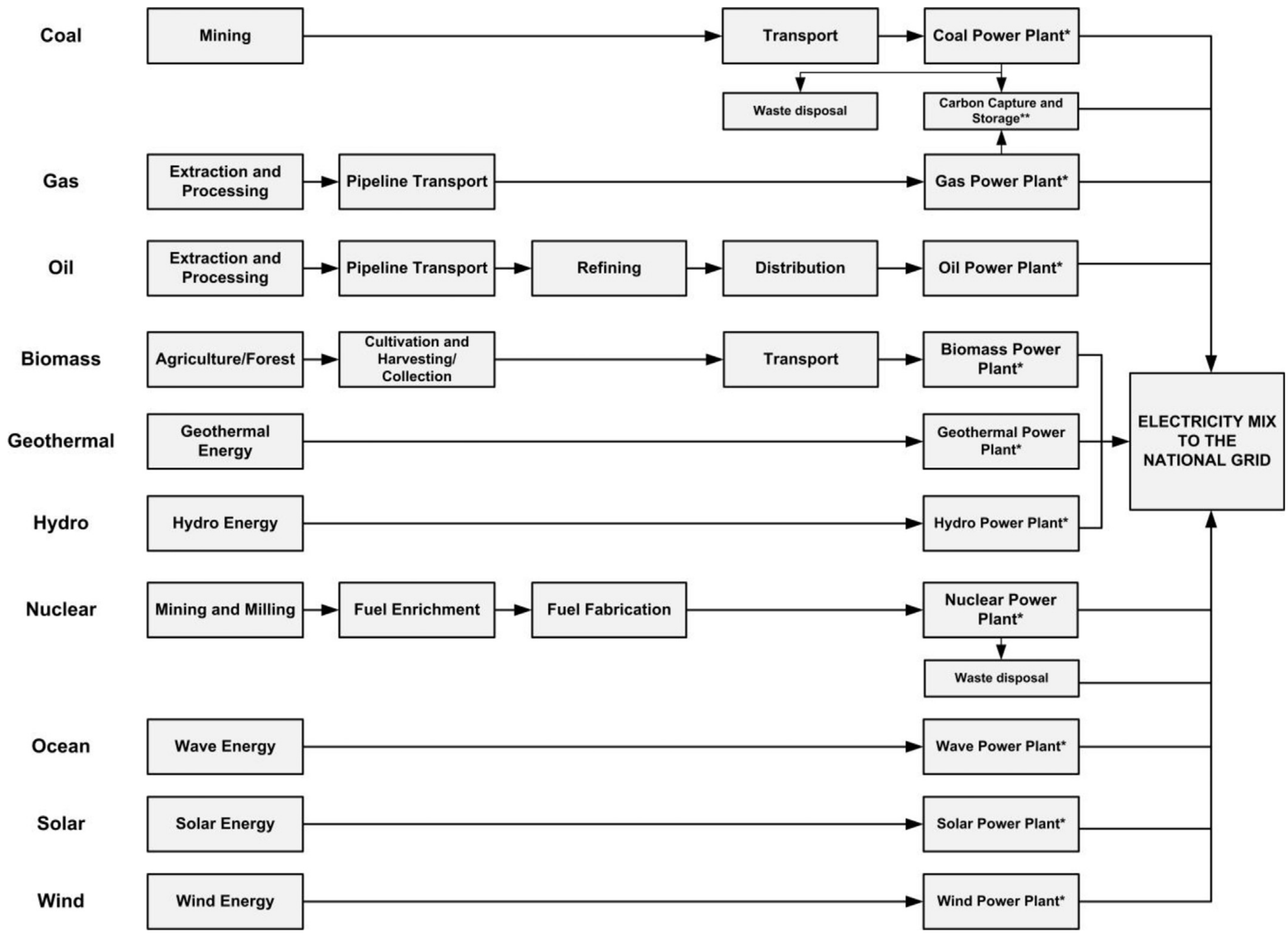

Fig. 2. The life cycle of electricity options considered in the scenarios (modified from Santoyo-Castelazo et al., 2011) [*Plant comprises construction and operation of power plant; **CCS shown for coal and gas power plants only but can also be used with biomass plants].

conjunction with the scenario analysis below and in Supplementary information.

3.3. Definition of scenarios

Eleven scenarios have been defined looking out to 2050. They are motivated by energy security and climate change drivers and therefore consider different climate change targets (Table 3) and technology mixes (Table 4). Two of the scenarios are based on those previously developed by other authors (IEA, 2004; Greenpeace and EREC, 2008a) and the rest have been defined in this study as follows:

- Business as usual (BAU) in terms of electricity mix and demand and no climate change targets (IEA, 2004; Greenpeace and EREC, 2008a);
- 'Green' scenario which considers efficiency improvements and reduction of energy demand as well as a 60% CO_2 reduction from the energy sector by 2050 on the 2005 levels (Greenpeace and EREC, 2008a); 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 further three sub-scenarios considering stabilisation (no increase), 60% and 85% reduction of GHGs on the 2000 levels, respectively. Scenario A is mainly based on the large-scale renewable energy technologies (wind, solar, hydro power, geothermal and biomass). In scenario B, fossil fuels (gas and coal) remain the main energy sources but integrated with a large-scale CCS. Scenario C depends mainly on nuclear power and renewables.

3.3.1. Assumptions and data sources

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 (SENER, 2006a) to 598,000 GWh in 2050 (Greenpeace and EREC, 2008a). Although this is below the current growth of 2.8% per year (SENER, 2006a), it is assumed to be feasible owing to the projected future increase in the efficiency of electricity generation. 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.

For the estimation of costs, a 10% discounting rate is used; all the costs are expressed as US dollars, assuming the currency value in 2008. Cost assumptions are detailed further below.

3.3.1.1. Environmental data. The assumptions for GHG emissions at the point of electricity generation (direct emissions) for different scenarios are given in Table 5. The life cycle environmental impacts

Table 3
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 (2004) and Greenpeace and EREC (2008a)	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 (2008a)	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 49%; 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.

of technologies are sourced from Santoyo-Castelazo et al. (2011, 2014), Ecoinvent (Dones et al., 2007; Jungbluth et al., 2007) and GEMIS (Öko Institute, 2005).

3.3.1.2. *Capital costs.* Table 6 shows the assumed capital costs of the electricity technologies in 2050. As fossil fuel power plants are technically mature, only minor improvements are expected from 2020. In contrast, CCS technologies will be only at the beginning of their learning curve (Viebahn et al., 2007). Despite the fact that some of the renewable energy technologies currently available are not yet fully competitive (e.g., biomass, geothermal, ocean and solar), a large potential for cost reductions is expected in the future owing to learning curves (Neij, 2008; Krewitt et al., 2009).

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

Table 4
Assumed contribution of different electricity sources to the total electricity mix for all scenarios (current mix shown for comparison).

Electricity mix (%)												
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
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[d]	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 (2006b).
[b] IEA (2004) and Greenpeace and EREC (2008a).
[c] Greenpeace and EREC (2008a).
[d] Geothermal electricity considers only contribution from conventional technologies and resources; its contribution could be even greater if future enhanced geothermal systems are exploited (MIT, 2006) but this has not been considered.

3.3.1.3. *Fuel costs.* The fuel cost projections for the scenarios have been sourced from the BAU (IEA, 2004) and Green scenarios (Greenpeace and EREC, 2008b). For fossil fuels, two options have been defined: 'low cost' and 'high cost' scenarios; see Fig. 3. The former is based on the BAU until 2030, using the oil and gas prices (IEA, 2004) before the recent price increases; these costs have been linearly extrapolated to 2050 by Greenpeace and EREC (2008b) and are used here. The 'high cost' scenario is based on the Greenpeace and EREC (2008b) projection from today to 2050, assuming a considerable increase in energy demand and fast depletion of fossil fuel reserves for the future.

As shown in Fig. 3, the 'low cost' scenario assumes an almost constant fuel price from 2010 to 2050, expecting the oil price to be $11.30/GJ (69 $/bbl) in 2050 (IEA, 2004). This assumption may be unrealistic given the fact that oil prices are already close to or over this value. To counter this underestimate, Greenpeace and EREC (2008b) assume a path whereby the price of oil reserves reaches 25.2 $/GJ (154 $/bbl) by 2050. A similar assumption has been made for gas and coal, with the costs increasing up to 27.1 and 16.9 $/GJ by 2050, respectively (Greenpeace and EREC, 2008b). These costs projections are in agreement with Krewitt et al. (2009) (for oil, coal and gas costs in 2050) and IEA and NEA (2010) (for oil in 2030). Moreover, higher fuel prices will lead to a greater competitiveness, development of low-carbon technologies and better learning curves (Neij, 2008; del Río, 2011). Hence, the current work assumes a 'high cost' scenario for the fossil fuels. These costs are presented in Table 7, alongside the costs of biomass and uranium. The operation and maintenance costs (variable and fixed) are given in Table 8.

Table 5
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] Direct emissions are from the operation of power plants (combustion of fossil fuels). 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 (PECC, 2009).
[c] The value estimated by Greenpeace and EREC (2008a,b) 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 (2008) 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%.

Table 6
Assumptions for overnight capital cost development for selected power plant technologies in 2050.

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

[a] Greenpeace and EREC (2008b).
[b] Bauer et al., 2008.
[c] EIA (2009) extrapolated value from year 2030 to year 2050, using Greenpeace and EREC (2008b) costs trends.
[d] IEA and NEA (2010).
[e] Lecointe et al., 2007.
[f] Capital costs for concentrating solar thermal power plants include thermal storage systems which facilitate high capacity factors.
[g] USC: Ultra-supercritical.
[h] IGCC: Integrated gasification combined cycle.

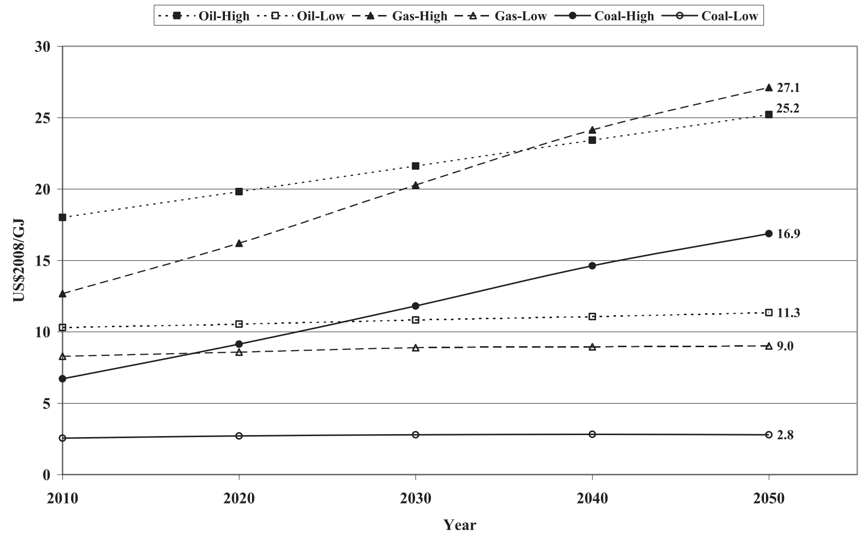

Fig. 3. Fossil fuel cost projections to 2050 for 'low' (BAU) and 'high' cost (Green) scenarios (based on the data from IEA, 2004; Greenpeace and EREC, 2008b).

3.4. Sustainability assessment

3.4.1. Environmental sustainability

As mentioned in Section 2.1.1, LCA is used as a tool to assess the environmental sustainability of the electricity scenarios. The functional unit is defined as 'annual generation of electricity in 2050'. Since the scenarios are driven by climate change targets, the results for the global warming potential are discussed first, followed by the other impacts.

3.4.1.1. Global warming potential (GWP). As shown in Fig. 4, the GWP for the BAU scenario doubles from the current 129 Mt CO_2 eq./yr (Santoyo-Castelazo et al., 2011) to 259 Mt in 2050. This is due to the high contribution from fossil fuels to the electricity mix, mainly coal and gas, together contributing 85% to the total generation. Conversely, the scenarios with the highest contribution from the renewables (and 85% GHG reduction target) have the lowest GWP. Scenarios C-3 and A-3 are the best options with the GWP of 27.3 and 27.7 Mt CO_2 eq./yr, respectively. In both scenarios, the GHG emissions are contributed equally from biomass, coal CCS, gas with and without CCS, and geothermal energy. The next best scenario is B-3 with the 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, essentially because of the emissions from the coal and gas power plants as this scenario does not include CCS. Scenarios A-2, C-2 and B-2 (60% GHG reduction) emit between 59 and 75 Mt of CO_2 eq./yr, respectively, with the GHG emissions related to gas with and without CCS, and coal with CCS, mainly owing to the emissions in the fuel supply chain. The scenarios assuming stabilisation of GHG emissions (A-1, B-1, and C-1) have the GWP between 129 and 139 Mt of CO_2 eq./yr but still considerably lower than the BAU scenario; the main GHG sources are again coal with and without CCS contributing 42–48% and gas power plants, adding further 44–54% to the total GWP.

3.4.1.2. Other environmental impacts. Owing to space restriction, the detailed results for the other life cycle environmental impacts can be found in Supplementary information, Tables S4–13 and Figure S1. A brief overview of the findings is given below.

Abiotic depletion potential: As expected, the BAU scenario has the highest ADP at 1.86 Mt Sb eq./yr, twice the current ADP. Like GWP, this is 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.

Table 7
Fuel costs assumed for scenarios for electricity production in Mexico in 2050.

Fuel	Cost ($/GJ)
Coal[a]	16.87
Gas[a]	27.11
Oil[a]	25.21
Biomass[a]	5.73
Uranium[b]	4.40

[a] Greenpeace and EREC, 2008b.
[b] Lecointe et al., 2007.

Table 8
Variable and fixed costs assumed for power plant technologies in Mexico in 2050.

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

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

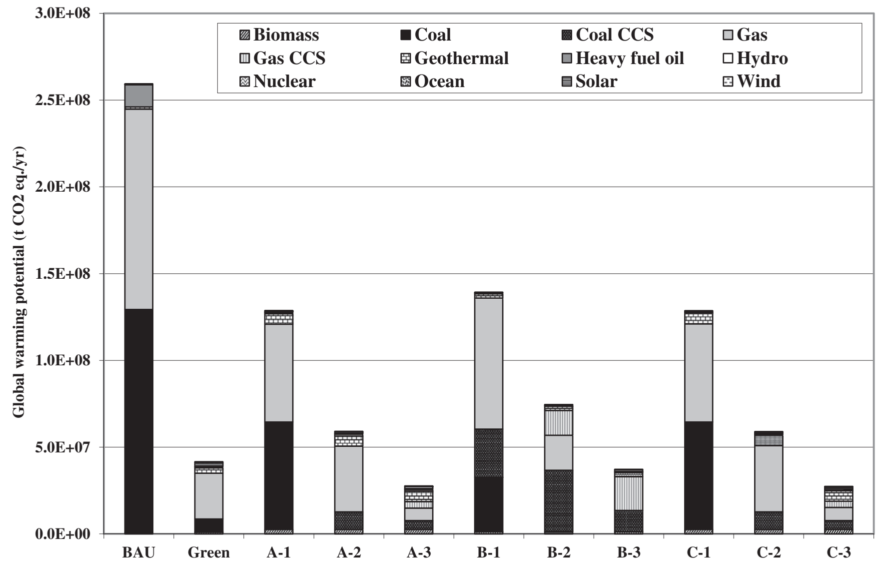

Fig. 4. Global warming potential (GWP) of scenarios in 2050 showing contribution of different electricity sources.

Acidification potential: The BAU scenario has the highest AP (531 kt SO_2 eq./yr), mainly because of the SO_2 emissions from heavy fuel oil and coal. 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.

Eutrophication potential: 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. The reason for this are NOx and NH_3 emissions from coal with CCS in B-2 and B-1, which contribute 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 4). The lowest EP is found in the Green scenario (8.8 kt PO_4 eq./yr), mainly related to the emissions from the construction of infrastructure for solar power plants.

Freshwater aquatic ecotoxicity potential: 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%).

Human toxicity potential: The BAU scenario again has the highest HTP, estimated at 46.8 Mt DCB eq./yr, mainly owing to the emission 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.

Marine aquatic ecotoxicity potential: 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. However, this is still half the current impact. The values for B-1 and B-2 are close to the

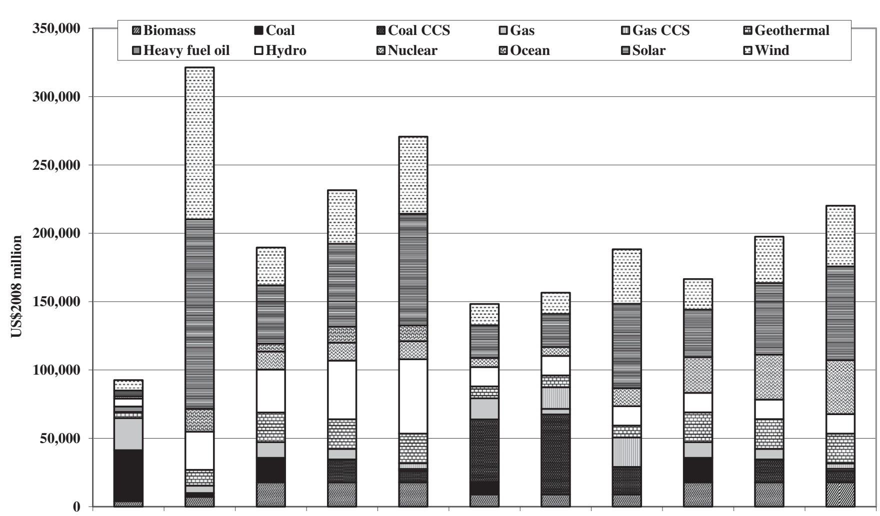

Fig. 5. Estimated capital costs in 2050 showing contribution of different electricity sources.

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.

Ozone layer depletion potential: For ODP, scenarios C-3 and A-3 are the best options, each emitting 3.5 t R11 eq./yr, mainly from gas with and without CCS. This is 10 times lower than at present. The Green scenario follows closely with 4.1 t R11 eq./yr. 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, mainly due to the NMVOC emissions from gas power.

Photochemical oxidants creation potential: 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. 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 geothermal, gas, and biomass power plants.

Terrestrial ecotoxicity potential: At 1.5 million t DCB eq./yr, the BAU scenario is the worst option for TETP; 82% of this impact is due to the emission of heavy metals from the operation of oil power plants. Compared to the current situation, however, the impact is three times lower. The lowest TETP (175 kt DCB eq./yr) is for 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%).

3.4.1.3. Summary. In summary, these results show that switching from the current fossil fuel mix to a higher contribution from 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. The Green, A-3 and C-3 scenarios are environmentally the most sustainable options for most impacts. They also achieve the highest reduction in GWP. If, on the other hand, the BAU scenario is realised, the GWP and resource depletion would double compared to the present values and ozone layer depletion would increase by 40%.

3.4.2. Economic sustainability

The capital, annualised and levelised costs of the scenarios are presented in the following sections. Detailed results can be found in Supplementary information, Tables S14–S16.

3.4.2.1. Capital costs. The estimated capital costs shown in Fig. 5 indicate that the BAU scenario is the most attractive option costing $92.6 billion in 2050. This is mainly because of the lowest required installed capacity (see Supplementary information, Table S1), which in turn is due to a high contribution of fossil fuels power plants with considerably higher capacity factors relative to renewable technologies (Supplementary information, Table S3). In contrast, the Green scenario is by far the most expensive option, requiring a total capital investment of $321.4 billion from today to 2050 (see Fig. 5). This is because this scenario has the highest contribution of renewable technologies (86%) which have higher overnight capital costs compared to the conventional technologies (Table 6).

Scenarios A, B and C are more expensive than the BAU but cheaper than the Green, with the capital costs ranging from $148.2–270.6 billion. Among these, the most economical options are scenarios B-1 and B-2, also because of the high contribution from fossil fuels (70%; see Table 4). Their costs are $148.2 and 156.5 billion, representing a 60% and 69% increase on the BAU scenario, respectively. Scenarios C are also in general more economical than their A counterparts, mainly owing to a lower contribution from the renewables and a higher contribution from nuclear power; scenario C-1 is the best option among C scenarios (Fig. 5). Scenario A-1 is the least expensive among scenarios A, requiring an investment of $189.5 billion, followed by scenario A-2 with $231.5 billion. Even though scenario A-3 has a 75% contribution from renewables (Table 4), it is still $50.7 billion cheaper than the Green scenario.

3.4.2.2. Total annualised costs. In contrast with the capital costs, herein the most expensive are the scenarios based on fossil fuels (BAU, B-2, B-1, and B-3; Fig. 6), mainly owing to the assumed high future fossil fuel costs (see Fig. 3). The most expensive option is BAU with the annualised costs of $87.9 billion, followed by B-2, B-1 and B-3 with $85.1, 81.4 and 72.4 billion/yr, respectively. On the other hand, scenarios with a high contribution from the renewable (Green and scenarios A), together with scenarios C, have considerably lower total annualised costs compared to the BAU and scenarios B, ranging from $52.8 to 64.6 billion/yr (Fig. 6). Scenarios C-3 and A-3 are the most attractive options among all the scenarios, followed by the Green, costing $52.8, 53.2 and 54.6 billion per year, respectively. It can be seen in Fig. 7 that fuel costs (especially fossil fuels) and discounted capital costs (mainly related to the

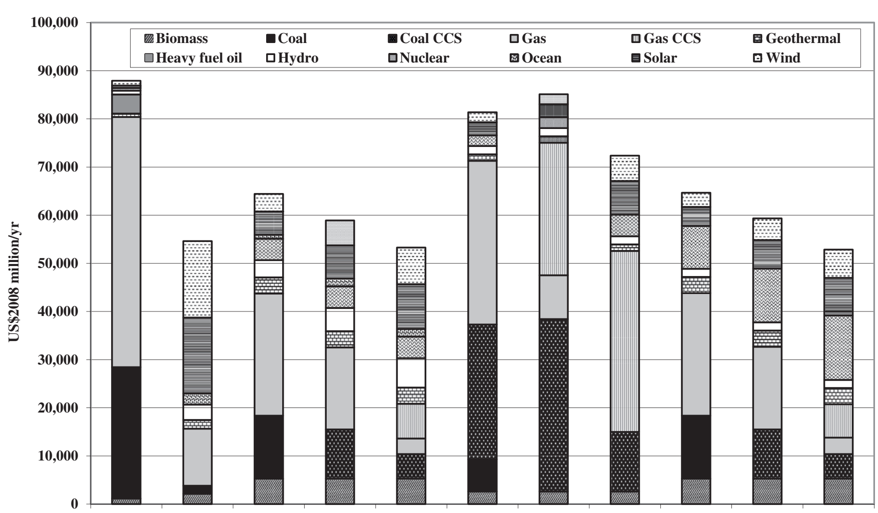

Fig. 6. Estimated annualised costs in 2050 showing contribution of different electricity sources.

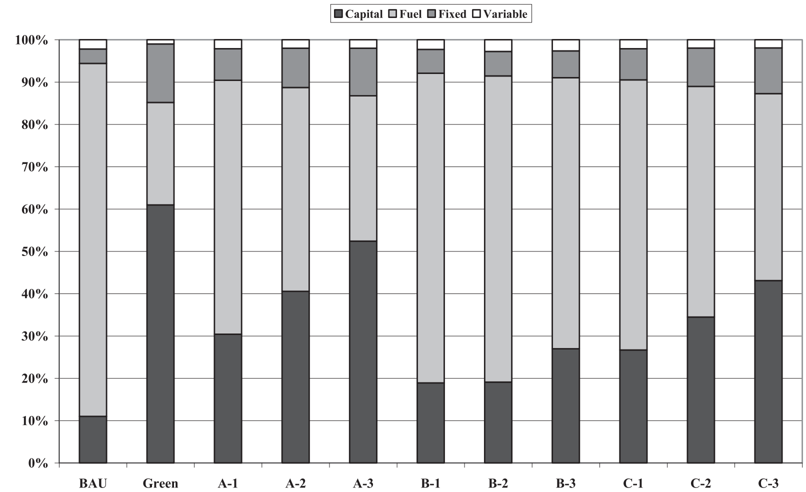

Fig. 7. Contribution of capital, fuel and variable costs to the total annualised costs.

renewables-based scenarios) dominate the total annualised costs in all the scenarios.

3.4.2.3. Levelised costs. The costs per unit of electricity generated show the same trends as the annualised costs (see Fig. 8), where the highest costs are for the fossil fuel-based B-1 and BAU, ranging between $121-147/MWh. In contrast, the lowest unit costs are for scenarios C-3, A-3 (88 $/MWh) and Green (91 $/MWh). The costs per MWh for the other scenarios range from $98 (scenario A-3) to $108.

3.4.2.4. Summary. The BAU scenario is overall the most economical option in terms of capital costs, requiring an investment of $92.6 billion, versus the Green which would cost $321.4 billion, by far the most expensive of all the scenarios. The capital costs for the other scenarios range between $148.2 billion for B-1 to $270.6 billion for A-3. In contrast, considering the total annualised costs in 2050, the BAU is the most expensive option at $87.9 billion/yr. The best scenarios are C-3 and A-3 ($52.8 and 53.2 billion/yr), followed by the Green ($54.6 billion/yr). The levelised costs follow a similar trend with the best options being C-3, A-3 (88 $/MWh) and Green (91 $/MWh) and the worst B-1 and BAU ($121–147/MWh).

However, it should be borne in mind that future costs are uncertain and the estimates obtained here are only valid for the assumptions made in the current work. This is a limitation inherent in all studies which consider future costs. Nevertheless, the cost assumptions are consistent across all the scenarios – while the absolute values would change with differing assumptions, the relative difference between the scenarios would still hold.

3.4.3. Social assessment

3.4.3.1. Security and diversity of supply. Security and diversity of supply are important for Mexico since its current electricity mix is dominated by fossil fuels and the domestic fossil fuels reserves will only last for another nine years at current consumption (Medina–Ross et al., 2005; PEMEX, 2008). Therefore, this indicator is one of the most important drivers for sustainable development of the country's energy sector (SENER, 2008).

As outlined in Section 2.1.3, indicators considered for the assessment of security supply comprise depletion of fossil fuels, import dependency, availability of renewable energy resources and reliability of electricity supply. These are discussed below, comparing and contrasting the implications for each scenario.

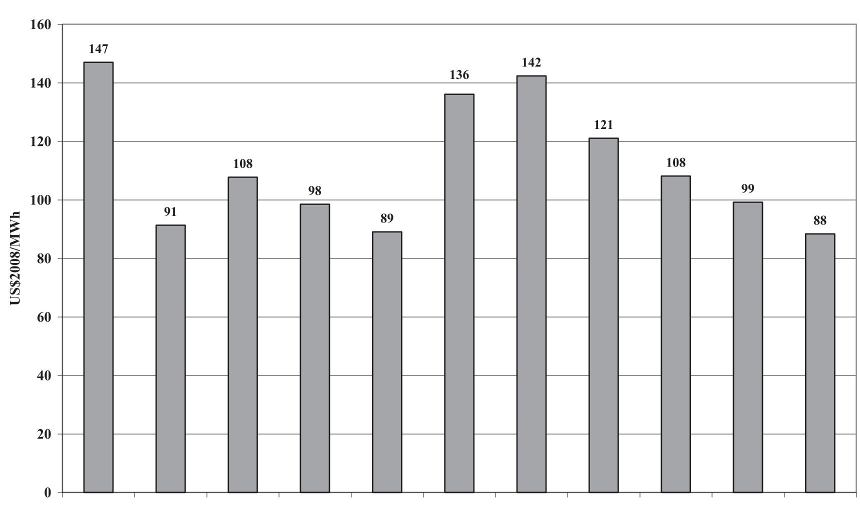

Fig. 8. Estimated levelised costs of electricity generation in 2050.

The BAU scenario can be considered as the least sustainable with respect to security and diversity of supply owing to a high dependence on fossil fuels, which contribute 87% to electricity supply in 2050 (see Table 4). Consequently, the BAU scenario has the highest abiotic depletion potential compared to the other scenarios (see Section 3.4.1.2 and Supplementary information, Figure S1).

On the other hand, the Green scenario seems to be a more secure scenario for electricity supply than the BAU because of its lower dependency on fossil fuels, contributing only 14% to the total, which results in the lowest depletion of abiotic resources. However, its considerably higher dependency on wind and solar power (63% of the total supply, see Table 4) opens questions in terms of diversification and reliability of supply (which is discussed further below). Scenario A-3 and C-3 can also be considered as more sustainable options in terms of security and diversity of supply owing to a low contribution of fossil fuels (15%) and a relatively low depletion of abiotic resources compared to some other scenarios.

Furthermore, when considering availability of renewable energy resources, the Green scenario assumptions exceed considerably the current estimates for renewable energy potential for electricity production in Mexico because of the high contribution from the renewables (86%). For example, this scenario requires an installed capacity of 70,357 MW of wind power (see Supplementary information, Table S1) which exceeds by 75% the estimated availability of 40,000 MW; similarly for ocean energy, the assumed capacity exceeds the availability by 44% (see Supplementary information, Table S17). However, the estimated potentials for renewables in Mexico are uncertain and, in some cases, data are not available for the whole country. For instance, the maximum potential for wind power is based on only one region (see footnotes to Table S17). Therefore the extent to which the Green scenario is technically feasible is uncertain.

By contrast, the required renewable resources for scenarios A, B and C are well below or similar to the currently estimated potential for the country, which makes these scenarios preferred options over the Green scenario.

Moreover, the intermittency of some renewables (like wind, solar and ocean energy) will pose new challenges to the stability, reliability and operation of the electricity grid. Therefore, the Green scenario has the lowest reliability of supply because of the high contribution from intermittent sources such as wind, solar PV and ocean energy (51% in total; see Table 4). This may change if energy storage becomes available in the future.

Overall, the A scenarios are considered as better options for security of supply because of the balance between the diversity of energy sources and contribution from renewables. Among these, A-3 is the preferred scenario, with nine different electricity sources (Table 4) and moderate contribution from wind and solar (19.5% each) and hydro-power (15%). For the C scenarios, the main issue is the high dependency on the imported uranium to meet the contribution from nuclear power of 20–30%. A similar issue applies to the fossil fuel-dominated scenarios (BAU and B-1 and B-2) as fossil fuels will have to be imported by 2050 to meet the electricity demand. Gas imports for electricity production are already growing (SENER, 2006a, 2007) and it is expected that contribution of gas will increase from 42% today to 55% in 2050. A similar concern applies to coal, with the imports expected to go up from 14% to 35% in 2050 (Greenpeace and EREC, 2008a).

3.4.3.2. Public acceptability. The discussion related to public acceptability of different electricity technologies considers the following aspects:

- local or regional issues (e.g. land-use change issues, landscape and visual impact, noise);
- distrust or uncertainty towards the development of unknown technologies; and
- perception of health and safety risks (note that the emphasis here is on public *perception* of health and safety issues, as opposed to *calculated* health and safety risks which are considered as a separate social indicator in the subsequent section).

Main barriers for development of renewable energy in Mexico are related to land and water issues, public awareness and legal and administrative aspects (Lokey, 2009). For example, independent power producers (IPPs) in Mexico have had the experience of purchasing land from 'legal' owners only to find later that people are living illegally on the land but claim it as their own. Relocating these people has been problematic and time-consuming. Another aspect would be local corruption affecting project developers. An example of this was reported when a private company (Fuerza Eolica) contracted a person to act as a community liaison in Baja California to handle the land leasing and community relations, only to find out that he was working for another company and started a land bidding war that raised the price of the land for a wind project development. In general, project developers have found that locals and officials, who study for example the impact of wind turbines on birds and bats, often demand illegal payouts to allow the project to be completed (Lokey, 2009).

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

Therefore, based on the above, among the scenarios with high contribution from renewables, the Green scenario could be viewed as the least acceptable by the public because it has the highest penetration of renewables.

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

For scenario B and BAU, which have the highest contribution from fossil fuels, the main public perception issues are related to health impacts from power plants and in the case of CCS, the long-term storage and potential leaks of CO_2 (Pires et al., 2011).

Therefore, each scenario has advantages and disadvantages with respect to public acceptability. However, the A scenarios, followed by the Green, could be considered to offer greater advantages than disadvantages, although their potentially higher acceptability over other scenarios would ultimately depend on the individual views of the communities where the electricity technologies are going to be installed.

3.4.3.3. Health and safety. As outlined in Section 2.1.3, health impacts in this work are quantified as human toxicity potential (HTP) estimated in LCA, while the safety risks are mostly related to occupational accidents and public hazards.

The BAU scenario has by far the highest HTP among all scenarios owing to the high contribution from fossil fuels and in particular the impact from heavy fuel oil. On the other hand, the Green scenario is the best option for the HTP, followed by scenarios A and C (see Section 3.4.1.2, Supplementary information, Figure S1). Furthermore, the scenarios with a high contribution from fossil fuels (BAU and B) have the highest number of fatalities and hazards from accidents along the life cycle (Boyle, 2003). Therefore, it could be argued that scenarios A-3 and Green pose the least health and safety risks and could be considered more sustainable from this perspective than the other scenarios.

3.4.3.4. Intergenerational issues. Intergenerational issues considered in this work include mitigation of climate change, depletion of fossil fuel reserves and management of long-lived hazardous waste related to nuclear waste and CO_2 storage (Section 2.1.3).

As discussed in 3.4.1.1, the best options for mitigation of climate change are scenarios A-3 and C-3 as they have the lowest estimated GWP (Fig. 4). They are followed by the B-3 and Green scenarios; the BAU scenarios is the worst option for this impact. The BAU scenario is also the worst option in terms of depletion of fossil resources, with the highest abiotic depletion potential (Supplementary information, Figure S1); the Green is the best scenario.

Regarding the long-lived hazardous waste management and storage, the C and, to some extent the A scenarios, pose concerns owing to the nuclear power and the B scenarios because of the CCS. Therefore, the Green scenario represents the most sustainable option with respect to long-lived hazardous waste as it avoids both nuclear power and CCS.

3.4.3.5. Summary. With respect to social issues, the BAU scenario has the highest risks related to security and diversity of supply, health and safety and intergenerational issues. Therefore, it is considered the least preferred option. All other future scenarios have different advantages and disadvantages. For example, the Green scenario shows a good performance in terms of fuel import dependency, climate change and intergenerational issues, but with significant social barriers related to public acceptability, availability of renewable resources and reliability of electricity supply. Scenarios B have similar characteristics to BAU, with the main difference being their considerably better climate change mitigation potential because of CCS. Scenarios A exhibit a balance between security and diversity of supply, health and safety and climate change mitigation (particularly A-3). However, like the Green, the main social barriers for these scenarios may be related to public acceptability because of the high contribution from renewables.

3.5. Multi-criteria decision analysis

As shown in the preceding sections, there is no overall ‘best’ scenario, as each option is better for some sustainability criteria but worse for others. Therefore, MCDA has been used to help identify the most sustainable options for future electricity generation in Mexico. The MCDA methodology used in this work has been described in Section 2.5.

The criteria considered within the MCDA comprise all the environmental impacts estimated in LCA (Section 3.4.1). The economic criteria considered are capital and annualised costs (Section 3.4.2); the levelised costs are not included as they show the same trends as the annualised costs, from which they are estimated. Since most social criteria are qualitative apart from human toxicity potential (HTP), also calculated as part of LCA, this is the only social criterion considered within the MCDA. However, the other social criteria are discussed when considering the results of the MCDA to ensure that these issues are taken into account.

The criteria included in the MCDA are listed in Supplementary information, Table S18, showing the values of the respective sustainability indicators for all the scenarios. The evaluation has first been performed assuming equal importance for all the sustainability indicators and these results are presented next. This is followed by a discussion on how the choice of the most sustainable options might change if the criteria have different assumed importance or priority.

3.5.1. Equal weighting of sustainability criteria

The ranking of scenarios and their total sustainability scores estimated using MAVT are shown in Table 9. As can be seen, the Green scenario ranks as the best option for eight out of 12 criteria, achieving the best (lowest) total score of 2.4. The next best options are scenarios C-3 and A-3 scoring 2.9 and 3.0, respectively. The worst option is BAU, ranking bottom for 10 sustainability criteria. However, although the Green scenario scores as the best option overall, it has some important drawbacks. For example, it ranks 4th for the global warming potential, 3rd for ozone layer depletion and total annualised costs and bottom for the capital costs. Moreover, as discussed in Section 3.4.3, the Green scenario has also some critical social aspects to be addressed. These include low reliability of electricity supply (the worst among all scenarios) and various public acceptability issues. Perhaps most importantly, however, it

Table 9
Overall score obtained using MAVT assuming equal preferences for each sustainability criterion (based on the indicator values presented in Supplementary information, Table S18).

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

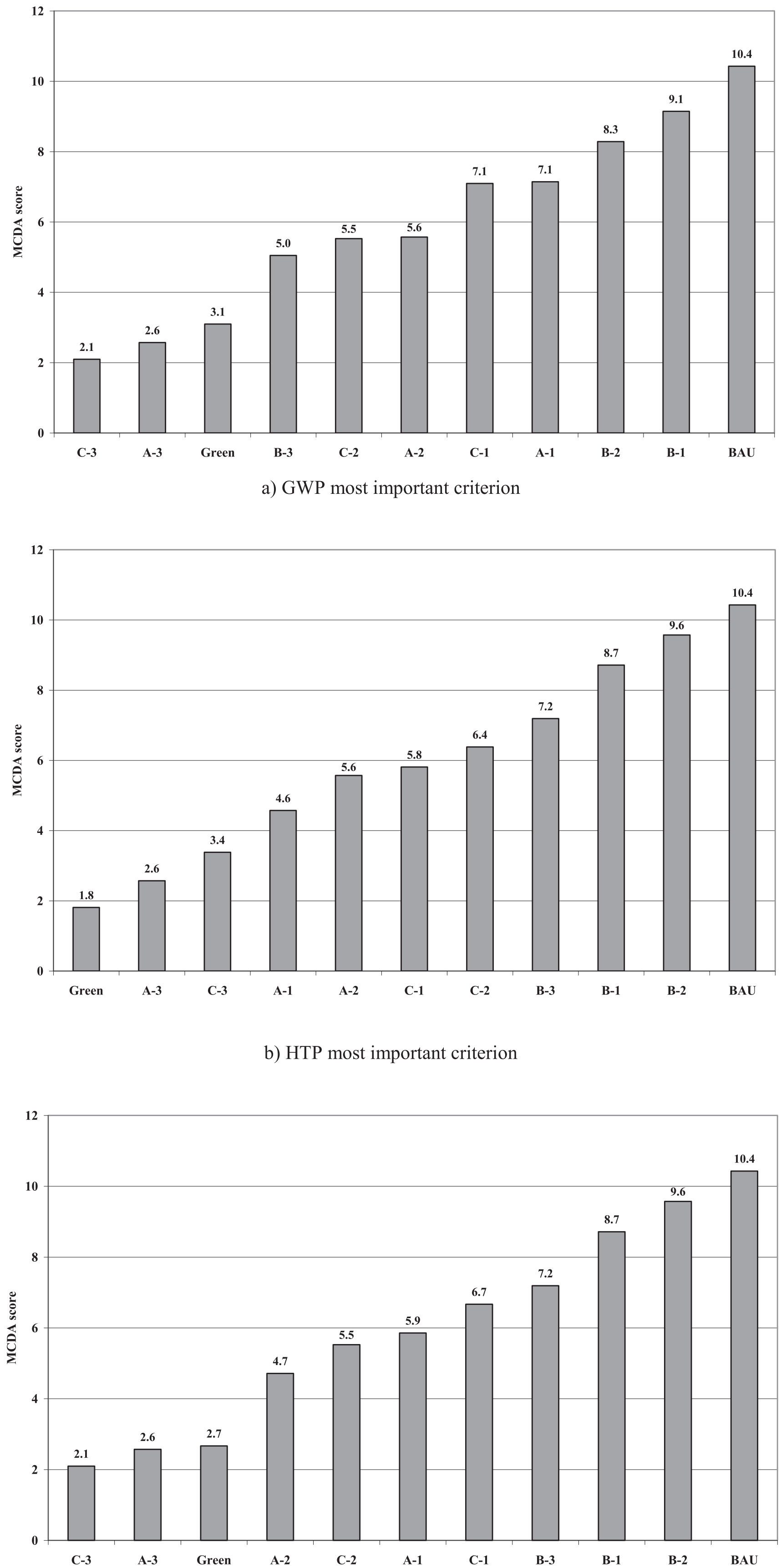

Fig. 9. MCDA score with GWP, HTP and annualised costs being 10 times more important, one at a time, than other criteria (importance weight assigned to each at a time: 48%).

exceeds considerably the estimated available renewable energy potential in Mexico (specifically for wind and ocean energy) and is therefore highly unlikely to be realised by 2050.

3.5.2. Different preferences for sustainability criteria

As discussed in Section 2.5, different stakeholders (e.g. industry, public, government, etc.) will have different priorities related to electricity generation and supply. For this reason, sensitivity analysis is carried out to find out if the ranking of the scenarios changes with different preferences for (and weighting of) the indicators. To limit the analysis to a reasonable number of runs, three indicators are considered – climate change (GWP), human toxicity (HTP) and costs (annualised) – as these have been found to be the important issues for some stakeholders (Roth et al., 2009; Stamford and Azapagic, 2011; Streimikiene, 2010). The SMART method has been used for these purposes (see Section 2.5 for the methodology) as follows:

i) 10 times higher preference is given to one of the three indicators at a time with all other indicators assuming equal importance; and
ii) 10 times higher preference is assigned to each of the three indicators at the same time.

If a 10 times higher preference is given to one of the three indicators at a time, the weight of preference is estimated at 48% (out of 100%). Based on the same assumption, when giving priority to all three indicators at the same time, a weight of 25.6% is estimated for each of the selected criteria, summing to a total weight between them of 77% (with the rest of the criteria accounting for the remaining 23%). Fig. 9 shows the MCDA results (sustainability scores) with the priority assigned to the GWP, HTP, and total annualised costs, respectively; the results considering higher preference for these three indicators at the same time are given in Fig. 10. The full MCDA results can be found in Supplementary information, Tables S19–21.

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

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

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

Finally, Fig. 10 shows that, when priority is given to the three indicators at the same time, scenarios C-3 and A-3 are the best options scoring 2.3. The Green scenario follows closely, ranking the 3rd best option with the score of 2.6. The BAU scenario is again the least sustainable, scoring 10.7. It is followed by B-1 and B-2 which each score 9.1.

3.5.3. Comparison of the results for different criteria preferences

Table 10 summarises the rankings of the scenarios obtained using different preferences for the sustainability criteria. As can be seen, in all the cases, the BAU scenario, which has the highest contribution from fossil fuels, is the least sustainable option for future electricity supply in Mexico. Despite its lowest requirement for capital investment, its poor overall sustainability score is mainly due to its high annualised costs and LCA impacts. The BAU scenario is also considered the worst option from the social perspective (as discussed in Section 3.4.3).

Scenarios B, also based on fossil fuels, perform overall better that the BAU. This is mainly because of their higher contribution of renewable energies and the use of CCS to mitigate climate change. Among the B scenarios, B-3 ranks the best. Therefore, this scenario demonstrates that an 85% reduction of direct GHG emissions can be achieved with fossil fuel options – however, at the expense of other environmental impacts such as depletion of fossil reserves, human and freshwater toxicity as well as the annualised costs and social aspects related to the use of CCS and CO_2 storage.

Overall, increasing the contribution from renewable energies and nuclear power translates into a better sustainability performance which is the case for scenarios A-2, A-1, C-2 and C-1, generally in the middle of the ranking regardless of the preferences for the criteria. The main drawbacks for these options, however, are

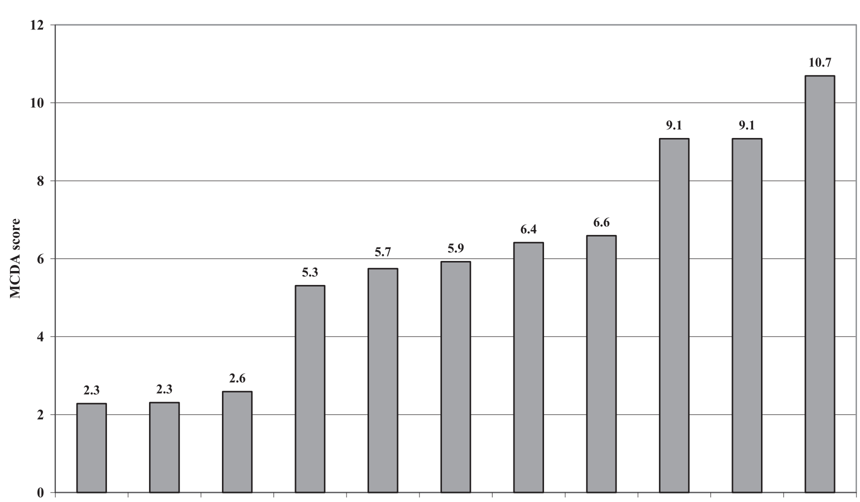

Fig. 10. MCDA score with GWP, HTP and annualised costs being 10 times more important, at the same time, than other criteria (an aggregated weight of importance: 77%).

Table 10
Ranking of scenarios for different preferences for the sustainability criteria (score of 1 denotes the best and 11 the worst option.

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

the public acceptability of a higher penetration of renewables (mainly for scenarios A), health and safety and intergenerational issues (for scenarios C).

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

4. Further discussion and policy recommendations

Although the Mexican Government has made an effort in reducing the environmental impacts by replacing heavy fuel oil-based power with gas combined cycle power plants and is recently increasing wind and hydro-power capacity, this is not a long-term solution for mitigation of climate change. Therefore, electricity policies in the country should be oriented towards increasing and diversifying the contribution from low-carbon technologies, in particular renewables. This would also mitigate against the uncertainty in future fossil fuel costs.

Among the renewable options, geothermal and hydro-power are already well established energy sources in Mexico, yet with a significant potential for development and proven to be reliable sources for electricity supply (for both the base and peak loads). In addition, hydro-power (together with wind) is the option with the lowest global warming potential among the renewables. However, the main barrier for large hydro-power plants is public acceptability, mainly owing to the environmental and social impacts related to dam constructions (e.g. ecosystem impacts, relocation of communities).

Of the emerging technologies, wind power is the fastest-growing and probably has the greatest potential in the short term. Solar power, on the other hand, although with a great potential in Mexico, still has high capital costs and it may be a while before it is affordable in countries such as Mexico. Ocean energy is at an early stage of development, still requiring significant work for the estimation of its energy potential and financial support. While Mexico has large and diverse biomass energy resources (forestry, energy crops and wastes), the implementation of these resources has been limited mostly to the use of sugar cane bagasse for electricity production, owing to the lack of appropriate policies and financial incentives. Therefore, main efforts from the Mexican Government should aim to strengthen the current renewable energy policies within the country.

Additionally, the decarbonisation of the Mexican power sector for the future should implement a more diverse electricity supply combining large-scale use of renewable energies, nuclear power and to a lesser extent the use of CCS for future fossil fuel-based power plants.

In the event the Government opts for a fossil-fuel based policy, scenario B-3 represents the most suitable option, enabling an 85% reduction of GHG by 2050. However, other environmental impacts such as ADP, HTP, FAETP would increase on today's values, mainly because of the use of CCS; the annualised costs would also go up owing to the expected high fossil fuel costs.

On the other hand, by increasing the share of renewable energies and nuclear power in the electricity mix, as in scenarios Green, A-3 and C-3, most of the life cycle environmental impacts are reduced considerably compared to the BAU scenario. Although renewable energy based scenarios require high capital costs, the total annualised costs will even out over time (as evidenced in scenarios C-3 and A-3) owing to lower fuel costs.

While the results of the sustainability assessment of electricity options for Mexico obtained in this work point at the scenarios Green, A-3 and C-3 as the most sustainable options, the selection of the 'best' option will depend highly on stakeholders' and decision makers' preferences. If the focus is on mitigation of climate change impacts, scenarios A-3 and C-3 are the most sustainable options. Scenarios A-3 and C-3 are also favoured when considering climate change, human toxicity and annualised costs as the most important sustainability criteria.

On the basis of this research, a number of policy recommendations can be made with respect to sustainable development of the electricity sector in Mexico:

- more stringent emission standards should be introduced and implemented to regulate the operation of fossil fuel based power plants and reduce their environmental and social impacts in the short term;
- a detailed techno-economic potential of all renewable energies available in Mexico (including ocean energy) should be carried out;
- a feasibility assessment should be carried for CCS (e.g. infrastructure requirements for carbon transport and the potential for carbon storage in Mexico);
- the potential for the expansion of nuclear power should be assessed considering the social aspects outlined in this work such as public acceptability, health and safety and intergenerational issues;
- a policy to stimulate a reduction in electricity demand should be developed and introduced — as the results for the BAU scenario show, the higher demand leads to much higher sustainability impacts than in similar scenarios which assume a lower demand (e.g. B scenarios);
- most sustainable pathways for mitigation of climate change should be identified and implemented (e.g. along the lines of scenarios A-3 and C-3);
- suitable policies and financial support mechanisms for the promotion of low-carbon power generation technologies should be considered and introduced (e.g. incentives, carbon tax);
- besides the existing international incentive mechanisms, such as the Kyoto Protocol (e.g., Clean Development Mechanism, and Emissions Trading), the Government should strengthen the collaboration between the public and private sectors to promote investment and implementation of low-carbon technologies for electricity generation for the future;
- a strategy for skills development and training of personnel for the large-scale deployment of renewable technologies should be developed; and
- activities for awareness raising of different energy technologies among population should be considered and introduced at the national level.

5. Conclusions

This work has proposed a new methodological framework for an integrated sustainability assessment of energy systems. The framework has been applied to the electricity system in Mexico, considering the country's key energy drivers and climate change targets in 2050. It is hoped that both the proposed methodology and the research outcomes from this work can be used as a decision support framework for decision makers to plan electricity supply for the future.

The results of this research illustrate the complexity of decision making in the energy sector, where there are multiple sustainability criteria and different preferences for each. The results also show that in such situations often there are no 'best' solutions and trade-offs are necessary to identify the 'most sustainable' option.

In the case of Mexico considered here as an illustrative example, the 'most sustainable' options identified through MCDA are the Green, A-3 and C-3 scenarios. If an equal weighting of the sustainability criteria is considered, the Green scenario (with 86% contribution from renewables and 14% from fossil fuels) seems to be the most attractive option; this is also so when assuming that human toxicity is the most important criterion. However, the technical feasibility of this scenario is uncertain owing to a very high penetration of renewables which, in addition to the intermittency issues and small base-load capacity, exceeds the currently estimated potential for some of the renewables. On the other hand, when climate change mitigation, costs and human toxicity are all considered more important than the other criteria, then C-3 (55% renewables, 30% nuclear and 15% fossil) and A-3 (75% renewables, 10% nuclear and 15% fossil) are better options. Therefore, these results indicate clearly which future electricity pathways decision and policy makers should consider for a sustainable development of the energy sector in Mexico.

Acknowledgements

This research was funded by the Mexican Council of Science and Technology (CONACYT, Consejo Nacional de Ciencia y Tecnología), the Mexican Ministry of Education (SEP, Secretaría de Educación Pública) and UK Research Councils (grant no. EP/F001444). The authors gratefully acknowledge this funding.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.05.061.

References

Azapagic, A., Perdan, S., 2005a. An integrated sustainability decision-support framework: problem structuring, part I. Int. J. Sustain. Dev. World Ecol. 12 (2), 98–111.

Azapagic, A., Perdan, S., 2005b. An integrated sustainability decision-support framework: methods and tools for problem analysis, part II. Int. J. Sustain. Dev. World Ecol. 12 (2), 112–131.

Azapagic, A., Perdan, S., 2011. Sustainability of nuclear power. Chapter 9. In: Azapagic, A., Perdan, S. (Eds.), Sustainable Development in Practice: Case Studies for Engineers and Scientists, second ed. John Wiley & Sons, Chichester.

Bauer, C., Heck, T., Dones, R., Mayer-Spohn, O., Blesl, M., 2008. Final Report on Technical Data, Costs, and Life Cycle Inventories of Advanced Fossil Power Generation Systems. European Commission within the Sixth Framework Programme, New Energy Externalities Developments for Sustainability.

Boyle, G., 2003. Energy Systems and Sustainability. Oxford University Press in association with The Open University, U.K.

Cancino-Solórzano, Y., Villicaña-Ortiz, E., Gutiérrez-Trashorras, A.J., Xiberta-Bernat, J., 2010. Electricity sector in Mexico: current status. Contribution of renewable energy sources. Renew. Sustain. Energy Rev. 14 (1), 454–461.

Chatzimouratidis, A.I., Pilavachi, P.A., 2009a. Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process. Energy Policy 37 (3), 778–787.

Chatzimouratidis, A.I., Pilavachi, P.A., 2009b. Sensitivity analysis of technological, economic and sustainability evaluation of power plants using the analytic hierarchy process. Energy Policy 37 (3), 788–798.

del Río, P., 2011. Analysing future trends of renewable electricity in the EU in a low-carbon context. Renew. Sustain. Energy Rev. 15 (5), 2520–2533.

Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Roder, A., Emmenegger, M.F., Frischknecht, R., Jungbluth, N., Tuchschmid, M., 2007. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. Ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

DONG Energy, 2008. Final Report on Offshore Wind Technology. European Commission within the Sixth Framework Programme, New Energy Externalities Developments for Sustainability.

Dorini, G., Kapelan, Z., Azapagic, A., 2010. Managing uncertainty in multiple-criteria decision making related to sustainability assessment. Clean. Technol. Environ. Policy 13 (1), 133–139.

EIA, 2009. Electricity Module Market 2009. U.S. Energy Information Administration. www.eia.doe.gov.

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy Rev. 13 (5), 1082–1088.

Frankl, P., Menichetti, E., Raugei, M., 2005. Final Report on Technical Data, Costs, and Life Cycle Inventories of PV Applications (NEEDS), Project no: 502687, European Commission.

Gallego-Carrera, D., Mack, A., 2010. Sustainability assessment of energy technologies via social indicators: results of a survey among European energy experts. Energy Policy 38 (2), 1030–1039.

Greenhalgh, C., Azapagic, A., 2009. Review of drivers and barriers for nuclear power in the UK. Environ. Sci. Policy 12 (7), 1052–1067.

Greenpeace and EREC, 2008a. Energy Revolution: a Sustainable Energy Outlook for Mexico (in Spanish). Greenpeace International and European Renewable Energy Council.

Greenpeace and EREC, 2008b. Energy Revolution: a Sustainable Global Energy Outlook. Greenpeace International and European Renewable Energy Council. http://ec.europa.eu/energy/nuclear/forum/opportunities/doc/competitiveness/2008_09_16_energy_revolution_2009.pdf (accessed on 17.05.14.).

Goodfellow, M.J., Williams, H.R., Azapagic, A., 2011. Nuclear renaissance, public perception and design criteria: an exploratory review. Energy Policy 39 (10), 6199–6210.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., 2001. Life Cycle Assessment: an Operational Guide to the ISO Standards; Part 2a. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of environmental Science (CML), The Netherlands.

Gujba, H., Mulugetta, Y., Azapagic, A., 2010. Environmental and economic appraisal of power generation capacity expansion plan in Nigeria. Energy Policy 38 (10), 5636–5652.

Gujba, H., Mulugetta, Y., Azapagic, A., 2011. Power generation scenarios for Nigeria: an environmental and cost assessment. Energy Policy 39 (2), 968–980.

Heinrich, G., Basson, L., Cohen, B., Howells, M., Petrie, J., 2007. Ranking and selection of power expansion alternatives for multiple objectives under uncertainty. Energy 32, 2350–2369.

IEA, 2004. World Energy Outlook. International Energy Agency, Paris, France.

IEA, OECD, 2008. Energy Technology Perspectives: Scenarios and Strategies to 2050. International Energy Agency and Organisation for Economic Co-operation and Development, Paris, France.

IEA, OECD, 2009. World Energy Outlook. International Energy Agency and Organisation for Economic Co-operation and Development, Paris, France.

IEA, OECD, 2010. World Energy Outlook. International Energy Agency and Organisation for Economic Co-operation and Development, Paris, France.

IEA, NEA, 2010. Projected Costs of Generating Electricity, 2010 Edition. International Energy Agency and Nuclear Energy Agency, France.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Working group I contribution to the fifth assessment report. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York.

Jacobson, M.Z., 2009. Review of solutions to global warming, air pollution, and energy security. Energy & Environ. Sci. 2 (2), 148–173.

Jazayeri, S., Kralovic, P., Honarvar, A., Naini, A., Rozhon, J., Shabaneh, R., Walden, T., 2008. Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario. Canadian Energy Research Institute. www.cna.ca/wp-content/uploads/CERI-ComparativeLCA.pdf (accessed on 17.05.14.).

Jeswani, H., Azapagic, A., Schepelmann, P., Ritthoff, M., 2010. Options for broadening and deepening the LCA aproaches. J. Clean. Prod. 18, 120–127.

Jeswani, H., Gujba, H., Azapagic, A., 2011. Assessing options for electricity generation from biomass on a life cycle basis: environmental and economic evaluation. Waste Biomass Valorization 2 (1), 33–42.

Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, M., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J., 2007. Life Cycle Inventories of Bioenergy. Ecoinvent report No.17. Swiss Centre for Life Cycle Inventories, Dubendorf, CH.

Keles, D., Most, D., Fichtner, W., 2011. The development of the German energy market until 2030 – A critical survey of selected scenarios. Energy Policy 39, 812–825.

Kowalski, K., Stagl, S., Madlener, R., Omann, I., 2009. Sustainable energy futures: methodological challenges in combining scenarios and participatory multi-criteria analysis. Eur. J. Oper. Res. 197 (3), 1063–1074.

Krewitt, W., Simon, S., Graus, W., Teske, S., Zervos, A., Schäfer, O., 2007. The 2 °C scenario – a sustainable world energy perspective. Energy Policy 35 (10), 4969–4980.
Krewitt, W., Teske, S., Simon, S., Pregger, T., Graus, W., Blomen, E., Schmid, S., Schäfer, O., 2009. Energy [R]evolution 2008-a sustainable world energy perspective. Energy Policy 37 (12), 5764–5775.
Lecointe, C., Lecarpentier, D., Maupu, V., Le Boulch, D., Richard, R., 2007. Final Report on Technical Data, Costs, and Life Cycle Inventories for Nuclear Power Plants. New Energy Externalities Developments for Sustainability (NEEDS). Project no: 502687, European Commission. www.needs-project.org/RS1a/RS1a%20D14.2%20Final%20report%20on%20nuclear.pdf (accessed on 17.05.14.).
Løken, E., 2007. Use of multicriteria decision analysis methods for energy planning problems. Renew. Sustain. Energy Rev. 11 (7), 1584–1595.
Lokey, E., 2009. Barriers to clean development mechanism renewable energy projects in Mexico. Renew. Energy 34 (3), 504–508.
MIT, 2006. The Future of Geothermal Energy. Massachusetts Institute of Technology, Massachusetts, United States. http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf (accessed on 17..05.14.).
May, J.R., Brennan, D.J., 2006. Sustainability assessment of Australian electricity generation. Process Saf. Environ. Prot. 84 (2), 131–142.
Maxim, A., 2014. Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis. Energy Policy 65 (2014), 284–297.
Medina-Ross, J.A., Mata-Sandoval, J.C., López-Pérez, R., 2005. Indicators for sustainable energy development in Mexico. Nat. Resour. Forum 29 (4), 308–321.
Nakata, T., Silva, D., Rodionov, M., 2011. Application of energy system models for designing a low-carbon society. Prog. Energy Combust. Sci. 37 (4), 462–502.
Neij, L., 2008. Cost development of future technologies for power generation—a study based on experience curves and complementary bottom-up assessments. Energy Policy 36 (6), 2200–2211.
Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508.
OECD, NEA, 2005. Radioactive Waste Management Programmes in OECD/NEA Member Countries. Organisation for Economic Co-Operation and Development and Nuclear Energy Agency, Mexico. www.oecd-nea.org/rwm/profiles/Mexico_profile_web.pdf (accessed on 17.05.14.).
Onat, N., Bayar, H., 2010. The sustainability indicators of power production systems. Renew. Sustain. Energy Rev. 14 (9), 3108–3115.
Öko Institute, 2005. Global Emission Model for Integrated Systems (GEMIS) Versión 4.3. Germany.
PECC, 2009. Special climate change programme (2009–2012) (in Spanish). Comisión Intersecretarial de Cambio Climático, México. http://web2.semarnat.gob.mx/programas/Documents/PECC_DOF.pdf (accessed on 17.05.14.).
PEMEX, 2008. Diagnosis: Status of PEMEX (in Spanish). Petróleos Mexicanos, México. http://rei.iteso.mx/bitstream/handle/11117/1298/AP%202008-1%20SEM_El%20diagnostico.pdf?sequence=2 (accessed on 17.05.14.).
Pires, J.C.M., Martins, F.G., Alvim-Ferraz, M.C.M., Simões, M., 2011. Recent developments on carbon capture and storage: an overview. Chem. Eng. Res. Des. 89 (9), 1446–1460.
Roth, S., Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Heck, T., Schenler, W., 2009. Sustainability of electricity supply technology portfolio. Ann. Nucl. Energy 36 (3), 409–416.
Rovere, E.L.L., Soares, J.B., Oliveira, L.B., Lauria, T., 2010. Sustainable expansion of electricity sector: sustainability indicators as an instrument to support decision making. Renew. Sustain. Energy Rev. 14 (1), 422–429.
Santoyo-Castelazo, E., Gujba, H., Azapagic, A., 2011. Life cycle assessment of electricity generation in Mexico. Energy 36 (3), 1488–1499.
Santoyo-Catelazo, E., Stamford, L., Azapagic, A., 2014. Environmental implications of decarbonising electricity supply in large economies: the Case of Mexico. Energy Conversion Manag. (in press). http://dx.doi.org/10.1016/j.enconman.2014.05.051.
Schenler, W., Hirschberg, S., Burgherr, P., Makowski, M., Granat, J., 2009. Final Report on Sustainability Assessment of Advanced Electricity Supply Options. New Energy Externalities Developments for Sustainability (NEEDS). Project no 502687, European Commission. www.needs-project.org/docs/NEEDS_RS2b_D10-2%20-%20Final%20Report.pdf (accessed on 17.05.14.).
SENER, 2006a. Prospective power sector 2007–2016 (in Spanish). Secretaria de Energía, México. www.sener.gob.mx/res/PE_y_DT/pub/Prospectiva%20Sector%20Electrico%20FINAS.pdf (accessed on 17.05.14.).
SENER, 2006b. National Energy Balance 2006 (in Spanish). Secretaria de Energía, México. www.sener.gob.mx/res/PE_y_DT/pub/Balance%20Nacional%20de%20Energia%202006.pdf. (accessed on 17.05.14.).
SENER, 2007. Prospective Power Sector 2008–2017 (in Spanish). Secretaria de Energía, México. www.sener.gob.mx/webSener/res/PE_y_DT/pub/Prospectiva%20SE%202008-2017.pdf (accessed on 17.05.14.).
SENER, 2008. National Strategy for Energy Transition and Sustainable use of Energy (in Spanish). Secretaria de Energía, México.
SENER, 2012. National Energy Strategy 2012–2026 (in Spanish). Secretaria de Energía, México. http://www.sener.gob.mx/res/PE_y_DT/pub/2012/ENE_2012_2026.pdf (accessed on 17.05.14.).
Sørensen, H.C., Naef, S., 2008. Report on Technical Specification of Reference Technologies (Wave and Tidal Power Plant). New Energy Externalities Developments for Sustainability (NEEDS), Project no. 502687, European Comission.
Stamford, L., Azapagic, A., 2011. Sustainability indicators for the assessment of nuclear power. Energy 36 (10), 6037–6057.
Stamford, L., Azapagic, A., 2012. Life cycle sustainability assessment of electricity options for the UK. Int. J. Energy Res. 36 (14), 1263–1290.
Streimikiene, D., 2010. Comparative assessment of future power generation technologies based on carbon price development. Renew. Sustain. Energy Rev. 14 (4), 1283–1292.
UNEP, SETAC, 2011. Towards a Life Cycle Sustainability Assessment. Making informed choices on products. UNEP and SETAC. www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf (accessed on 17.05.14.).
Viebahn, P., Nitsch, J., Fischedick, M., Esken, A., Schüwer, D., Supersberger, N., Zuberbhüler, U., Edenhofer, O., 2007. Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany. Int. J. Greenh. Gas. Control 1 (1), 121–133.
Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, J.-H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain. Energy Rev. 13 (9), 2263–2278.