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An integrated life cycle sustainability assessment of electricity generation in Turkey

Burcin Atilgan, Adisa Azapagic*

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

HIGHLIGHTS

- First integrated life cycle sustainability assessment of the electricity sector in Turkey.
- 11 environmental, three economic and six social sustainability indicators estimated.
- Multi-criteria decision analysis carried out to identify most sustainable options.
- Hydro is the most sustainable option for Turkey, followed by geothermal and wind.
- This work demonstrates how tensions among sustainability aspects can be reconciled.

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ABSTRACT

This paper presents for the first time an integrated life cycle sustainability assessment of the electricity sector in Turkey, considering environmental, economic and social aspects. Twenty life cycle sustainability indicators (11 environmental, three economic and six social) are used to evaluate the current electricity options. Geothermal power is the best option for six environmental impacts but it has the highest capital costs. Small reservoir and run-of-river power has the lowest global warming potential while large reservoir is best for the depletion of elements and fossil resources, and acidification. It also has the lowest levelised costs, worker injuries and fatalities but provides the lowest life cycle employment opportunities. Gas power has the lowest capital costs but it provides the lowest direct employment and has the highest levelised costs and ozone layer depletion. Given these trade-offs, a multi-criteria decision analysis has been carried out to identify the most sustainable options assuming different stakeholder preferences. For all the preferences considered, hydropower is the most sustainable option for Turkey, followed by geothermal and wind electricity. This work demonstrates the importance for energy policy of an integrated life cycle sustainability assessment and how tensions between different aspects can be reconciled to identify win-win solutions.

1. Introduction

Sustainable development is becoming increasingly important for many nations. The publication of ‘Our Common Future’ (WCED, 1987), gave the most widely used definition of sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. It is now widely recognised and accepted that sustainable development involves balancing environmental, economic and social issues (Perdan, 2011). Taking a life cycle approach to sustainable development ensures that sustainability aspects are taken into account over the whole life cycle of a system being considered (Perdan, 2011; UNEP/SETAC, 2011). Life cycle sustainability assessment (LCSA) is ideally suited for evaluating the environmental, economic and social sustainability (UNEP/SETAC, 2011). LCSA integrates environmental life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA) to help estimate the level of sustainability of a product, sector or an economy (Guinée et al., 2011; Zamagni et al., 2013).

The electricity sector is important for sustainable development of a region or a country as it affects various environmental, economic and social issues across the supply chain. As indicated in Table 1, these issues have been studied on a life cycle basis for different countries, including Australia, Germany, Mexico, Nigeria, Singapore and the UK. The studies varied with respect to the methodology used for the assessment as well as the electricity technologies and sustainability indicators considered. Life cycle assessment (LCA) has been the most widely used methodology for

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

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Table 1
Recent studies on life cycle sustainability assessment of electricity technologies in different countries.

Authors	Scope	Country	Technologies considered	Sustainability issues (number)
Hirschberg et al. (2004)	Sustainability of electricity supply technologies	Germany	Coal, oil, natural gas, nuclear, hydro, wind, solar	Economic (7): Financial requirements and resources Environmental (5): Climate change, emissions to air, waste, land use, severe accidents Social (6): Employment, proliferation, human health, local disturbances, risk aversion, critical waste confinement time
May and Brennan (2006)	Sustainability assessment of electricity	Australia	Coal, natural gas	Economic (5): Wealth generation, capital requirements Environmental (12): Climate change, resource depletion, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, solid wastes, particulates, water consumption Social (4): Employees, health and safety
Kannan et al. (2007)	Life cycle energy, emissions and costs of power	Singapore	Coal, gas, oil, solar	Economic (3): Total levelised costs Environmental (2): Climate change, energy use
Genoud and Lesourd (2009)	Characterization of sustainable development indicators for various power generation technologies	Not specified	Coal, natural gas, oil, nuclear, hydro, solar, wind, geothermal	Economic (5): Efficiency, renewability, production capacity upon demand, possibility of growth, cost Environmental (10): CO_2, NO_x, SO_2, VOCs, Cd, CH_4 emissions, particles, biochemical oxygen demand, radioactivity, noise pollution Social (6): Notion of public good, land area requirement, energy payback, employment, supply risk, use of local energy resources
Evans et al. (2009)	Assessment of sustainability indicators for renewable energy technologies	Not specified	Solar PV, wind, hydro, geothermal	Techno-economic (3): Levelised costs, efficiency of energy conversion, availability, technical limitations Environmental (3): Climate change, water consumption, land use Social (8): Toxin release, noise, bird strike risk, visual amenity, effect on agriculture and seismic activity, odour, river damage
Gujba et al. (2010)	Sustainability assessment of energy systems	Nigeria	Coal, natural gas, oil, hydro, biomass, solar, wind	Economic (3): Levelised costs, capital costs, total annualised costs Environmental (10): Climate change, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion
Jeswani et al. (2011)	Assessing options for electricity generation from biomass	UK	Coal, direct-fired biomass, gasified biomass	Environmental (5): Climate change, acidification, eutrophication, photochemical smog, human toxicity Economic (2): Capital costs, total annualised costs
Stamford and Azapagic (2012)	Sustainability assessment of electricity	UK	Nuclear, coal, natural gas, offshore wind, solar	Techno-economic (13): Operability, technological lock-in, immediacy, levelised costs, cost variability, financial incentives Environmental (11): Climate change, recyclability, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, land use Social (19): Provision of employment, human health impacts, large accident risk, local community impacts, human rights and corruption, energy security, nuclear proliferation, intergenerational equity
Maxim (2014)	Sustainability assessment of electricity generation technologies	Not specified	Coal, natural gas, piston engine, combined heat and power (CHP), fuel cell, hydro (large and small), wind (onshore and offshore), solar, geothermal, biomass, nuclear	Techno-economic (4): Ability to respond to demand, efficiency, capacity factor, levelised costs Environmental (2): Land use, external costs (environmental) Social (4): External costs (human health), job creation, social acceptability, external supply risk
Santoyo-Castelazo and Azapagic (2014)	Sustainability assessment of electricity	Mexico	Nuclear, coal, natural gas, oil, hydro, geothermal, wind	Economic (3): Levelised costs, capital costs, total annualised costs Environmental (10): Climate change, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion Social (4): Energy security, public acceptability, health and safety, intergenerational issues

evaluating the environmental sustainability. All of the studies considered environmental and economic issues and most assessed the social sustainability, except Kannan et al. (2007), Jeswani et al. (2011) and Gujba et al. (2010). Some studies also included technological issues such as efficiency, capacity factor, availability and operability (Evans et al., 2009; Stamford and Azapagic, 2012; Maxim, 2014).

However, to date, there have been no sustainability studies of electricity generation in Turkey. Turkey is developing rapidly and its electricity consumption is growing fast. In 2010, the total installed capacity of 49,524 MW generated 211,208 GWh of electricity, four times more than in 1990 (TEIAS, 2012). Although the country's electricity mix includes hydropower, wind and geothermal power, coal and natural gas dominate, providing 73% of the total generation (EUAS, 2011). As a result of its growing electricity demand and a lack of domestic fossil fuels (apart from lignite), Turkey has become dependent on other countries with the share of imported power continuing to increase each year. The security of energy supply, especially of natural gas imports, is one of the most important energy strategy objectives in Turkey (MENR, 2009). Moreover, the high share of fossil fuels in the national electricity mix, together with the increasing demand, has led to a steady increase in greenhouse gas emissions and other environmental impacts from the electricity sector.

Being a party to Kyoto Protocol (Annex I), Turkey is under pressure to reduce its emissions. On the other hand, the price of electricity is high owing to the import dependency: 14.8 US$ cent/kWh for industrial and 18.5 US$ cent/kWh for domestic consumers, around 20% and 10% above the OECD average, respectively (IEA, 2014). Additionally, there are serious issues related to the occupational safety in the Turkish electricity sector, with over 300 deaths in 2014 alone as a result of coal mine accidents (Acar et al., 2015). However, beyond these scant data, there is little information on the sustainability of the electricity sector in Turkey, particularly on a life cycle basis.

Therefore, this paper sets out to evaluate the life cycle sustainability of the Turkish electricity sector by considering different technologies currently operational in Turkey and integrating environmental, economic and social aspects. As far as the authors are aware, this is a first study of its kind for Turkey, aiming to inform future energy policy.

2. Methodology

As outlined in Fig. 1, the methodology for evaluating the sustainability applied in this work involves five steps: definition of the goal and scope of the assessment; identification of sustainability issues and related indicators; life cycle sustainability assessment of different electricity options taking into account environmental, economic and social aspects; integration of these aspects using multi-criteria decision analysis; and policy recommendations. These steps, together with the data and assumptions used in the study, are described in more detail in the following sections.

2.1. Goal and scope definition

The goal of this study is to evaluate the life cycle sustainability of the Turkish electricity sector by considering environmental, economic and social impacts of different technologies currently present in the electricity mix. The findings will be used to identify the most sustainable electricity options for the country and make policy recommendations for improving the sustainability in the electricity sector.

The unit of analysis (functional unit) is 'generation of 1 kWh of electricity in Turkey'. The scope of the study is from 'cradle to grave', taking into account extraction, processing and transportation of raw materials and fuels (where relevant) as well as construction, operation and decommissioning of power plants (Fig. 2). In total, there are 516 power plants in Turkey, all of which are considered. The focus is on electricity generation so that its transmission, distribution and use are outside the scope of the study.

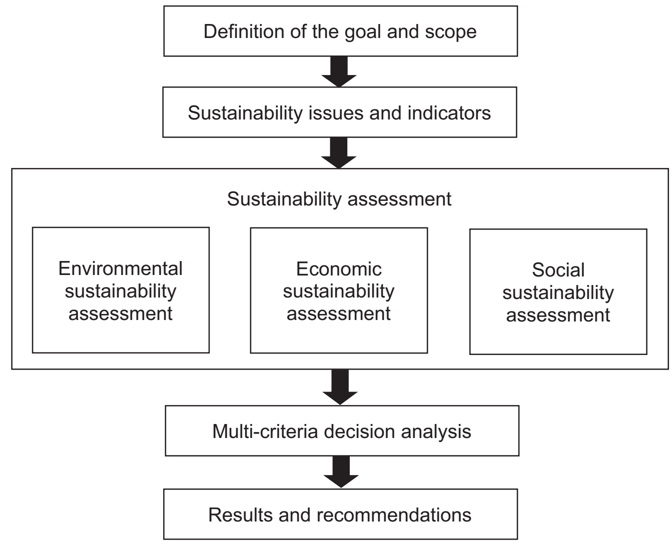

Fig. 1. Methodology for assessing the sustainability of electricity generation.

2.2. Sustainability issues and indicators

The sustainability issues and indicators relevant to the Turkish electricity sector have been identified through an extensive literature survey, taking into account government and industry reports and strategy documents (e.g. IAEA (2005), MENR (2009), Chatzimouratidis and Pilavachi (2009), Onat and Bayar (2010), Kaygusuz (2011), Serencam and Serencam (2013)) as well as previous sustainability studies of electricity elsewhere (e.g. those listed in Table 1). The issues and related indicators are summarised in Table 2 with a brief overview given below; for further details on how the individual indicators have been calculated, see Section 1 in the Supplementary material.

As indicated in Table 2, the following environmental issues are considered: climate change, resource depletion and emissions to air, water and soil. Since LCA has been used in this work to assess the environmental sustainability, these issues have been translated into 11 environmental indicators typically considered in LCA and quantified using the CML 2001 impact assessment method (Guinée et al., 2001), November 2010 update. The LCA has been carried out following the guidelines in the ISO 14040 and 14044 standards (ISO, 2006a,b). The software packages GEMIS 4.8 (Öko Institute, 2012) and GaBi v.6 (PE International, 2013) have been used to model the systems and estimate the impacts.

Three economic indicators are estimated – capital, annualised and levelised costs – all related to the issue of electricity costs. The capital costs represent the total construction costs of a power plant, including land, planning, construction, commissioning and working capital costs (May and Brennan, 2006). Total annualised costs are related to the annual costs of operating the system while levelised or unit costs are the average costs over the lifetime of a plant expressed per unit of electricity generated (Rubin et al., 2013). Their estimation is detailed in Section 1 in the Supplementary material.

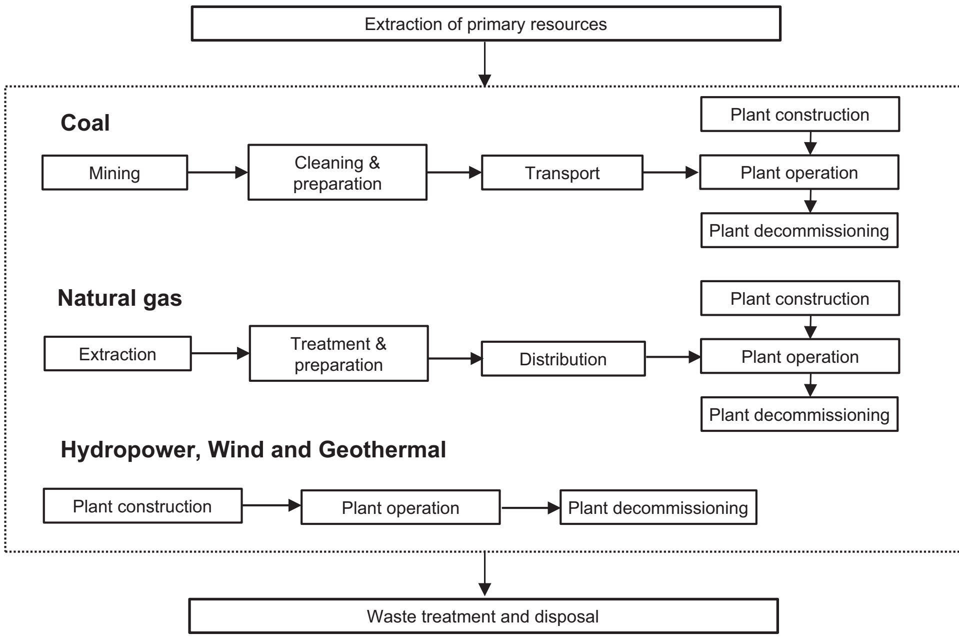

Fig. 2. The life cycle of the electricity options currently present in Turkey.

Table 2
Environmental, economic and social issues and indicators.

Sustainability aspects	Sustainability issues	Sustainability indicators	Units
Environmental	Resource depletion	Abiotic resource depletion potential (elements)	kg Sb eq./kWh
		Abiotic resource depletion potential (fossil fuels)	MJ/kWh
	Climate change	Global warming potential	kg CO_2 eq./kWh
	Emission to air, water and soil	Acidification potential	kg SO_2 eq./kWh
		Eutrophication potential	kg PO_4 eq./kWh
		Fresh water aquatic ecotoxicity potential	kg DCB[a] eq./kWh
		Human toxicity potential	kg DCB[a] eq./kWh
		Marine aquatic ecotoxicity potential	kg DCB[a] eq./kWh
		Ozone layer depletion potential	kg CFC-11 eq./kWh
		Photochemical oxidants creation potential	kg C_2H_4 eq./kWh
		Terrestrial ecotoxicity potential	kg DCB[a] eq./kWh
Economic	Costs	Capital costs	US$
		Total annualised costs	US$/year
		Levelised costs	US$/kWh
Social	Provision of employment	Direct employment	Person-years/TWh
		Total employment (direct+indirect)	Person-years/TWh
	Worker safety	Injuries	No. of injuries/TWh
		Fatalities due to large accidents	No. of fatalities/TWh
	Energy security	Imported fossil fuel potentially avoided	koe[b]/kWh
		Diversity of fuel supply mix	Score (0–1)[c]

[a] DCB: dichlorobenzene.
[b] koe: kilogram oil equivalent.
[c] A score of 1 represents a diverse fuel supply and a score of 0 indicates an over-reliance on one exporter.

Three social issues pertinent to the electricity sector in Turkey are evaluated: provision of employment, worker safety and energy security. For each issue, two relevant indicators have been formulated (Table 2) and estimated using a life cycle approach where relevant (see Section 1 in the Supplementary material).

Two types of employment are estimated: direct and total. The former refers to the number of jobs during the construction, operation, maintenance and decommissioning of a power plant. The total employment is a sum of direct and indirect employment with the latter relating to the number of jobs in fuel extraction and processing as well as manufacturing of plant parts.

The safety issues are quantified through the number of worker injuries and fatalities. The former takes into account the total number of injuries per unit of electricity generated over the lifetime of an electricity technology and the latter the number of fatalities in large accidents in the supply chain (Stamford and Azapagic, 2012).

Finally, energy security is measured via two indicators: imported fossil fuel potentially avoided and diversity of fuel supply. The former estimates the amount of imported fossil fuels potentially avoided through the utilisation of technologies that do not rely on imported fossil fuels while the latter evaluates the national supply diversity based on the Simpson diversity index (Stamford and Azapagic, 2012).

2.3. Sustainability assessment: data and assumptions

To evaluate the sustainability of individual electricity options as well as the overall electricity sector in Turkey, data have been collected from a variety of sources. The data represent the annual averages and thus do not account for the variations in the fuel mix and operational parameters that may happen during the year. The most complete data set was available for the year 2010 which is considered here as the base year.

As mentioned in the introduction, the total installed capacity in that year was 49,524 MW which generated 211,208 GWh (TEIAS, 2012). There were 16 lignite, eight hard coal, 187 gas, 55 reservoir and 205 run-of-river hydropower, 39 wind and six geothermal power plants, all of which are considered in this study (see Table 3 and Tables S2-1–S2-7 in the Supplementary material). The contribution of the liquid-fuel power plants to the total generation of electricity is small (1%) and for simplicity this has been substituted with the equivalent amount of electricity generated by the gas power plants. The data on the specific technologies for other renewables and waste have not been available. As their contribution to the total electricity generation is very small (0.2%), they have been substituted by small reservoir hydropower. Furthermore, the data on the specific technologies for multi-fuel plants have not been available either. Thus, the solid-liquid multi-fuel plants have been substituted by the data for lignite plants and the gas-liquid plants by gas plants.

The assumptions and data sources for different electricity technologies for the environmental, economic and social indicators are discussed in the following sections.

2.3.1. Environmental data and assumptions

The inventory data and the assumptions for the power plants are summarised in Table 4. The background life cycle inventory data have been sourced largely from Ecoinvent v2.2 (Dones et al., 2007) but have been adapted as far as possible to Turkey's conditions. Where the appropriate data were not available in Ecoinvent or were not detailed enough, other sources have been used, specifically for hydropower (Flury and Frischknecht, 2012), onshore wind (Kouloumpis et al., 2015) and geothermal (PE International, 2013). For the latter, only aggregated data for a 30 MW flash-steam plant have been available so that it has not been possible to adapt them to Turkish conditions. However, as flash-steam plants provide two thirds of electricity from geothermal sources in Turkey (Parlaktuna et al., 2013) and geothermal power contributes only 0.3% to electricity generation (Table 3), this limitation is not deemed significant.

Table 3
Power plants in Turkey in 2010.

Type of power plant	Number of plants	Installed capacity (MW)	Annual generation (GWh/year)	Contribution to generation (%)
Lignite	16	8140	35,942	17.0
Hard coal[a]	8	3751	19,104	9.0
Natural gas	187	18,213	98,144	46.5
Large reservoir hydropower (capacity > 500 MW)	8	8459	30,583	14.5
Small reservoir hydropower (capacity < 500 MW)	47	4608	13,885	6.6
Run-of-river hydropower	205	2764	7327	3.5
Onshore wind	39	1320	2916	1.4
Geothermal	6	94	668	0.3
Total		**47,349 (49,524)**[b]	**208,569 (211,208)**[c]	

[a] Hard coal type power plant includes hard coal, imported coal and asphaltite power plants in Turkey.
[b] The total installed capacity in 2010 was 49,524 MW. The difference from the installed capacity shown in the table is due to multi-fuel, liquid fuel and other renewable-waste plants not included in the table. However, the total actual installed has been used to estimate the impacts from electricity generation.
[c] The total generation was 211,208 GWh. The difference from the generation shown in the table is due to liquid fuel and other renewable-waste plants not included in the table. However, the total actual electricity generation has been used to estimate the impacts from electricity mix.

The size and capacity of the hydropower plants and wind turbines in Ecoinvent differ from the plants in Turkey so that it has been necessary to scale them up or down. The scaling approach typically used to estimate the costs of plants with differing capacities (Coulson et al., 1993) has been used for these purposes. This method takes into account the 'economies of scale', whereby larger plants cost less to build per unit of capacity than smaller installations. The same analogy has been applied to the environmental impacts, which would also be lower per unit of capacity for bigger than smaller plants. Thus, the impacts have been scaled according to the following relationship (Greening and Azapagic, 2013):

$$E_2 = E_1 \times \left(\frac{C_2}{C_1}\right)^{0.6} \quad (1)$$

where:

E_1 environmental impacts of the larger plant.
E_2 environmental impacts of the smaller plant.
C_1 capacity of the larger plant.
C_2 capacity of the smaller plant.
0.6 'six-tenths' scaling factor.

2.3.2. Economic data and assumptions

The cost data used in the analysis correspond to the year 2012 rather than 2010 because of better data availability; thus all costs are expressed in 2012 US$. However, the 2012 costs have been applied to the electricity mix in the base year so that the basis of analysis remains the same as for the other two sustainability aspects. The cost data given in Table 5 have been sourced from Turkey's electricity generation plan (TEIAS, 2013). Specific capital costs data were not available for different hydropower options; therefore, the costs of large and small reservoir and run-of-river hydropower plants have been assumed based on the data from government reports and academic literature (Lako et al., 2003; TEIAS, 2013; Schröder et al., 2013; IRENA, 2012; Kucukali and Baris, 2009).

The assumed lifetimes of the power plants are given in Table 4. The discounting rate of 10% has been applied for the calculation of the annualised capital costs (TEIAS, 2013). This is congruent with the discounting rate commonly applied in the electricity sector and therefore enables more valid comparison to existing studies (e.g. IEA/NEA (2011, 2005) and IEA et al. (2015)).

2.3.3. Social data and assumptions

Direct and indirect employment for each technology has been estimated by using the employment factors for different life cycle stages, i.e. construction and installation, manufacturing of plant parts, operation and maintenance, fuel extraction and processing, and decommissioning. The employment factors for Turkey have been calculated based on the employment factors in the OECD countries (Rutovitz and Harris, 2012) and labour productivity in Turkey. The latter is estimated by dividing the Gross Domestic Production (GDP) by the total employment in each life cycle stage. Thus, the employment factors EF_i have been estimated for each life cycle stage according to the following relationship (Yilmaz, 2014):

Table 4
Assumptions and summary of inventory data.

Coal	Gas	Hydropower	Wind
Mining and processing **Lignite** Domestic (see Table 7), open pit and underground mining Composition (% w/w): Sulphur: 0.8–4.5%; ash: 19–40%; water: 20–50% Net heating value (NHV): 7.2–13.9MJ/kg **Hard coal** Domestic and imported (see Table 7), open pit and underground mining Composition (% w/w)[a]: Sulphur: 0.5–0.9%; ash: 7–11%; water: 4–7% NHV: 27–27.5MJ/kg **Transport**[b] **Lignite** Power plants adjacent to the mine **Hard coal** Russia: Freight train (4500 km); freight ship (500 km) USA: Freight train (1000 km); freight ship (9500 km) South Africa: Freight train (500 km); freight ship (12,500 km) **Plant construction** Lifetime: 30 years[c] **Lignite** Data from Ecoinvent[d] based on average size of the plant of 380 MW (a mix of 500 MW and 100 MW plants in a 70:30 ratio) **Hard coal** Data from Ecoinvent[d] based on average size of the plant of 460 MW (a mix of 500 MW and 100 MW plants at 90:10 ratio) **Plant operation** Efficiency Lignite: 29–38%; hard coal: 31–40% Average water use: 37.3 kg/kWh for lignite; 32.7 kg/kWh for hard coal **Plant decommissioning**[e] Metals: 50% recycled, 50% landfilled Concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled	**Mining and processing** Imported (see Table 7), Composition (% vol.)[a]: C_1: 94.7–97.3%; C_2: 1–3.4%; C_3:0.3–0.6%; C_4: 0.1–0.4%; C_{5+}: 0.02–0.1%; CO_2:0.06–0.6%; N_2: 0.1–4.6% NHV: 36.5–40.4 MJ/kg Leakage during extraction: 0.38% **Transport**[b] Pipeline Russia: 5750 km Iran: 2700 km Azerbaijan: 1150 km Nigeria: 4000 km Other: 4500 km **Plant construction** Lifetime : 25 years[c] Data from Ecoinvent[d] assuming 400 MW plant **Plant operation** All plants assumed to be CCGT with efficiency of 55% Average water use: 3.4 kg/kWh **Plant decommissioning**[e] Metals: 50% recycled, 50% landfilled Concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled	**Plant construction** **Reservoir** Lifetime: 150 years[d,f] Large reservoir Data based on Ecoinvent[d,g] with average size of 175.6 MW plant and scaled up to 1057 MW plant Small reservoir Data based on ESU[f] with average size of 95 MW plant and scaled up to 98 MW plant **Run-of-river** Lifetime: 80 years[d,f] Data based on ESU[f] with average size of 8.6 MW plant and scaled up to 13.5 MW plant **Transport**[b] Construction materials[h] Freight train: 200 km Lorry > 16 tonne: 100 km **Plant operation** **Reservoir** Large reservoir Lubricating oil: 7.0×10^{-6} kg/kWh Small reservoir Lubricating oil: 3.24×10^{-8} kg/kWh **Run-of-river** Lubricating oil: 1.22×10^{-7} kg/kWh **Plant decommissioning**[e] Metals: 50% recycled, 50% landfilled Concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled	**Plant construction** Onshore Lifetime: 40 years for fixed parts and 20 years for moving parts[d] Number of turbine:682 Data based on the average size of 2 MW turbine[i] and scaled down to 1.94 MW turbine **Transport**[b] Construction materials Freight train: 200 km Lorry > 16 tonne: 100 km Turbine Freight train: 2000 km Lorry > 16 tonne: 150 km Maintenance Passenger car: 100 pkm/year **Plant operation** Lubricating oil: 4.31×10^{-5} kg/kWh **Plant decommissioning**[e] Metals: 50% recycled, 50% landfilled Concrete: 50% recycled, 50% landfilled Plastics: 20% recycled, 80% landfilled

[a] Based on data from different mines and countries.
[b] Estimated by using online mapping.
[c] Source: TEIAS (2013).
[d] Source: Dones et al. (2007).
[e] The system has been credited for recycling. The recycling rates are assumed due to a lack of data.
[f] Source: Flury and Frischknecht (2012).
[g] Source: Bauer and Bolliger (2007).
[h] It is assumed that gravel is extracted at the construction site.
[i] Source: Kouloumpis et al. (2015).

Table 5
Costs of power plants in Turkey (TEIAS, 2013)[a].

Power plant type	Capital costs (US$/kW)	Fixed costs (US$/kW-year)	Variable costs (US$ cents/kWh)	Fuel costs (US$/t)[b]
Lignite	1750	33.7	1.98	25
Hard coal				
Domestic	1750	44.3	1.48	75
Imported	1900	53.6	2.03	115
Natural gas	800	5.6	0.7[c]	750
Large reservoir	1600	6.0	6.0[d]	–
Small reservoir	1800	6.0	6.0[d]	–
Run-of-river	2300	6.0	6.0[d]	–
Onshore wind	2000	14.0	2.0	–
Geothermal[e]	2500	14.0	2.0	–

[a] All values in 2012 US$.
[b] Gas: US$/1000 N m^3 (standard conditions: 1 atm and 15 °C).
[c] Estimated based on two power plants due to lack of data.
[d] US$/kW-year.
[e] Source: Sener and Aksoy (2007).

$$EF_i=\frac{\frac{GDP_{OECD}}{E_{i,OECD}}}{\frac{GDP_{Turkey}}{E_{i,Turkey}}}\times EF_{i,OECD} \quad (2)$$

where:

GDP_{OECD} gross domestic product for member countries of the Organization for economic cooperation and development (OECD) (US$).
GDP_{Turkey} gross domestic product for Turkey (US$).
$E_{i,\ OECD}$ employment in the life cycle stage i in the OECD countries (jobs/MW).
$E_{i,\ Turkey}$ total employment in the life cycle stage i in Turkey (jobs/MW).
$EF_{i,\ OECD}$ employment factor in the OECD countries for the life cycle stage i (jobs/MW).
$GDP_{OECD}/E_{i,\ OECD}$ labour productivity factors for the OECD for the life cycle stage i.
$GDP_{Turkey}/E_{i,\ Turkey}$ labour productivity factors for Turkey for the life cycle stage i.

The estimated employment factors for Turkey are presented in Table 6. Owing to the lack of data, the employment in the decommissioning stage is assumed to be 20% of construction employment. For the lignite fuel cycle, regional employment factors have been calculated using the data from government and industrial reports as well as academic literature (Ersin, 2006; WEC, 2011). As most hard coal used in Turkey is imported from the USA, Russia and South Africa (Table 7), fuel cycle employment factors were calculated using the employment factors in these countries (Rutovitz and Harris, 2012).

The worker injuries and fatalities have been estimated using the worker injury and fatality rates and the number of jobs in each life cycle stage. The data on injuries and fatalities for the life cycle stages occurring in Turkey have been sourced from the statistical yearbook of the Social Security Institution (SSI, 2013). Owing to the lack of data, the same injury and fatality rates have also been used for the parts of the life cycle taking place elsewhere. Although this is a limitation of the study, this assumption is reasonable given that the majority of the fuels are imported from developing countries (see Table 7) where safety regulation and practices may be similar to those in Turkey.

The amount of imported fossil fuel that can potentially be avoided through the utilisation of technologies that do not rely on imported fossil fuels is based on the average efficiency of the hard coal and gas plants (for details see Table 4). The proportions of national fuel demand supplied domestically and imported in 2010 (see Table 7) have been used to calculate the diversity of the fuel supply mix.

2.4. Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) has been used to integrate the three aspects of sustainability and help identify the most sustainable electricity options taking into account different preferences for the aspects. MCDA helps decision makers to choose the best option when a wide range of criteria has to be considered (Azapagic and Perdan, 2005a). There are many types of MCDA methods; examples include multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT) and analytical hierarchy process (AHP). For an overview of MCDA methods, see e.g. Azapagic and Perdan (2005b) and Wang et al. (2009).

Multi-attribute value theory (MAVT) has been used for these purposes because it allows a simultaneous consideration of all three aspects of sustainability, allowing compensation among them, which is often needed in policy applications (Azapagic and Perdan, 2005b). In this method, the overall sustainability score for each alternative is estimated as follows (Azapagic and Perdan, 2005b):

$$v(a)=\sum_{i=1}^{I} w_i v_i(a) \quad (3)$$

Table 6
Employment factors in different sectors in Turkey estimated in this study.

Power plant type	Construction and installation (job-years/MW)	Manufacturing (job-years/MW)	Operation and maintenance (jobs/MW)	Fuel extraction and processing (jobs/PJ)
Lignite	13.48	7.25	0.18	31.80
Hard coal	13.48	7.25	0.18	21.20
Natural gas	2.98	2.07	0.14	17.00
Large reservoir [a]	6.00	1.50	0.30	–
Small reservoir [b]	10.50	3.11	0.53	–
Run-of-river [c]	15.44	11.39	0.98	–
Onshore wind	4.38	12.63	0.36	–
Geothermal	12.08	8.07	0.71	–

[a] Owing to the lack of data, the large hydropower plant employment factors in OECD countries (Rutovitz and Harris, 2012) have been used directly for large reservoir hydropower plants in Turkey.
[b] The employment factors for small reservoir hydropower plants in Turkey have been calculated based on the large hydropower plant employment factors of the OECD countries (Rutovitz and Harris, 2012) by using the average labour productivity in Turkey.
[c] Owing to the lack of specific data for run-of-river hydropower plants, the average employment factors for the construction and operation stages have been assumed based on the environmental impact assessment reports for different sizes of the run-of-river plants in Turkey (Dokay, 2009; MGS, 2011; Doga, 2011; Topcuoglu, 2011; Cinar, 2011; EN-CEV, 2012; Nazka, 2014; Akya, 2014; Topcuoglu, 2008; Golder Associates, 2008; AK-TEL, 2009).

Table 7
Domestic and imported fuels in Turkey in 2010[a].

	Natural gas (million m^3)	Hard coal (million tonnes)	Lignite (million tonnes)
Domestic	–	0.20	55.89
Imported			
Russia	9921	4.45[b]	–
Iran	4383	–	–
Azerbaijan	2551	–	–
Algeria	2205	–	–
Nigeria	671	–	–
USA	–	1.48	–
South Africa	–	1.48	–
Other (spot market)	1738	–	–
Total	**21,469**	**7.61**	**55.89**

[a] Own calculations based on various sources.
[b] This includes the amount of hard coal imported from Colombia but as there are no LCA data for the Colombian coal, the LCA impacts from the Russian coal have been used instead.

where:

v(a) overall sustainability score of electricity option a.
w_i weight of importance for decision criterion i (sustainability indicator or aspect).
$v_i(a)$ score reflecting the performance of option α on criterion i (sustainability indicator or aspect).
I total number of decision criteria (sustainability indicators or aspects).

To obtain the overall sustainability score for each electricity option, the MCDA has been carried out in two stages. First, Eq. (3) has been used to obtain the scores for each sustainability aspect (environmental, economic and social), based on the values of the corresponding sustainability indicators estimated in the sustainability assessment and their weights of importance. In that case, the decision criteria in Eq. (3) represent the sustainability indicators. In the second stage, the decision criteria are the sustainability aspects and Eq. (3) is applied to estimate the overall sustainability score of an option using the scores for the sustainability aspects estimated in the first stage and the weights of importance for each aspect.

The MCDA was first performed assuming equal importance of all the aspects and indicators. This was followed by assuming in turn a much higher preference for one aspect at a time to find out how the sustainability performance of different electricity options may change. Since elicitation of preferences by decision makers and stakeholders has been outside the scope of the study, potential preferences have been assumed as part of this work. To test the robustness of the MCDA results, a sensitivity analysis has been carried out to determine how the ranking of the technologies would change with different weighting of the sustainability aspects.

3. Results and discussion

This section first discusses the results of the environmental sustainability assessment, followed by the economic and social assessments. The latter parts of the paper discuss the findings of the integrated sustainability assessment through MCDA. Further details on the sustainability assessment results can be found in Tables S3-1 and S3-2 in the Supplementary material.

3.1. Environmental sustainability assessment

The results of the environmental sustainability assessment are given in Figs. 3 and 4. The former shows the impacts of each type of electricity option and the latter the impacts of the Turkish electricity mix in the base year. They are discussed in turn in the next sections.

3.1.1. Environmental sustainability of electricity technologies

The results in Fig. 3 suggest that geothermal power is the most sustainable option for six out of 11 impacts (eutrophication, ozone layer depletion and all the toxicity categories). Large reservoir hydropower has the lowest depletion of elements and fossil resources as well as acidification. Run-of-river is the best option for the global warming potential and small reservoir is the best for photochemical oxidants, precursors of summer smog. The worst option overall is lignite with eight impacts higher than for any other option. Hard coal power has the highest depletion of elements and the global warming potential while gas has the highest ozone layer depletion. These results are discussed in more detail below.

3.1.1.1. Abiotic depletion potential (ADP elements and fossil). As shown in Fig. 3, hard coal has the highest ADP elements (81 µg Sb-eq./kWh) followed by wind (67 µg Sb-eq./kWh). This impact is primarily due to the use of chromium, copper, molybdenum and nickel for construction of the plants and coal supply. Large reservoir hydropower is the best options for this indicator with a value of 3 µg Sb-eq./kWh.

As expected, the depletion of fossil resources is highest for fossil-fuel power plants with 15.1 MJ/kWh for lignite, 13.5 MJ/kWh for hard coal and 8.8 MJ/kWh for gas. Fuel extraction is the single largest contributor to this impact. By comparison, the depletion of fossil resources for the renewable options is several orders of magnitude lower, ranging from 0.02 MJ/kWh for small-reservoir hydro and geothermal power to 0.1 MJ/kWh for wind electricity.

3.1.1.2. Acidification potential (AP). The lignite life cycle is the worst option for this indicator, with a value of 10.8 g SO_2-eq./kWh. AP for hard coal is around 1.8 times lower (6 g SO_2-eq./kWh) than for lignite. The vast majority of this impact is due to the high sulphur content in lignite and a lack of desulphurisation at some coal power plants (see Supplementary material, Table S2-1). Large reservoir hydropower is best for this environmental impact, with a value of 3 mg SO_2-eq./kWh.

3.1.1.3. Eutrophication potential (EP). This impact shows the same trend as AP: lignite power is the worst option with 11.9 g PO_4-eq./kWh, mainly owing to the emissions of phosphates to fresh water, primarily from mining. Estimated at 2.3 g PO_4-eq./kWh, EP from hard coal power is around five times lower than for lignite. By comparison, geothermal and large reservoir power have EP of 1 and 1.2 mg PO_4-eq./kWh, respectively.

3.1.1.4. Freshwater aquatic ecotoxicity potential (FAETP). As can be seen in Fig. 3, the ranking of the options for this environmental impact is the same as for AP and EP. With FAETP of 2.1 kg DCB-eq./kWh, lignite is the worst option, predominantly because of the emissions of metals to freshwater during mining, including nickel, beryllium, cobalt, vanadium, copper and barium. The value for hard coal power is estimated at 0.4 kg DCB-eq./kWh, around five times lower than for lignite. Both values are still several orders of magnitude higher than for gas and the renewables: for example, the impact from geothermal power is 0.002 g CO_2-eq. per kWh.

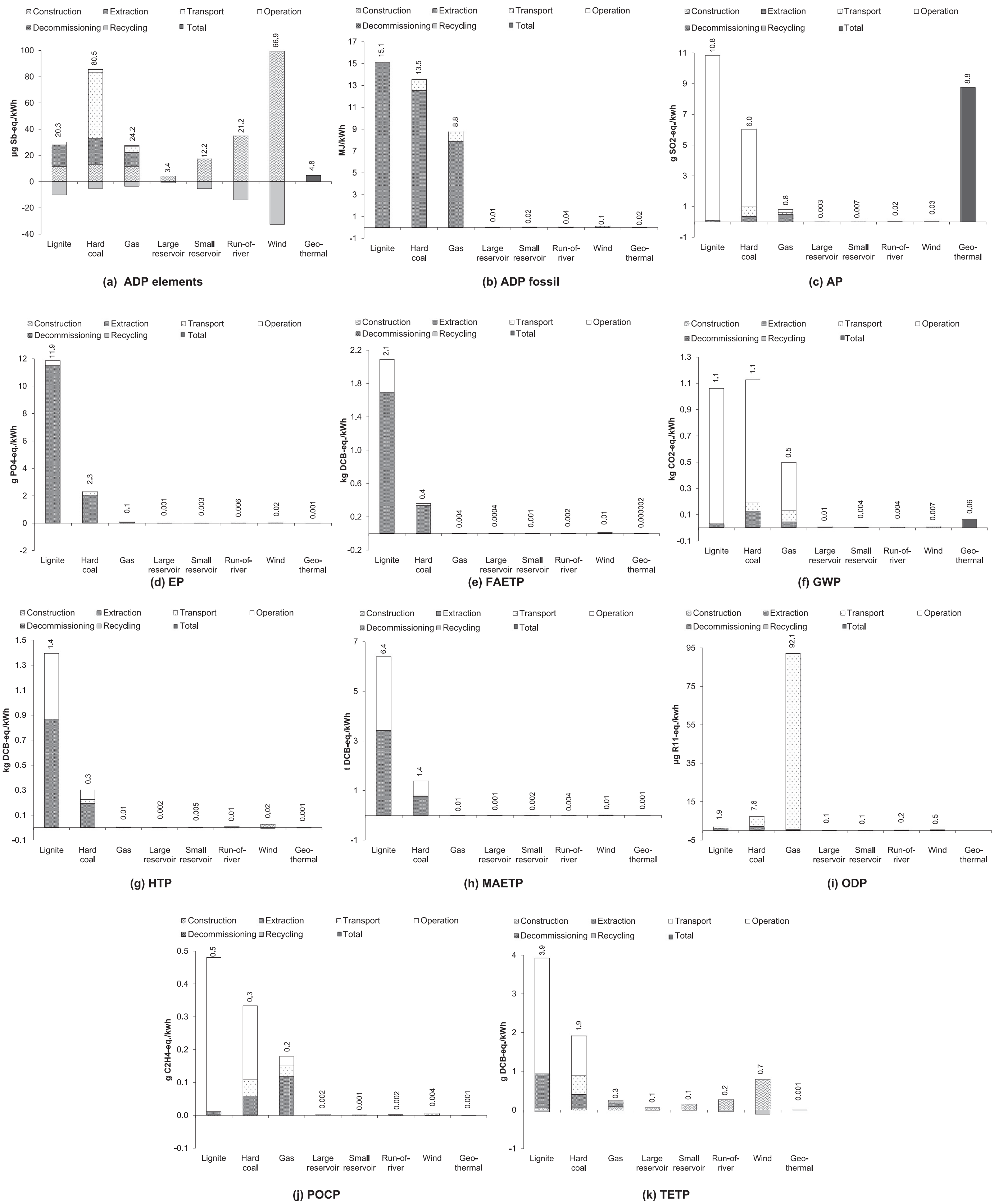

Fig. 3. Environmental sustainability of electricity technologies in Turkey. [All impacts expressed per kWh of electricity generated. The values shown on top of each bar represent the total impact after the recycling credits for the plant construction materials have been taken into account. Extraction refers to fuel and includes fuel processing. Some values have been rounded off and may not correspond exactly to those quoted in the text. ADP: Abiotic depletion of elements; ADP fossil: Abiotic depletion of fossil; AP: Acidification potential; EP: Eutrophication potential; FAETP: Fresh water aquatic ecotoxicity potential; GWP: Global warming potential; HTTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone layer depletion potential; POCP: Photochemical oxidants creation potential; TETP: Terrestrial ecotoxicity potential.]

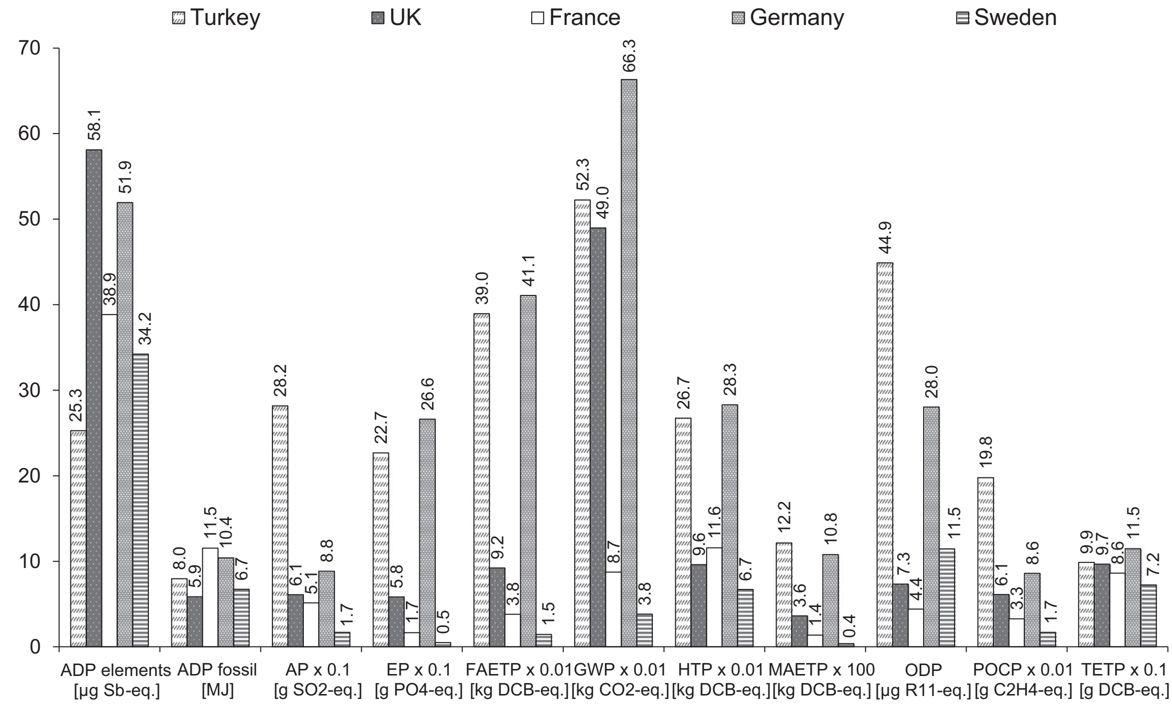

Fig. 4. Environmental sustainability assessment of electricity in Turkey in comparison to electricity in some European countries. [All impacts expressed per kWh. For impacts nomenclature, see Fig. 3. LCA data for the other countries are from Ecoinvent (Dones et al., 2007) except for the UK which are from Stamford and Azapagic (2014).]

3.1.1.5. Global warming potential (GWP). Small reservoir and run-of-river hydropower options have the lowest GWP, estimated at 4.2 and 4.1 g CO_2-eq./kWh, respectively. Wind power is also a relatively good option with GWP of 7.3 g CO_2-eq./kWh. Large reservoir emits 8.3 g CO_2-eq./kWh which is almost two times higher than for the other hydropower options owing to the emissions of CO_2 and CH_4 from the degradation of biomass submerged in the water. Geothermal power is estimated to generate 63 g CO_2-eq./kWh which makes it the worst option among the renewables. However, hard coal is significantly worse than any other option, with an estimate of 1126 g CO_2-eq./kWh, followed by lignite with 1062 g CO_2-eq./kWh and gas with less than half of that (499 g CO_2-eq./kWh). For all three fossil fuel options, the majority of GWP is from fuel combustion. Hard coal has a higher GWP than lignite, despite the higher efficiency per unit of electricity generated (Table 4), because of the additional GHG emissions from long-range transport. The recycling credits are also lower for the hard coal plants as they are more efficient and need a lower amount of construction material per unit of electricity generated. The same applies for the other impacts.

3.1.1.6. Human toxicity potential (HTP). Lignite is the worst option for this indicator, with a value of 1.4 kg DCB-eq./kWh. This is largely due to mining, particularly as a result of emissions of selenium, molybdenum, beryllium and barium. The next largest contributor is lignite combustion to generate electricity. The most sustainable option is geothermal power with HTP of 1 g DCB-eq./kWh.

3.1.1.7. Marine aquatic ecotoxicity potential (MAETP). As shown in Fig. 3, lignite is significantly worse than any other option considered, with MAETP of 6.4 t DCB-eq./kWh, followed by hard coal with 1.4 t DCB-eq./kWh. The impact from the other options is several orders of magnitude lower, with geothermal power being the best option at 0.5 kg DCB-eq./kWh. The main reason for the high impact from the coal power technologies is the discharge of heavy metals to water during mining.

3.1.1.8. Ozone layer depletion potential (ODP). With ODP of 92 μg CFC-11-eq./kWh, power from natural gas is environmentally least sustainable. This is around 12 times the impact of hard coal and 48 times that of lignite. This is mainly due to transport of fuels and, in particular, emissions of halons 1211 and 1301 used as fire suppressants in gas pipelines. The ODP from the renewables is several orders of magnitude smaller than that of gas (see Fig. 3).

3.1.1.9. Photochemical oxidant creation potential (POCP). Geothermal and small reservoir hydropower are the most sustainable options with POCP of 1.2 mg C_2H_4-eq./kWh. Lignite and hard coal have the highest estimated values: 0.48 and 0.33 g C_2H_4-eq./kWh, respectively. The large majority of this impact is due to the emissions of SO_2, NO_x and CO from coal combustion.

3.1.1.10. Terrestrial ecotoxicity potential (TETP). Lignite power is significantly worse than any other option, with an estimated TETP of 3.9 g DCB-eq./kWh, followed by hard coal with 1.9 g DCB-eq./kWh. Geothermal power is the best option with 1 mg DCB-eq./kWh, which is around two orders of magnitude lower than for wind power (0.68 g DCB-eq./kWh).

3.1.2. Environmental sustainability of the Turkish electricity mix

The environmental impacts of the electricity mix have been estimated based on the impacts of each technology discussed in the previous sections and their contribution to the total electricity generated in the base year (see Fig. 3). The results are summarised in Fig. 4. For example, the total GWP is estimated at 523 g CO_2-eq./kWh which translates to nearly 111 Mt CO_2-eq. per year, 54% of which is due to coal and nearly 46% to gas power. Renewable energy options contribute only 0.4% to the total GWP. Like the GWP, fossil-fuel based power electricity generation is also responsible for the majority of other environmental impacts.

As far as we are aware, no other authors have carried out an evaluation of the environmental sustainability of the Turkish electricity sector on a life cycle basis. Therefore, comparison of the results with other works is not possible. Instead, the

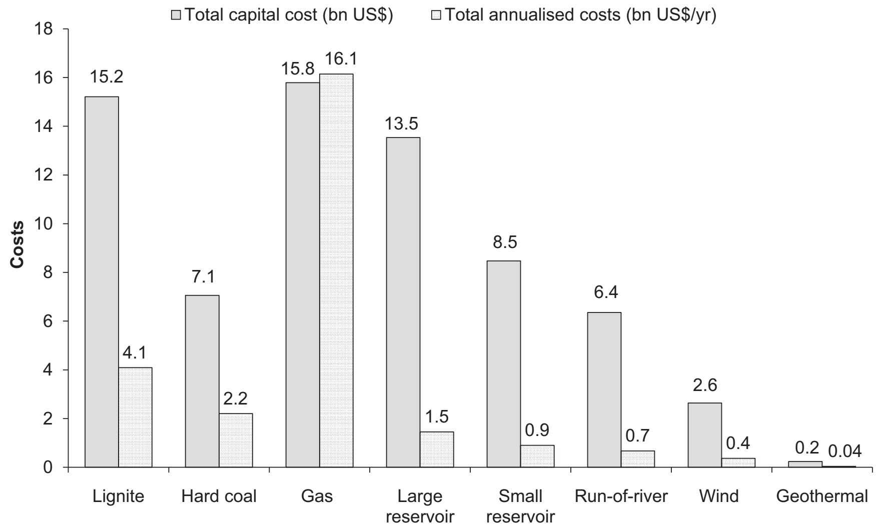

Fig. 5. Estimated capital and total annualised costs from different power technologies in Turkey (billion US$). [Total capital costs for the installed capacity in 2010: 69.3 bn US$. Total annualised costs: 25.9 bn US$. Billion = 10^9.]

environmental impacts estimated here are compared to those from electricity generation in some European countries, to provide context (Fig. 4). The electricity mix in the UK, France, Germany and Sweden are considered as illustrative examples covering a range of electricity mixes, two of which share some similarities with the Turkish grid (Germany and UK) and others are quite different (France and Sweden). It can be observed from the figure that the impacts from the electricity mix in Germany are the highest for five out of 11 impact categories considered, including the GWP. This is mainly due to a high contribution from lignite and hard coal (~22% each). On the other hand, the AP, MAETP, ODP and POCP are highest from electricity generation in Turkey. This is mainly due to the poor quality of lignite in Turkey, lack of air pollution control systems at some of the plants as well as long-range transport of imported hard coal and gas. ADP elements from the UK grid is the highest owing to the higher proportion of offshore wind power in the electricity mix. Compared to France, the majority of the impacts (apart from ADP elements and fossil) for Turkey are higher because of the high contribution of nuclear power (75%) in France. The electricity mixes in the UK and Sweden have lower environmental impacts that in Turkey for 10 out of 11 impacts; the exception is the depletion of elements which is lower for Turkey because of the lowest share of wind power.

3.2. Economic sustainability assessment

As mentioned previously, the economic analysis involves estimation of capital, total annualised and levelised costs. The results reveal that, overall, large reservoir hydropower has the lowest levelised costs and gas power by far the highest, despite its lowest capital costs. The coal power options are more expensive than hydropower and geothermal but cheaper than gas and wind power in terms of levelised costs. These results are discussed in more detail in the following sections for both individual technologies and the Turkish electricity mix.

3.2.1. Capital costs

As indicated in Table 5, at 2500 US$/kW the capital costs are highest for the geothermal plants (Sener and Aksoy, 2007), followed by the run-of-river (2300 US$/kW) and the wind (2000 US$/kW) power (TEIAS, 2013). Based on these data, the total capital costs for 49,524 MW of the installed capacity in 2010 have been estimated here at US$69.3 billion. The majority of this is due to the hydropower (41%), coal (32%) and gas (23%) plants (Fig. 5). Although the latter have the lowest capital costs, their contribution to the total costs is still significant because of the high contribution to the electricity mix (46.5%, see Table 3).

3.2.2. Total annualised costs

Key variables used to calculate the total annualised costs are capital, fixed, variable and fuel costs (see the Supplementary material, Section 2). The total annualised costs are estimated at US$25.9 bn/year. Fuel costs account for 64% of the total, followed by the capital costs (28%). The rest is attributable to the variable (5%) and fixed costs (3%).

Fig. 5 also shows the annualised costs for different types of power plant. Gas and coal together contribute 87% of the total annualised costs (62% for gas, 16% for lignite and 9% for hard coal); this is largely due to the high fuel costs.

The contribution of different cost components to the total costs varies by technology (Fig. 6). For renewable technologies that have no fuel costs, such as wind power, the total annualised cost is mainly due to the capital (79%) and variable costs (16%). By contrast, for gas electricity, fuels contribute 88% to the total cost, while the capital and fixed costs represent only 11% and 1% of total, respectively.

3.2.3. Levelised costs

The estimated levelised costs per unit of electricity generated are given in Fig. 7 for different types of plant. The results suggest that electricity from large reservoir hydro-plants is the cheapest (48 US$/MWh), followed by geothermal (61 US$/MWh) and small reservoir (63 US$/MWh). Onshore wind is the most expensive option (126 US$/MWh) among the renewable electricity technologies considered in this study. However, the most expensive option overall is electricity from natural gas, estimated here at 161 US$/MWh. This is due to the high costs of fuel (see the previous section). The costs of the two coal-based options are close to each other, estimated at around 115 US$/MWh. It should be noted that these costs apply for the discount rate of 10%; choosing a different rate could affect the levelised costs of the different technologies as well as the cost break down of each technology.

Taking into account the levelised costs for each technology and their contribution to the mix in the base year gives the unit cost of

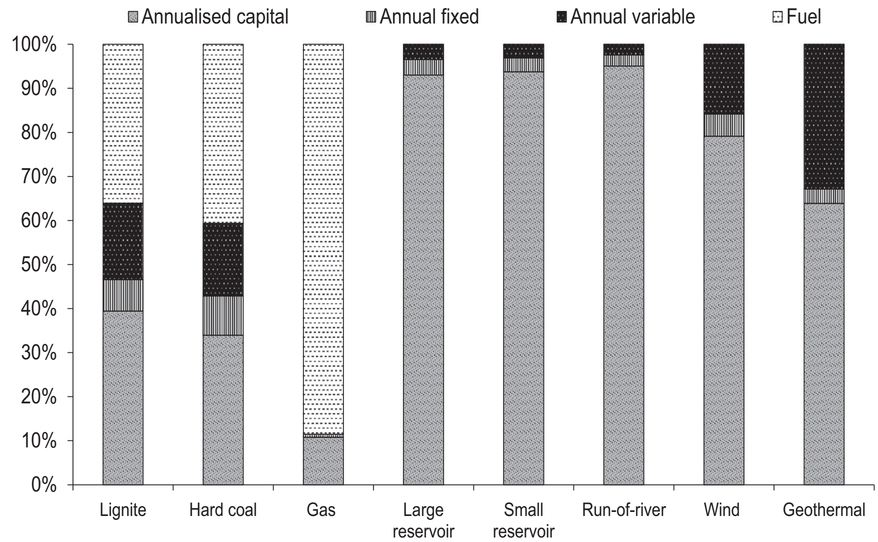

Fig. 6. Contribution of different costs to the total annualised costs for different electricity technologies.

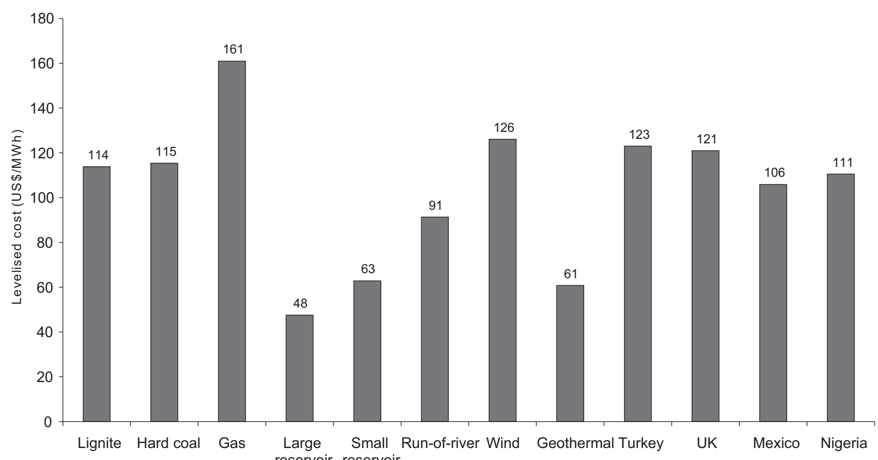

Fig. 7. Levelised costs of electricity in Turkey in comparison to some other countries.

electricity mix of 123 US$/MWh. For context, the commercial and industrial prices of electricity in Turkey are 185 and 148 US$/MWh, respectively (IEA, 2014).

As far as the authors are aware, this is the first time the levelised costs have been reported for Turkey; hence, it is not possible to compare these findings with previous estimates. However, a recent report (IEA et al., 2015) provides estimates for wind (84 US $/MWh), geothermal (121 US$/MWh) and large reservoir hydropower (54 US$/MWh) in Turkey. While the latter agree well with the costs estimated here, the results for the other two options differ, with the costs of wind power being 50% higher and that of geothermal twice as low here. This is due to the different methodologies, assumed capital costs, size of the plants and capacity factors used in the two studies.

It is also not possible to compare the results obtained here with the same example countries considered in the environmental assessment. Although some estimates exist for some of the technologies contributing to the electricity generation in these countries, to our knowledge, the levelised costs for their electricity mixes are not available. The exception is the UK for which the costs are estimated at 121 US$/MWh, following a similar methodology as here (Stamford and Azapagic, 2014). This is quite close to the estimate for Turkey because of the similar contribution from fossil fuels to the electricity mix in these two countries. However, the values for levelised costs are available for some other countries and, as an example, we compare Turkey to two other developing countries: Mexico and Nigeria. Their electricity costs are reported at 106 US$/MWh and 111 US$/MWh, respectively, also using the same methodology as in the current work (Gujba et al., 2010; Santoyo Castelazo, 2012). The difference in the costs is mainly due to the differing electricity mixes and plant technologies in these countries. Note that all the costs discussed in this section refer to the value of US$ in 2012.

3.3. Social sustainability assessment

The social sustainability assessment has been evaluated on the basis of six indicators discussed below. In summary, run-of-river hydropower provides the highest life cycle employment of the eight options considered but has high worker injuries and large-accident fatalities. However, the latter two are highest for lignite and hard coal, with the majority of these related to fuel mining. Large reservoir hydropower provides the lowest life cycle employment in the supply chain but it is the best option in terms of worker injuries and fatalities. Being fuel free, renewable options score highly for the energy security indicators.

As for the other sustainability aspects, this is the first time a social sustainability assessment has been attempted for the Turkish electricity sector so that the results cannot be compared to previous studies. Instead, we compare the results to a similar study in the UK which applied the same methodology (Stamford and Azapagic, 2014). Comparison with other studies is not meaningful owing to different methodologies.

3.3.1. Direct employment

As explained in Section 2.2, direct employment comprises jobs provided during the construction, operation, maintenance and decommissioning of a power plant. The results in Fig. 8 suggest that run-of river hydropower provides the highest direct employment, equivalent to 459 person-years/TWh. The next best option is onshore wind with 256 person-years/TWh, followed by small reservoir hydropower at 202 person-years/TWh. For this indicator, gas power is the least sustainable, providing only 56 person-years/TWh. The reason that some of the renewable power options have such high direct employment per unit of electricity is due to their low capacity factors.

Overall, electricity generation in Turkey provided 24,632 direct jobs in 2010 or 117 person-years per TWh. The majority of the direct employment is from lignite (25%), natural gas (23%) and run-of-river hydropower (14%) in Turkey.

By comparison, the equivalent value for the UK electricity is 52 person-years/TWh, 35% of which from coal, 25% from gas and 23% from nuclear power (Stamford and Azapagic, 2014). The difference between the direct employment values for Turkey and the UK is mainly due to the differences in labour productivity which is around 1.5 times higher in the UK than in Turkey (OECD, 2015).

3.3.2. Total employment (direct and indirect)

In addition to the direct, total employment also considers indirect jobs provided by other activities in the life cycle, such as fuel extraction and processing and manufacturing of power plant parts. Like direct employment, run-of-river hydropower also has the highest total employment (512 person-years/TWh), followed closely by lignite (509 person-years/TWh); see Fig. 8. Large reservoir hydropower provides the lowest life cycle employment (99 person-years/TWh); this is due to its relatively high capacity factor and lower labour requirements per unit of electrical output. In total, the Turkish electricity sector provided 56,979 jobs in 2010, equivalent to 270 person-years per TWh.

Again for context, the total number of jobs associated with electricity generation in the UK has been estimated at 123 person-years/TWh (Stamford and Azapagic, 2014). Like direct employment, this value is lower than in Turkey because of the higher labour productivity in the UK.

3.3.3. Worker injuries

For every TWh of electricity generated in Turkey, 68 injuries are caused in the lignite life cycle; hard coal is only slightly better with 50 injuries/TWh (Fig. 9). Around 94% of these occur in mining. Wind power also has high injury rates (10.4 injuries/TWh), mainly because of the relatively high employment provision; around 80% of the injuries occur during maintenance. The best option is large reservoir hydropower with 0.7 injuries/TWh.

A total of 3700 worker injuries are estimated to occur in the electricity sector annually in Turkey; this equates to 17 injuries/TWh. The equivalent rate in the UK is nine times lower (Stamford and Azapagic, 2014), reflecting much more stringent occupational health and safety standards.

3.3.4. Large accident risk

The lignite and hard coal power have the highest life cycle fatality rate of the power options considered here, causing an estimated 0.25 and 0.18 fatalities per TWh of electricity generated, respectively. Around 82% of these occur in mining. An estimated 0.064 fatalities per TWh electricity generated are caused in the wind power life cycle. Run-of-river has also relatively high fatality rates (0.04 fatalities/TWh). The reason for this is the higher employment provision per unit electricity than for the other options. Large reservoir hydropower is the best option with 0.01 fatalities/TWh.

On average, 14 fatalities occur every year in large accidents in the electricity sector in Turkey, particularly in the mining sector, compared to 3 fatalities in the UK (Stamford and Azapagic, 2014). This is again due to lax health and safety regulations in Turkey but also because the mining activity in the UK is low.

3.3.5. Imported fossil fuel potentially avoided

The amount of imported fossil fuel potentially avoided relates to the amount of imported hard coal and gas that would have to be combusted to provide an equivalent amount of electricity from technologies that do not rely on imported fossil fuels, i.e. lignite, renewable and nuclear power plants. It is estimated that the current fleet avoids 72 t of oil equivalent (toe) per GWh or around 15.2 Mtoe per year. This is equivalent roughly to electricity generated by 85 coal or 150 gas power stations. By comparison,

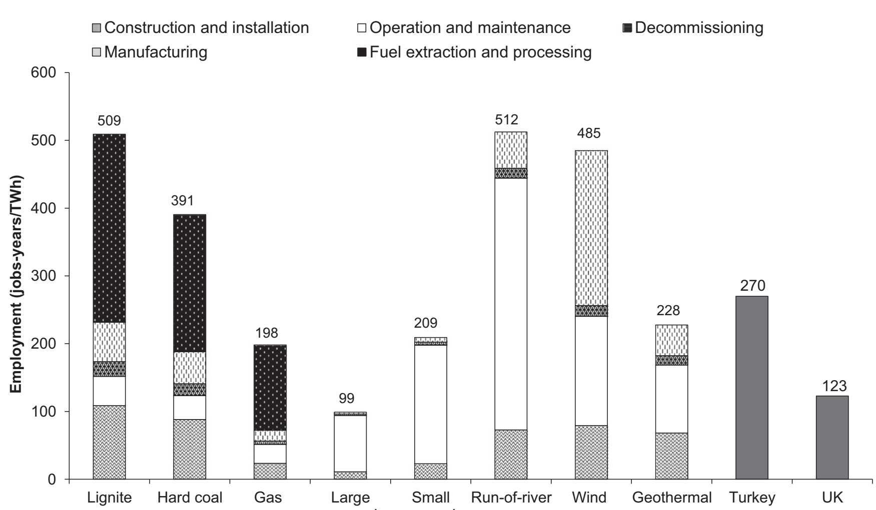

Fig. 8. Direct and total employment provided by different electricity options and the Turkish electricity mix. [Direct employment: construction, operation, maintenance and decommissioning. Indirect employment: manufacturing and fuel extraction and processing.]

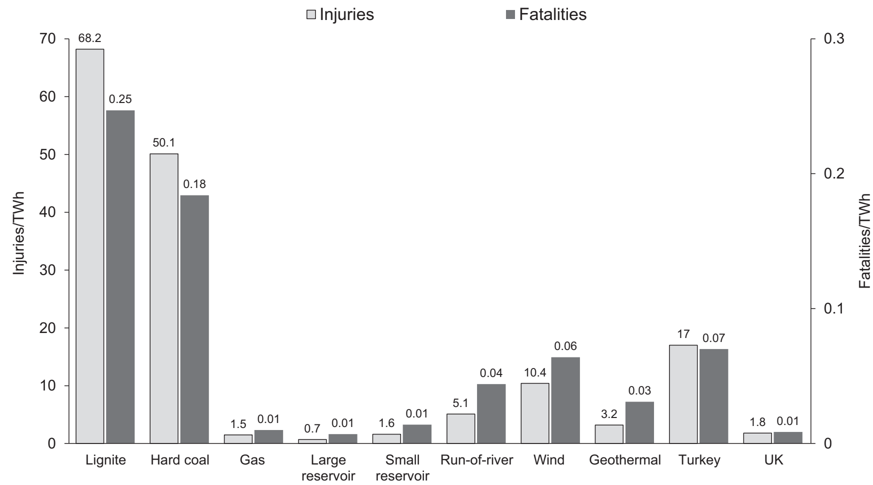

Fig. 9. Worker injuries and large-accident fatalities for different electricity technologies and the overall electricity mix.

50.6 toe/GWh or 19 Mtoe/year of fossil fuel are avoided in the UK (Stamford and Azapagic, 2014). The differences are mainly due to the differing electricity mixes and power plant efficiencies in the two countries.

3.3.6. Diversity of fuel supply mix

The diversity of Turkish fuel supply has been calculated using Simpson's Diversity Index (see the Supplementary material, Section 2). The score for gas supply is estimated at 0.56 and for hard coal at 0.57. Therefore, the diversity of fuel supply is low as a result of high reliance on imports from Russia, which in 2010 supplied 58% of hard coal and 46% of gas used in Turkey. The total diversity index for the Turkish electricity mix is equal to 0.75. This is lower than 0.82 estimated for the UK (Stamford and Azapagic, 2014) mainly because of the high reliance of Turkey on imports from Russia.

3.4. Multi-criteria decision analysis

As discussed in the previous sections, different electricity options have differing advantages and disadvantages so that identifying the most sustainable among them is not easy. Therefore, MCDA has been used to aid that process using Web-HIPRE V1.22 software and the MAVT method (Mustajoki and Hämäläinen, 2000). The MCDA decision tree can be found in the Supplementary material (Fig. S4-1).

First an equal importance for all the sustainability aspects has been assumed, assigning the same weighting to each ($w_i=0.33$), followed by assuming in turn a much higher (five times) importance of environmental, economic and social aspects to test the robustness of the outcomes. Given the different number of indicators for each sustainability aspect and to avoid bias, the weights for the indicators have been assigned as follows:

- 11 environmental indicators: $w_i=1/11=0.09$;
- 3 economic indicators: $w_i=1/3=0.33$; and
- 6 social indicators: $w_i=1/6=0.167$.

The MCDA results are discussed in the following section. Note that the option with the highest total score is considered most sustainable.

3.4.1. Equal preferences for the sustainability criteria

The sustainability scores for each option estimated using Eq. (3) are displayed in Fig. 10; further details can be found in the Supplementary material, Figs. S4-2 and S4-3. As indicated in the figures, hydropower is most sustainable with each hydro technology scoring around 0.83. Wind and geothermal follow closely with 0.76. All the renewables perform similarly well on the environmental sustainability but there is a greater difference between them for the other two aspects. From the economic perspective, large reservoir is the best option and wind the worst. However, the opposite is true for the social sustainability.

Lignite power is the least sustainable technology overall, scoring only 0.42, largely owing to a poor environmental performance. However, it scores most highly for the social sustainability among the fossil options (0.18), followed closely by gas power (0.12). On the other hand, gas is the least sustainable economically but most sustainable environmentally among the fossil-fuel technologies.

A sensitivity analysis suggests that the weight on the environmental aspect would have to change significantly (from 0.33 to 0.24) to incur a change in the technology ranking (Supplementary material, Fig. S4-3a). In that case, hard coal electricity would become the worst option, after gas and lignite. The ranking of the renewable options would remain the same.

For the economic aspect, the rank order of the fossil fuel options would change if the weighting on this aspect doubled, from the current 0.33 to 0.51. In that case, gas power would be the worst option, after lignite and hard coal. Moreover, the ranking of the hydropower options would change, with large reservoir becoming the best option, followed by small reservoir and run-of-river hydropower (see Fig. S4-3b in the Supplementary material).

An increase in the weighting for the social aspect would be needed from 0.33 to 0.57 for the ranking of the options to change (Supplementary material, Fig. S4-3c), in which case wind power would be the third preferred option, after run-of-river and small reservoir hydropower. The ranking of fossil fuel options would also change and hard coal would become the least favourable option.

3.4.2. Different preferences for the sustainability criteria

To find out how the ranking of the options might change with different preferences for the sustainability aspects, it has been assumed in turn that each aspect is more important than the other two. For these purposes, an extreme (arbitrary) importance of five times ($w_i=0.71$) has been considered. The weights for the sustainability indicators remain the same as before. The results are presented in Fig. 11.

If the environmental aspect is considered most important (Fig. 11a), hydropower technologies are still most sustainable, each scoring around 0.93. The next best option is geothermal power (0.85), followed by wind electricity (0.84). Lignite power is the worst option with a score of 0.27. The sensitivity analysis suggests

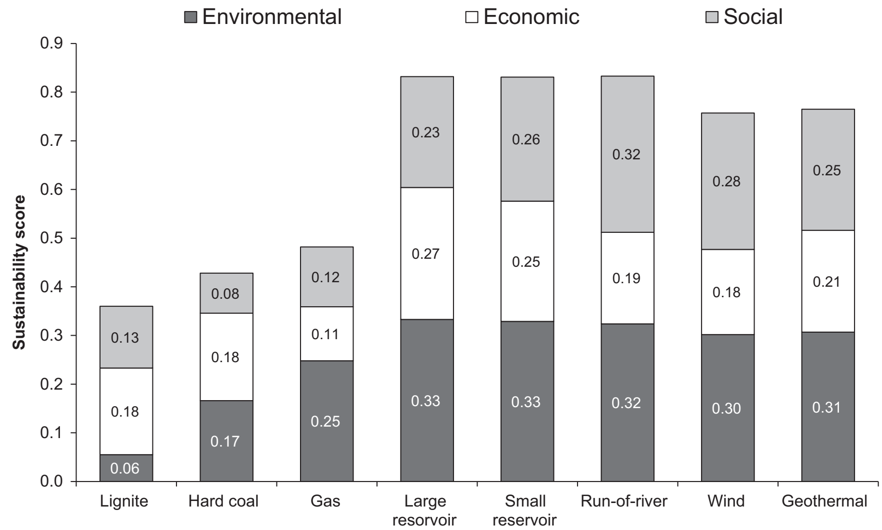

Fig. 10. Ranking of the electricity options with equal weights on the environmental, economic and social aspects. (a) The environmental aspect five times more important than the economic and social. (b) The economic aspect five times more important than the environmental and social. (c) The social aspect five times more important than the environmental and economic.

that the ranking of the renewables is robust over the whole range of the weighting (0-1) and only changes for the fossil-fuel options at $w_i = 0.14$, in which case lignite becomes the best and gas the worst option (see Figure S4-4 in the Supplementary material).

Assuming that the economic aspect is five time more important than the other two (Fig. 11b), large reservoir hydropower emerges as the most sustainable option (0.82). Small reservoir hydropower is ranked second best (0.78), followed by geothermal (0.69), run-of-river (0.68) and wind power (0.63). Gas power is least sustainable scoring 0.4, largely because of its high levelised costs. The ranking of the options would change if the weighting on the economic aspect changed from the current 0.71–0.47 (see Fig. S4-5 in the Supplementary material). In that case, lignite would become the least favourable option.

When the social aspect is the priority, run-of-river hydropower is a clear winner, scoring 0.91 (Fig. 11c). This is mainly due to its good social performance, compared to other technologies. Wind power is ranked second with the score of 0.81, followed by small reservoir (0.79), geothermal (0.76) and large reservoir hydropower (0.75). Hard coal power is now the least sustainable alternative, scoring only 0.32, followed by gas (0.42) and lignite (0.49). The sensitivity analysis suggests that this ranking would change if the importance of the social aspect dropped significantly, from 0.71 to 0.31 (Fig. S4-6). In that case, large reservoir hydropower would become the best and lignite the worst alternative.

3.4.3. Summary of the MCDA outcomes

As discussed in the previous sections, the ranking of the electricity options varies with the weights of importance placed on the sustainability aspects. To summarise the results and help identify the most sustainable option(s), simple ranking has been used with the most sustainable technology assigned a score of 1, the next best a 2, etc., up to 8 which denotes the least sustainable option.

As indicated, in Table 8, hydropower technologies are most sustainable if all the aspects are considered equally important as well as when the highest priority is given to the environment. Large reservoir remains the best option if the economic aspect is most important but falls to the fifth place if the social impacts are prioritised, in which case run-of-river is ranked first. Geothermal power appears to be slightly better than wind for most cases, except for the high preference for the social criteria, in which case wind is the second best option overall, after run-of-river.

The fossil-fuel options are the least sustainable, with gas power being the best and lignite the worst, if all the aspects are considered equally important and if the priority is given to the environment. However, gas becomes the least sustainable option if the economic sustainability is considered most important. When the social aspect is prioritised, hard coal is the worst option.

4. Conclusions and policy implications

As a developing country, it is important for Turkey to evaluate the sustainability of its energy sector to help identify and implement the most sustainable options for the future. In an attempt to contribute towards this goal, this paper presents for the first time an integrated sustainability assessment of the electricity sector in Turkey, considering all the power plants and electricity technologies currently operating in the country. Taking a life cycle approach, each technology has been assessed on 20 sustainability indicators (11 environmental, three economic and six social). These results have been used to evaluate the overall sustainability of the whole electricity sector.

The findings at the sectoral level indicate that fossil-fuel options are responsible for the majority (88–99.9%) of the environmental impacts associated with electricity generation in Turkey. The results from the economic assessment suggest that the total capital costs are US$69.3 billion, with hydropower contributing the majority (43%), followed by coal (31%) and gas (22%) power plants. The annualised costs are estimated at US$25.9 billion/year and levelised costs at 123 US$/MWh. The evaluation of social sustainability indicates that the electricity sector provides around 57,000 jobs. Around 3700 worker injuries and 15 fatalities are estimated to occur in the supply chain annually. The energy security is low because of a reliance on imported fuels, with the diversity of fuel supply index equal to 0.75. On the other hand, the high contribution of hydropower and lignite in the electricity mix helps to avoid the use of 15 Mtoe of imported fossil fuels per year, equivalent to electricity generated by 85 coal or 150 gas power stations.

Comparing the specific technologies, lignite power is the least environmentally sustainable for eight out of 11 environmental impacts. It has the highest fossil fuel depletion, acidification, eutrophication, photochemical smog and all the toxicity-related

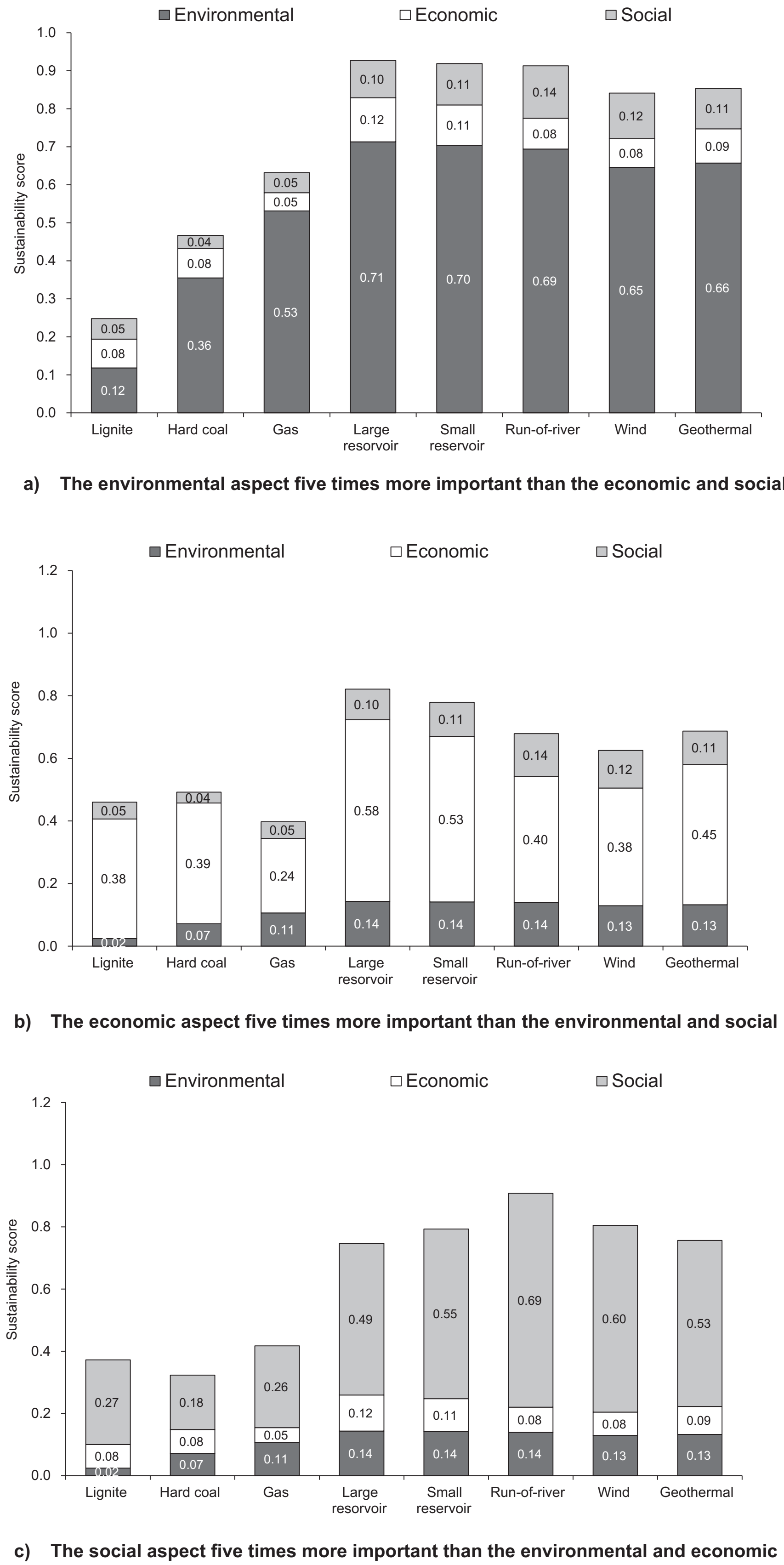

Fig. 11. Ranking of the electricity options with different preferences for the sustainability aspects. (a) The environmental aspect five times more important than the economic and social. (b) The economic aspect five times more important than the environmental and social. (c) The social aspect five times more important than the environmental and economic.

Table 8
Sustainability ranking of the electricity options with different weights on the environmental, economic and social aspects.

Technology	Equal weights	Five times more important at a time		
		Environmental	Economic	Social
Lignite	8	8	7	6
Hard coal	7	7	6	8
Gas	6	6	8	7
Large reservoir	1=	1=	1	5
Small reservoir	1=	1=	2	3
Run-of-river	1=	1=	4	1
Wind	5	5	5	2
Geothermal	4	4	3	4

impacts. As a domestic source, lignite scores highly for the energy security. Hard coal power has the highest abiotic depletion of elements and global warming potential. Gas power is the worst option for ozone layer depletion, life cycle employment and levelised costs; however, it has the lowest capital costs. Large reservoir hydropower is the most sustainable in terms of depletion of elements and fossil resources as well as acidification, and is the second best for a further six environmental indicators. Moreover, it has the lowest levelised costs and worker injuries and fatalities. Environmentally, small reservoir hydropower has relatively low impacts and is comparable with large reservoir hydropower. However, both large and small reservoir hydropower options provide lower total employment than lignite, hard coal, run-of-river, wind and geothermal power. Run-of-river hydropower is the most sustainable option for the global warming potential and provides the highest employment but it has high capital costs. Wind power is significantly cheaper than gas per unit of electricity generated, although still higher than the other options considered here. Geothermal power has six environmental impacts lower than any other option. It only performs badly for acidification because of air emissions of hydrogen sulphide. Geothermal power is also the best option for the total annualised costs, but has the highest capital costs. Being fuel free, all renewable options score highly for the energy security indicators.

Given these trade-offs, the choice of the most sustainable options will depend on stakeholder views on the importance of each sustainability aspect. Therefore multi-criteria decision analysis has been carried out to determine which technologies are sustainable for electricity generation in Turkey. The results reveal that, for all the preferences considered, hydropower emerges as the most sustainable followed by geothermal and wind electricity. Fossil fuel power is the least sustainable. Therefore, the results of this study show clearly that reducing the share of fossil fuels in the electricity mix would not only reduce significantly the environmental impacts, but also the costs, injuries and fatalities from electricity generation in Turkey, while also improving energy security. For example, the global warming potential of fossil-fuels electricity is around 270 times higher than for renewable electricity, despite the fossil-based plants generating only 2.7 times more electricity. Gas and coal electricity together contribute 87% of the annualised costs and coal has the highest life cycle worker injuries and fatalities.

Based on the results from this work, the following policy recommendations can be made to improve the sustainability of the electricity sector in Turkey:

- Current energy policy in Turkey is mainly driven by the need to improve energy security and reduce greenhouse gas emissions. To avoid solving one issue at the expense of another, the government should consider wider environmental, economic and social impacts when planning a sustainability strategy for the electricity sector. This will help to make more sustainable decisions for the future.
- The government should adopt a life cycle approach in decision and policy making. This will help to identify hot spots and opportunities for reducing the environmental, economic and social impacts across the whole electricity supply chains.
- A techno-economic feasibility assessment of all energy sources available in Turkey should be carried out.
- The results of this study quantify for the first time the significant improvements in the sustainability of the electricity sector in Turkey that would be achieved if the share of fossil power in the electricity mix was reduced. Therefore, future policies should be oriented towards reducing the contribution of fossil fuels to electricity generation.
- The government's current policy is aimed at increasing electricity generation from lignite to improve the security of supply. The results of this work demonstrate that electricity from lignite is the least sustainable option. The only exception to this is if the economic aspect is considered most important, in which case it becomes a middle ranking option. Therefore, if the main energy driver is energy security, the sustainability performance of the existing lignite power plants should be improved.
- More efficient fossil fuel electricity technologies should be deployed in preference to conventional fossil fuel options. This will help to reduce the environmental impacts, operational costs and fatalities and injuries, while improving energy security. However, the capital costs will increase because of a higher investment needed for the advanced fossil fuel technologies.
- Turkey has a significant potential for a variety of renewable energy resources, including solar, wind, geothermal, bioenergy and hydropower. A greater penetration of renewable electricity sources into the grid as an alternative to fossil fuels is important for Turkey to reduce the dependence on imported fuels, improve the security of supply and reduce the environmental impacts from the electricity sector. Therefore, the government should encourage and possibly incentivise increasing the share of renewables in the electricity mix as well as diversifying the portfolio of options to include offshore wind and solar power.
- However, renewable power options should be chosen with care. For example, increasing the proportion of wind power in the electricity mix would increase depletion of elements while a higher share of geothermal power would increase acidification. As mentioned earlier, these trade-offs should be considered carefully to avoid solving one problem at the expense of another.
- Hydropower is well established in Turkey and has a large potential for further deployment. Many hydropower plants are currently under construction or in the planning stage. While this option has been found the most sustainable in this work, there are social issues that must be addressed, such as public acceptability of large reservoir power plants and how they affect water supply in the neighbouring countries. The government should consider these and other social aspects judiciously before making plans for further development of hydropower in Turkey.
- The government should support research into environmental improvements of electricity technologies as well as improving legislation to limit environmental impacts from electricity generation.

This work has focused on the current electricity mix in Turkey and, by definition, has considered a limited number of technologies. The results are also subject to uncertainty due to the data limitations. Further improvements to the data could be made through the use of more regionally-specific and recent data, as well as more complete economic and social data. For a future sustainable development of the electricity sector, further research is needed to evaluate the life cycle sustainability of other options that could be deployed in the country in the medium to long terms, including solar, bioenergy and nuclear power. This is the subject of a forthcoming paper by the authors.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2016.02.055.

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