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Energy challenges for Turkey: identifying sustainable options for future electricity generation up to 2050

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Abstract

This paper presents for the first time a life cycle environmental, economic and social sustainability assessment of future electricity scenarios for Turkey up to 2050. Fourteen scenarios have been developed and assessed for 19 sustainability indicators, using multi-criteria decision analysis (MCDA) to help identify the most sustainable scenarios. The fossil fuel dominated scenarios are environmentally the least sustainable for seven out of 11 impacts, including the global warming potential (GWP) which increases up to four times on today's impact. Opting for renewable-intensive pathways would halve the current GWP and reduce the use of fossil fuels by three times; however, the depletion of elements would increase 70-fold and investment costs 10-fold. MCDA shows that renewable and nuclear intensive scenarios outperform those dominated by fossil fuels, except for the very high preference for the economic criteria. However, their poor environmental and social performances makes them least sustainable overall. The renewable-nuclear intensive scenarios are the most sustainable options with respect to most of the environmental, economic and social impacts considered. 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, while also improving energy security.

Keywords: Electricity generation; scenario analysis; sustainability assessment; life cycle assessment; Turkey

1. Introduction

Turkey is a fast developing country with the second highest growth rate in natural gas and electricity demand worldwide after China (IBP, 2015). As it lacks domestic gas sources, and gas provides almost half of the electricity demand (TEIAS, 2012), the country has become increasingly dependent on imports, particularly from Russia (TPAO, 2011). Given the unstable geo-political situation, improving security of energy supply is one of the main objectives of the Turkish energy policy which aims to reduce the dependency on natural gas by up to 30% by 2023 (MENR, 2009a). Diversifying gas supplies, both in terms of countries and transit routes, is also an important goal for the country (MENR, 2009b; MENR, 2009a). Furthermore, to meet the growing energy demand and reduce gas import dependency, Turkey also aims to expand coal power capacity by utilising domestic coal through clean coal technologies (MENR, 2009b). There are significant domestic reserves of coal, with lignite being much more abundant than hard coal (TKI, 2012). However, most of the Turkish lignite is of poor quality with a low calorific value and high sulphur and ash content. In contrast to gas and coal, the contribution from oil power plants has been declining over the years and today almost no oil power plants remain in Turkey as most have been converted to natural gas combined cycle power plants (MMO, 2010). As a results, gas and coal supply 72.5% of the electricity demand (TEIAS, 2012).

On the other hand, Turkey has abundant renewable energy resources. Despite this, renewable electricity accounted for 26.4% of the total electricity generation in 2010, mainly from hydropower (24.5%) (MENR, 2012). In an attempt to reduce the dependence on fuel imports and maximise the use of the domestic energy potential, the government has set a target for 30% of electricity to be provided from renewable resources by 2023 (MENR, 2009a). In addition to hydropower, the options being currently considered for wider deployment include wind, geothermal and solar power. The target for 2023 is to exploit fully the technically (216 TWh/year) and economically (140 TWh/year)

viable hydropower potential (DSI, 2010); to increase the wind installed capacity to 20 GW out of 48 GW estimated total potential (EMRA, 2014); to utilise the full geothermal power potential of 600 MW; and to promote electricity generation from solar energy (MENR, 2009a). With around seven hours of sunshine per day, the solar power potential is estimated at 380 TWh per year (EMRA, 2014). However, at present, the contribution of solar electricity is almost non-existent, with only a few photovoltaic installations connected to the grid due to the issues related to the financial support and regulatory system (Toklu, 2013; YEGM, 2013). Furthermore, despite a significant biomass potential of 117 million tonnes per year, equivalent to 1.3 TWh/year (EMRA, 2014), currently there is no target for increasing the capacity of biomass plants.

Turkey has no nuclear power, in spite of trying to introduce it since the 1970s. All previous attempts have invariably failed owing to various financial, environmental and regulatory issues (Lorenz and Kidd, 2010). Nevertheless, the current target is to have 5% of nuclear electricity by 2020 and to increase it further in the long term (MENR, 2009a). In 2010, the government signed a cooperation agreement with Russia and, as a result, the construction of the first nuclear plant is about to start in the south of Turkey, on the Mediterranean coast. The plant will have four pressurised water reactors (PWR) with a total capacity of 4.8 GW and, according to current plans, it will be operational by 2022 (Akkuyu NGS, 2011). A further agreement was signed in 2013 with Japan to build and operate a 4.48 GW plant, also with four PWR reactors. The plant will be situated on the Black Sea coast (MENR, 2014a).

The high share of imported fuels is not only a security of supply threat but it also creates a huge economic burden for the country. As a result, electricity prices are high: 148 US\$/MWh for industrial and 185 US\$/MWh for domestic consumers, 10%-20% above the OECD average (IEA, 2014). Furthermore, there are serious issues related to the occupational safety in the electricity sector, with over 300 deaths in two major coal mine accidents in 2014 alone (Acar et al., 2015).

The high contribution of fossil fuels in the electricity mix, together with the increasing demand, has led to a steady increase in GHG emissions. Since Turkey is a signatory to the Kyoto Protocol (Annex I) and an associate member of the European Union (EU), it is under pressure to reduce its emissions. Therefore, it is important to identify sustainable technologies suitable for the country to reduce the climate change and other impacts from a future electricity sector.

Several studies have considered future electricity demand for Turkey, including MENR (2014b), Hamzaçebi (2007), Kankal et al. (2011), Hotunluoglu and Karakaya (2011), Çunkaş and Taşkıran (2011) and Yumurtaci and Asmaz (2004). However, no studies have considered the sustainability of the future electricity sector considering environmental, economic and social aspects. The only study that we are aware of is the environmental sustainability assessment of potential future scenarios up to 2050 (Greenpeace and EREC, 2008; Özer et al., 2013; MENR, 2006) which focused only on direct GHG emissions, i.e. from the operation of fossil fuel power plants. This paper goes beyond any of the previous studies to carry out a sustainability assessment of a range of different scenarios up to 2050, integrating environmental, economic and social aspects and taking a life cycle approach. Eleven environmental, three economic and five social indicators are considered for these purposes using multi-criteria decision analysis (MCDA) to help identify the most sustainable pathways for future electricity generation in Turkey. As far as the authors are aware, this is the first study of its kind for this country.

The following sections detail the methodology and data used in this research, including the description of the scenarios and the electricity technologies. The results are presented and discussed in Section 3 and the conclusions are drawn in Section 4. Further details on the assumptions and results can be found in the Supplementary material.

2. Methodology

The methodology applied for assessing the sustainability of future electricity generation in Turkey shown in Figure 1 involves the following steps: identification of sustainability issues and indicators; selection and specification of electricity technologies; definition of future scenarios to 2050 assuming different targets for reducing GHG emissions; life cycle sustainability assessment of scenarios taking

into account environmental, economic and social aspects; integration of these aspects using multi-criteria decision analysis; and identification of most sustainable scenarios and policy recommendations. These stages are described in turn in the sections that follow.

2.1 Sustainability issues and indicators

The sustainability issues and the related indicators relevant to Turkey's electricity sector are summarised in Table 1. The environmental issues considered here are resource depletion, climate change and environmental pollution. These have been quantified through the environmental indicators typically considered in life cycle assessment (LCA). The key economic issue for Turkey is the cost of electricity which has been assessed through the capital, total annualised and levelised costs. Finally, the social sustainability indicators have been selected based on the social issues identified as a priority in Turkey: employment provision, health and safety and security of energy supply. Each indicator assesses a particular issue on a life cycle basis, from 'cradle to grave'.

The study is based on two functional units. The first is defined as "generation of 1 kWh of electricity" to enable comparisons for individual scenarios as well as for electricity technologies. The second functional unit is defined as the "total annual electricity generation" to estimate the total annual environmental, economic and social impacts for each scenario.

The indicators are described in more detail in Section S1 in the Supplementary material, also showing how they are calculated.

Figure 1: Methodology for assessing the sustainability of future electricity scenarios

Table 1: Indicators used for assessing the sustainability of electricity scenarios

Sustainability aspects	Sustainability issues	Sustainability indicators	Units (per functional unit) ^a
Environmental	Resource depletion	Abiotic resource depletion potential (elements)	kg Sb eq.
		Abiotic resource depletion potential (fossil fuels)	MJ
	Climate change	Global warming potential	kg CO ₂ eq.
	Emission to air, water and soil	Acidification potential	kg SO ₂ eq.
		Eutrophication potential	kg PO ₄ eq.
		Fresh water aquatic ecotoxicity potential	kg DCB ^b eq.
		Human toxicity potential	kg DCB ^b eq.
		Marine aquatic ecotoxicity potential	kg DCB ^b eq.
		Ozone layer depletion potential	kg CFC-11 eq.
		Photochemical oxidants creation potential	kg C ₂ H ₄ eq.
		Terrestrial ecotoxicity potential	kg DCB ^b eq.
Economic	Costs	Capital costs	US\$
		Total annualised costs	US\$/year
		Levelised costs	US\$/kWh
Social	Provision of employment	Direct employment	jobs-years
		Total employment (direct + indirect)	jobs-years
	Worker safety	Injuries	no. of injuries
		Fatalities due to large accidents	no. of fatalities
	Energy security	Imported fossil fuels potentially avoided	kg oil eq. (koe)

^a For the functional unit “generation of 1 kWh of electricity”, all indicators are expressed per unit of electricity generated. For “total annual electricity generation”, all indicators are expressed per year. The exceptions are capital costs which are always in US\$, total annualised costs which are in US\$/year and levelised costs which are always in US\$/kWh.

^b DCB: dichlorobenzene.

Figure 2: The life cycles of electricity technologies considered in this study

[*Comprises plant construction, operation and decommissioning. The dashed line indicates an optional step.]

2.2 Electricity technologies

The following sources of electricity are considered, all on a life cycle basis (Figure 2): coal and gas, both with and without carbon capture and storage (CCS), nuclear, solar photovoltaics (PV), onshore and offshore wind, biomass, hydro and geothermal power. As the focus is on electricity generation, its transmission, distribution and use are outside the scope of the study.

The specific technologies for each electricity source are listed in Table 2, together with their capacity factors and lifetimes. They are either available currently or represent the most promising options for future electricity generation in Turkey. For most technologies, future technological improvements have been taken into account, based on the projections by various sources (e.g. Frankl et al., 2006; Bauer et al., 2008; Gärtner, 2008; Kouloumpis et al., 2015). For some technologies, both 'optimistic' and 'pessimistic' cases have been considered, to reflect the uncertainty in their future development. The former assume considerable technological developments and better geographical conditions leading to best outcomes, while the pessimistic case assumes the worst outcomes. The optimistic case is denoted as "min" and the pessimistic as "max", referring to their best (minimum) and worst (maximum) sustainability performance. The technical data and assumptions for the future technologies are summarised in Table 3. Further assumptions for each future technology are discussed below.

2.2.1 Fossil fuels and nuclear power

Coal (lignite and hard coal) and gas are currently the main sources of electricity in Turkey, generating 72.5%, and they are likely to play a major role in the future electricity mix (TEIAS, 2013). As given in Table 3, a mix of pulverised coal (PC) and integrated gasification combined cycle (IGCC) plants is considered for lignite and hard coal and combined cycle gas turbine (CCGT) is assumed for natural gas power plants. The reason for choosing these technologies is that the majority of the plants are currently PC and CCGT and it is expected that they will continue to play an important role in a future electricity supply, together with IGCC plants (TEIAS, 2013). Since Turkey has no CCS programme at present, a mix of post-combustion and oxy-fuel CCS technologies likely to be implemented in the future (NEEDS, 2010) is assumed for coal plants and post-combustion CCS for gas installations. More efficient fossil fuel technologies and emission control systems have been assumed for the future fossil fuel plants, anticipating technological and legislative improvements. PWRs are assumed for future nuclear plants as they are currently the only option considered in Turkey (MENR, 2014a). For further data on technology specifications, see Table 3.

Table 2: Capacity factors and lifetimes of future electricity technologies

Technology	Capacity factor (%)	Lifetime (year)
Nuclear	88.7	60
Lignite	47	30
Lignite CCS	47	30
Hard coal	58	30
Hard coal CCS	58	30
Gas	62	25
Gas CCS	62	25
Solar	23	25
Biomass	88	25
Reservoir	39	150
Run-of-river	30	80
Wind onshore	30	25 ^a
Wind offshore	43	25 ^a
Geothermal	81	25

^a 40 years for fixed and 20 years for moving parts.

Table 3: Assumptions for future electricity generation technologies

Technology	Contribution to the technology mix (%)	Assumed characteristics in 2050	Data sources
Lignite			
Pulverised (min)	40	380 MW, 54% efficiency	Bauer et al. (2008)
Pulverised (max)	40	380 MW, 50% efficiency	- -
IGCC (min)	10	450 MW, 52.5% efficiency	- -
IGCC (max)	10	450 MW, 51.5% efficiency	- -
Lignite CCS			
Pulverised (min)	40	800 MW, oxy-fuel combustion, carbon sequestration 200 km away in an 800 m deep aquifer	- -
Pulverised (max)	40	800 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field	- -
IGCC (min)	10	450 MW, oxy-fuel combustion, carbon sequestration 200 km away in an 800 m deep aquifer	- -
IGCC (max)	10	450 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field	- -
Hard coal			
Pulverised (min)	30	460 MW, 54% efficiency	- -
Pulverised (max)	30	460 MW, 50% efficiency	- -
IGCC (min)	20	450 MW, 54.5% efficiency	- -
IGCC (max)	20	450 MW, 53.5% efficiency	- -
Hard coal CCS			
Pulverised (min)	30	500 MW, oxy-fuel combustion, carbon sequestration 200 km away in an 800 m deep aquifer	- -
Pulverised (max)	30	500 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field	- -
IGCC (min)	20	450 MW, oxy-fuel combustion, carbon sequestration 200 km away in an 800 m deep aquifer	- -
IGCC (max)	20	450 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field	- -
Gas			
CCGT (min)	50	400 MW, 65% efficiency	- -
CCGT (max)	50	400 MW, 62% efficiency	- -
Gas CCS			
CCGT (min)	50	500 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field, assumes low impacts	- -
CCGT (max)	50	500 MW, post combustion, carbon sequestration 400 km away in an 2500 m deep depleted gas field, assumes high impacts	- -
Nuclear			
PWR	100	1000 MW, centrifuge fuel enrichment, the average burnup 53 GWd/kg heavy metal	Dones et al. (2007)
Reservoir hydropower			
Large	67	1057 MW, same technology as currently	Bauer and Bolliger (2007)
Small	33	98 MW, same technology as currently	Flury and Frischknecht (2012)
Run-of-river hydropower			
Run-of-river	100	13.5 MW, same technology as currently	- -
Onshore wind			
Onshore 2 MW	60	2 MW turbines, 30% capacity factor	Kouloumpis et al. (2015)
Onshore 3 MW	40	3 MW turbines, 30% capacity factor	- -
Offshore wind			
Offshore 5 MW (min)	35	5 MW turbines, 50% capacity factor	- -
Offshore 5 MW (max)	35	5 MW turbines, 40% capacity factor	- -
Offshore 10 MW (min)	15	10 MW turbines, 50% capacity factor	- -
Offshore 10 MW (max)	15	10 MW turbines, 40% capacity factor	- -
Biomass			
Wheat straw	60	6 MW, cogeneration plant, electric conversion efficiency 20%, heat 65%.	Gärtner (2008)
Miscanthus	20	50 MW, cogeneration plant, direct combustion, 100% miscanthus, plant efficiency 45%	Jungbluth et al. (2007)

Wood residues	20	50 MW, cogeneration plant, direct combustion, 100% wood residues, plant efficiency 45%	Jungbluth et al. (2007)
Geothermal			
Geothermal	100	30 MW, flash-steam plant, same technology as currently	Dones et al. (2007)
Solar photovoltaics (PV)			
PV roof (min)	30	1 kW, tilted roof insulation, average annual solar radiation: 1800 kWh/m ²	Frankl et al. (2006)
PV roof (max)	30	1 kW, tilted roof insulation, average annual solar radiation: 900 kWh/m ²	- -
PV ground (min)	20	3.5 MW, ground-mounted, average annual solar radiation: 1800 kWh/m ²	- -
PV ground (max)	20	3.5 MW, ground-mounted, average annual solar radiation: 900 kWh/m ²	- -

2.2.3 Renewables

As mentioned earlier, hydropower currently provides 24.5% of electricity in Turkey and will continue to play an important role into a foreseeable future. It is a mature technology with long lifetimes, particularly for reservoir and run-of-river plants (Table 2), so that future technological changes will be modest. For these reasons, it is assumed that in the future hydropower will have the same characteristics as today.

Future development of wind power is assumed to be mainly onshore with a capacity of individual turbines from 2-3 MW. However, as the country plans to exploit its offshore wind potential in the future, offshore wind is also considered, assuming larger turbines, ranging 5-10 MW. Wheat straw, miscanthus and wood are assumed as the main biomass feedstocks, co-generating electricity and heat in combined heat and power (CHP) plants. Owing to the lack of data for future development of geothermal plants, it is assumed that flash-steam plants used currently will continue to be used in the future with no change in the design. A combination of small scale PV and large scale ground mounted plants is considered for future solar technologies (Table 3).

2.3 Scenarios

As shown in Table 4, four main scenarios are considered for the year 2050: business as usual (BAU), A, B and C. The latter three are driven by the need to reduce GHG emissions and mitigate climate change while BAU assumes that there are no emission targets. Each scenario includes several sub-scenarios, assuming different emission levels in 2050 and a differing mix of electricity technologies. In total, 14 alternative scenarios have been defined.

For comparison, the sustainability of the current electricity grid is also considered with 2010 taken as the base year. The assumed electricity mixes for the scenarios are shown in Figure 3, along with the current mix. As can be seen, the latter is dominated by natural gas (47%), coal (26%) and hydro-power (~25%). Currently, there are 187 gas, 16 lignite, eight hard coal, 55 reservoir, 205 run-of-river, 39 wind and six geothermal power plants, all of which are considered in the base case scenario. For full details of the technologies in the base case scenario, see Atilgan and Azapagic (2016). For a more detailed description of the sub-scenarios, see Section S2 in the Supplementary material.

Electricity generation is assumed to increase on average by 3.55% per annum to 2050 (MENR, 2014b). To make them comparable, energy demand is assumed to be 852 TWh in 2050 across all the scenarios (MENR, 2014b). This represents a four-fold increase on current generation of 211 TWh. A brief description of each scenarios is provided below; the detailed assumptions for the sub-scenarios can be found in Section S2 in Supplementary material.

In the BAU scenarios, fossil fuel power generation would continue dominating the electricity mix in 2050 without any additional energy and climate change policies. These scenarios also assume that no CCS is present in the future electricity mix. Direct GHG emissions (emitted during the operation of power plants) are up to five times higher than in 2000.

Scenarios A, B and C are driven by different targets for direct GHG emissions. In A-1 to A-4, limited action takes place to mitigate climate change and emissions double relative to the levels in 2000,

growing by around 1.1% annually. Scenarios B-1 to B-4 assume that the GHG emissions from the electricity sector are equal to 2000 levels by 2050. Here, low carbon technologies gain importance to limit the increase in direct emissions to around 0.7% per year. For C-1 to C-4, the emissions are equal to 1990 levels, decreasing by 2.7% year on year up to 2050. As these scenarios are more constrained than B, low carbon technologies have a leading role in electricity generation.

Table 4: Overview of the current electricity mix and scenarios in 2050

Scenario	Direct emissions ^a (Mt CO ₂ -eq./year)	Assumptions
Current (2010)	99 ^b	Current electricity mix. Coal and gas contribute 46.5% and 26.1%, respectively, to the total generation of 211 TWh. The next largest contribution is from hydropower (24.5%). Onshore wind contributes 1.4% and geothermal 0.3%.
BAU-1	370	The scenario was originally developed by Greenpeace and EREC (2008). There are no GHG emission targets and GHG emissions are five times greater than in 2000. A mix of fossil fuel (83.9%) and renewable (16.1%) technologies is assumed. CCS and nuclear plants are not considered.
BAU-2	297	Follows the current energy trends, policies and planned projects. There are no GHG emission targets and the emissions are four times higher than in 2000. Assumes a mix of fossil fuel technologies (69.5%), renewables (21.5%) and nuclear power (9%). The use of CCS is not considered.
A-1	150	Limited action is taken to reduce GHG emissions which double by 2050 relative to 2000. There is a strong support for fossil –fuel options, assuming a 46% contribution from such options without CCS and 29% with CCS, with the rest being renewable technologies. Nuclear power is not considered.
A-2		Limited action is taken to reduce GHG emissions which double by 2050 relative to 2000. There is a strong support for fossil fuel and nuclear plants, assuming a 41% contribution from fossil-fuel technologies without CCS and 19% with CCS, and 15% from nuclear power. The remaining 25% is from renewables.
A-3		Limited action is taken to reduce GHG emissions which double by 2050 relative to 2000. There is a strong support for renewable and nuclear electricity. It assumes the contribution of fossil-fuel technologies without CCS of 39%, renewables 36% and nuclear power 25%. The use of CCS is not considered.
A-4		Limited action is taken to reduce GHG emissions which double by 2050 relative to 2000. There is a concentration of investment in renewable technologies, assuming a contribution of 56%. Fossil-fuel technologies without CCS contribute 39% and nuclear 5%. The use of CCS is not considered.
B-1	75	GHG emissions are equal to 2000 levels by 2050. There is a strong support for fossil-fuel options. Technologies without CCS contribute 22% and with CCS 53%, with the rest being from renewables. Nuclear energy is not considered.
B-2		GHG emissions are equal to 2000 levels by 2050. There is a strong support for fossil fuel and nuclear electricity. Technologies without CCS contribute 23% and with CCS 37%, nuclear 15% and renewables 25%.
B-3		GHG emissions are equal to 2000 levels by 2050. There is a strong support for renewable and nuclear power with the former contributing 44% and the latter 30%. The rest is from fossil-fuel technologies without CCS (21%) and with CCS (5%).
B-4		GHG emissions are equal to 2000 levels by 2050. There is a concentration of investment in renewable technologies which contribute 69%. The rest is from fossil-fuel technologies (21% without CCS and 5% with CCS), renewables (69%) and nuclear (5%).
C-1	33	GHG emissions are equal to 1990 levels by 2050. There is a strong support for fossil fuel technologies with CCS contributing 60% and plants without CCS 5%. Renewables make up the remaining 35%. Nuclear plants are not considered.
C-2		GHG emissions are equal to 1990 levels by 2050. There is a strong support for fossil fuel and nuclear electricity. Fossil-fuel plants with CCS generate 42% of electricity and those without 8%. Renewables contribute 35% and nuclear 15%.
C-3		GHG emissions are equal to 1990 levels by 2050. There is a strong support for renewable and nuclear electricity which contribute 49% and 35%, respectively. Fossil-fuels without CCS generate 11% and with 5%.
C-4		GHG emissions are equal to 1990 levels by 2050. There is a concentration of investment in renewable technologies which generate 79% of total electricity. The rest is from fossil fuels (11% without CCS and 5% with CCS) and nuclear (5%).

^a Direct emission refer to emissions from operation of power plants, as opposed to life cycle emissions which span the whole life cycle of electricity generation.

^b Source: FutureCamp (2011). For comparison, direct emissions in 1990 were 33 Mt CO₂-eq./yr and in 2000 75 Mt CO₂-eq./yr (TUIK, 2013).

Figure 3: Current electricity mix (2010) and future scenarios (2050)

2.4 Sustainability assessment

The scenarios are assessed on environmental, economic and social sustainability using the indicators summarised in Table 1 and detailed in Section S1 in the Supplementary material. The environmental sustainability assessment has been carried out using LCA, in accordance with the guidelines in the ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b). The software package GaBi v.6 (PE International, 2013) has been used to model the systems and estimate the environmental impacts following the CML 2001 methodology (Guinée et al., 2002), November 2010 update. All 11 impacts included in CML 2001 are considered (see Table 1). The inventory data discussed in Section 2.2 have been collected from a variety of sources and adapted as far as possible to Turkey's conditions. There are no other LCA studies of future electricity technologies in Turkey for the year 2050, so the assumptions are based on European conditions assuming that by then Turkey will be part of the EU and achieve a technological alignment with the rest of Europe. The background life cycle inventory data have been sourced mainly from NEEDS (2010) and Ecoinvent (2010), which are also based on European conditions.

As indicated in Table 1, three indicators are considered in the economic assessment: capital, total annualised and levelised costs (for estimations, see Section S1 in the Supplementary material). While levelised costs are used most often to distinguish the costs of electricity options, capital costs are also important in developing countries such as Turkey, where access to investment is difficult. This is the reason for considering this indicator here, aiming to help investors and policy makers compare different electricity options on the basis of the required capital investment. For the same reasons, it is necessary to consider total annualised costs to provide an indication as to the expected yearly expenditure for each technology.

The costs for the current electricity options have been sourced mainly from Turkey's electricity generation plan (TEIAS, 2013). Data for the costs of future electricity technologies in Turkey are not available. Therefore, future cost projections for the technologies in Europe have been assumed based on the information in Bauer et al. (2008), Gärtner (2008), Fürsch et al. (2011), Schröder et al. (2013), Greenpeace and EREC (2012) and Sensfuß and Pfluger (2014). The cost assumptions for different technologies and fuels can be found in Section S3 in the Supplementary material. Note that future fuel costs are the main source of uncertainty for two reasons: first, the data are available for a limited number of technologies (see Figure S3-1d) and secondly, the current fuel prices are specific to

Turkey while the future fuel costs have been sourced mainly from European data. In an attempt to reduce the uncertainty, wherever possible and available, a range of cost values for each option has been considered. For the estimation of annualised capital costs, the discounting rate of 10% has been applied (TEIAS, 2013). All costs are expressed in 2012 US\$ in order to make the results for the future scenarios comparable with the current situation.

The social sustainability assessment is based on the following five indicators (Table 1): direct employment, total employment (direct and indirect), injuries, large accident fatalities and imported fossil fuels potentially avoided. Their definitions can be found in Section S1 and the assumptions for the social sustainability assessment in Section S4 in the Supplementary material. To estimate the provision of employment in the life cycle of each technology, the employment factors have been calculated based on the relationship between employment factors in the OECD countries (Rutovitz and Harris, 2012) and the labour productivity (Yilmaz, 2014); for details, see eqn. [17b] in Section S1 in the Supplementary material. The employment factors have been adjusted by taking into account a 'decline factor' for each technology to reflect a reduction in the employment per unit of electricity with improvements in technology efficiencies (Rutovitz and Harris, 2012). As the decline factors are not available beyond 2030, the 2030 data have been used for 2050. For the fossil fuel technologies with carbon capture and storage (CCS), the employment factors are assumed to be 30% higher than for the conventional fossil fuel systems (the same assumption as for the costs) because of the higher number of components and material requirements but also because of the efficiency penalty and the related effects in the fuel supply chain.

Worker injuries and large accident fatalities for each technology are calculated using the worker injury and fatality rates and the number of jobs in each life cycle stage. Changes in the injury and fatality rates over time have been estimated using an annual average rate of decline of 4% until 2050, based on the historical trends from 1996 to 2013 (SSI, 2013). Data are not available for the injury and fatality rates for biomass, nuclear, offshore wind and solar power so that they have been estimated in proportion to the employment rates.

Given Turkey's current dependence on imported fossil fuels (see the Introduction), avoiding fossil fuel imports is important for the national energy security. Therefore, the indicator 'imported fossil fuels potentially avoided' is used to reflect this issue. The amount of imported fossil fuel avoided is estimated taking into account the contribution to the total generation of electricity options which are not using imported fossil fuels, i.e. lignite (as it is a domestic source), renewables and nuclear. For the estimations, see Section S1 in the Supplementary material.

2.5 Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) has been used to integrate the three dimensions of sustainability and help identify the most sustainable scenario(s), taking into account different preferences for the aspects. In this work, the MCDA analysis has been carried out using the multi-attribute value theory (MAVT) as incorporated in the Web-HIPRE V1.22 software, (Mustajoki and Hämäläinen, 2000); for the calculation method, Section S1 in the Supplementary material.

The MCDA has been carried out in two stages. First, the scores for the environmental, economic and social sustainability aspects have been calculated, based on the values of the corresponding sustainability indicators, obtained in the sustainability assessment, and their weights of importance. In the second stage, the overall sustainability score of an option has been estimated using the scores for the environmental, economic and social aspects, estimated in the first stage, and the weights of importance for each aspect.

The MCDA was first performed assuming an equal importance of all the environmental, economic and social aspects and indicators. This was followed by assuming in turn a high preference for each sustainability aspect to find out how the results may change if the environmental, economic and social aspects have different importance. 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 MCDA results, a sensitivity analysis has been carried out to find out if the ranking of the scenarios changes with different weighting of the aspects.

3. Results and discussion

This section presents the results of the sustainability assessment comparing the current electricity mix and future scenarios on different sustainability aspects. The results are discussed in turn for the environmental, economic and social indicators in the sections below. Further details can be found in Sections S3-S6 in the Supplementary material.

3.1 Environmental sustainability assessment

The results of environmental sustainability assessment are displayed in Figure 4-Figure 14 and are discussed for each impact below.

3.1.1 Abiotic depletion potential (ADP elements)

Figure 4 reveals that in all the scenarios the depletion of elements would increase by 2050 compared to the present day. The best options are the BAU scenarios, with an estimated impact of 46-48 μg Sb-eq. per kWh; however, this is still almost double the current impact (Figure 4a). Annually, this difference is even higher, exceeding seven times for BAU and 71 times for C-4 (Figure 4b). This is largely due to a four times higher electricity demand than today but also because of the high contribution of renewables in the case of C-4. For the same reason, the other renewable-intensive scenarios (A-4 and B-4) also have high depletion of elements, mainly because of the high contribution from solar power (for the impact from the individual technologies, see Figure S5-1a in the Supplementary material).

3.1.2 Abiotic depletion potential (ADP fossil)

All the scenarios show a decrease in the ADP fossil per kWh electricity by 2050 (Figure 5a). This is mainly due to the efficiency improvements for the future fossil fuel plants. However, the increase in electricity demand means that the annual depletion of fossil resources is higher for all the scenarios than at present, except for C-3 and C-4 (Figure 5b). This is because these scenarios have a low penetration of fossil fuel technologies (see Figure 3). The worst options are BAU-1 and A-1, with around three times higher impact than from the current electricity grid.

3.1.3 Acidification potential (AP)

As shown in Figure 6, all the scenarios have a much lower AP than today's grid, both per kWh and for the electricity generated per year. The A-1 scenario has the highest impact because of the high contribution of fossil fuel options which have the highest AP among the technologies considered (see Figure S5-1c). However, this is still 4.5 times lower per kWh and 10% lower per annum than from the existing grid. The best option is C-3 with a 57% lower impact than at present (Figure 6b) because of the high penetration of nuclear power which has a low AP. The worst scenario is A-1 mainly because of the conventional gas and coal CCS; however, its impact is still 10% lower than at present.

Figure 4: Abiotic depletion potential (ADP elements) for the current situation (2010) and future scenarios (2050)

a) ADP fossil per kWh
b) ADP fossil per year
Figure 5: Abiotic depletion potential (ADP fossil) for the current situation (2010) and future scenarios (2050)

a) AP per kWh
b) AP per year
Figure 6: Acidification potential (AP) for the current situation (2010) and future scenarios (2050)

a) EP per kWh
b) EP per year
Figure 7: Eutrophication potential (EP) for the current situation (2010) and future scenarios (2050)

3.1.4 Eutrophication potential (EP)

The BAU scenarios have the highest EP and, although it is two times lower per kWh than currently, when the electricity demand is taken into account the annual impact doubles on the present value (Figure 7). All other scenarios have a lower annual impact than the current electricity mix, with the best option (C-3) having 12 times lower EP. All other C scenarios as well as B-1 and B-2 also perform well for this impact. This is due to a low or no contribution from coal which is by far the worst source of power for this category among the options considered (Figure S5-1d).

3.1.5 Freshwater aquatic ecotoxicity potential (FAETP)

Replacing the current mix with any of those considered in the future scenarios would lead to a reduction in the FAETP per unit of electricity generated, but for some scenarios the annual impact would be higher, in particular for BAU for which it doubles by 2050 on today's value (Figure 8a). This is largely due to a high proportion of coal which has a much higher FAETP than the other power options (Figure S5-1e). On the other hand, for the best cases, B-1 and C-1, the annual impact is up to 24 times lower than currently. All other C scenarios also result in significant FAETP savings as they have a small contribution of fossil fuel electricity (without CCS).

3.1.6 Global warming potential (GWP)

As indicated in Figure 9a, the current GWP per kWh of electricity would be reduced in all the scenarios, including the BAU. This is due to the fossil fuel technologies becoming more efficient in the future as well as the use of CCS; for the GWP of the technologies, see Figure S5-1f in the Supplementary material. However, when the annual electricity demand is taken into account, most scenarios have a higher GWP than today (Figure 9b). BAU-1 is the worst option, with nearly four times greater impact than at present. This is due to the high contribution of coal and gas to the electricity mix. The best scenarios are C-3 and C-4, generating about a half of today's GHG emissions.

3.1.7 Human toxicity potential (HTP)

All scenarios have a lower HTP per unit of electricity than currently, with the reductions ranging between two (BAU-1) and 14 times (C-4). The highest values are found for BAU (Figure 10a) because of the emissions of heavy metals from coal power plants. However, the annual impact is higher for the BAU and A scenarios than from the current grid owing to the extensive use of conventional coal plants and the increase in electricity demand. Scenario C-4 is the best option with around three times lower HTP than at present. All other B and C scenarios as well as A-1 also have a lower impact than today.

Figure 8: Freshwater aquatic ecotoxicity potential (FAETP) for the current situation (2010) and future scenarios (2050)

Figure 9: Global warming potential (GWP) for the current situation (2010) and future scenarios (2050)

Figure 10: Human toxicity potential (HTP) for the current situation (2010) and future scenarios (2050)

Figure 11: Marine aquatic ecotoxicity potential (MAETP) for the current situation (2010) and future scenarios (2050)

3.1.8 Marine aquatic ecotoxicity potential (MAETP)

As for the FAETP, all future scenarios would lead to a reduction in the MAETP per kWh of electricity (Figure 11a). The BAU scenarios again have the highest impacts, largely because of the contribution from coal power (Figure 11b). A similar trend applies for the annual impact, except for the BAU scenarios which have around 50% higher MAETP than the current electricity mix. The best scenario is C-4 with 12 times lower impact than currently because it does not involve any conventional coal power.

3.1.9 Ozone layer depletion potential (ODP)

Although the ODP is lower per kWh for all the scenarios, the annual impact is several times higher than today for all the options considered (Figure 12). The exceptions to this are C-3 and C-4 which would reduce the ODP by 16% relative to the current situation. In the worst case (A-1), the annual impact would be three times higher. This is due to the high contribution to the electricity mix from conventional gas, which in turn is due the leakage of halons used as fire suppressants in gas pipelines. Therefore, the other scenarios with a high contribution from gas power also have a high ODP (Figure 12b).

3.1.10 Photochemical oxidant creation potential (POCP)

Like the ODP, all the scenarios show a decrease in this impact per unit of electricity but an increase on an annual basis compared to the present POCP value (Figure 13). The worst scenarios are BAU-1 and A-1 and the best C-3. This is due to the contribution of fossil fuels to the generation mix which is higher in the former and low in the latter.

3.1.11 Terrestrial ecotoxicity potential (TETP)

Per kWh of electricity generated, the TETP is lower for all the scenarios than for the current grid, including BAU (Figure 14a). However, the opposite trend is found for the annual impact, with all the scenarios being worse than the current situation. The worst option is BAU-1, with 3.5 times higher impact than today. Even the best scenario (C-4) still has nearly two times higher TETP. The high electricity demand is the main reason for this increase in the annual impact.

3.1.12 Summary

Overall, the scenarios C-3 and C-4 have the lowest environmental impacts on an annual basis, with the former being the best option for four impacts, including the GWP, and C-4 for five. However, the latter is the worst option for the depletion of abiotic elements for which BAU-1 is most sustainable. On the other hand, this scenario is the least sustainable for seven other impacts, including the GWP.

Figure 12: Ozone layer depletion potential (ODP) for the current situation (2010) and future scenarios (2050)

Figure 13: Photochemical oxidant creation potential (POCP) for the current situation (2010) and future scenarios (2050)

Figure 14: Terrestrial ecotoxicity potential (TETP) for the current situation (2010) and future scenarios (2050)

3.2 Economic sustainability assessment

This section presents the capital, total annualised and levelised costs of the scenarios in comparison to the present costs. For each, minimum, central and maximum values have been estimated as shown in Figure 15-Figure 17. Note that the discussion below is based on the central estimates. For the costs of different electricity technologies, see Section S3 in the Supplementary material.

3.2.1 Capital costs

As indicated in Figure 15a, the total capital costs for all the scenarios are estimated to be up to 11 times higher than presently. The BAU scenarios are the least expensive, with the central estimates of US\$388-443 bn. This is mainly due to the lowest required installed capacity and the high contribution of conventional coal and gas power plants which are less expensive compared to the other options (see Figure S3-1a in the Supplementary material). Among the other scenarios, the next best options are A-1, B-1 and C-1 (US\$486-522 bn), also because of the high contribution of fossil fuels in the electricity mix. In contrast, the scenarios with a high contribution from renewables (A-4, B-4 and C-4) are the most expensive, requiring a total capital investment of up to US\$760 billion. The main contributors to the costs in these scenarios are hydropower and solar power (Figure 15b).

3.2.2 Annualised costs

Key variables used to calculate the total annualised costs are capital, fixed, variable and fuel costs (see Section S1 in the Supplementary material). As indicated in Figure S3-1b-d in the Supplementary material, the future technologies tend to have higher fixed and lower variable costs than currently; however, the fuel prices decrease.

The results in Figure 16a suggest that the total annualised costs for all the scenarios will increase by 4-5 times relative to the present. Scenarios with a high contribution from renewables (A-4, B-4 and C-4) are more expensive, ranging from US\$105-114 bn/yr. This is due to the higher annualised capital cost which contribute 70% to the total. The scenarios with a high penetration of fossil fuels (A-1, B-1 and C-1) are also expensive, costing from US\$103 to 112 bn/yr. For these, the annualised capital and fuel costs contribute around 50% and 30% of the total annualised costs, respectively. On the other hand, the BAU scenarios have the lowest total annualised costs (around US\$87 bn/yr). Here, the annualised capital costs account for 47% of the total, followed by fuel (39%) costs. The annualised costs for the other scenarios range between US\$96-111 bn/yr.

3.2.3 Levelised costs

The results in Figure 17 indicate the same ranking of the future scenarios per unit cost of electricity as for the total annualised costs. Overall, they range from US\$71-174/MWh across all the scenarios, averaging at US\$122.5/MWh, which compares well with the current levelised cost of electricity of US\$123/MWh. However, for the central estimates, the levelised cost is lower for most scenarios than today. The best options are the BAU scenarios at around 102 US\$/MWh in the central case, around 20% cheaper than today. The most expensive options are those with a high penetration of renewables (A-4, B-4 and C-4) and fossil fuels (A-1, B-1 and C-1), averaging between 121 and 133 US\$/MWh, respectively. Nevertheless, the most expensive scenario (C-4) is still only 10% more expensive than currently.

3.2.4 Summary

From an economic point of view, BAU-1 is overall a clear best and C-4 the worst option. However, they all have much higher capital and total annualised costs than the current electricity mix. On the other hand, the range of levelised costs estimated for the scenarios compares well with the present cost of electricity.

Figure 15: Total capital costs for the current situation (2010) and future scenarios (2050)

[Costs expressed in US\$2012. a) The bars represent central estimates and the error bars cost ranges. b) The contribution to the costs is based on the central estimates which correspond to the contribution of each electricity option to the technology mix in Table 3.]

Figure 16: Total annualised costs for the current situation (2010) and future scenarios (2050)

[a) The bars represent central estimates and the error bars cost ranges.]

Figure 17: Levelised costs for the current situation (2010) and future scenarios (2050)

[a) The bars represent central estimates and the error bar cost ranges.]

3.3 Social sustainability assessment

Five indicators have been considered to assess the social sustainability of the scenarios as discussed below. The results for each technology that have been used to assess the social sustainability of the scenarios can be found in Section S4 in the Supplementary material.

3.3.1 Direct employment

The direct employment, which includes jobs provided in Turkey during the construction, operation, maintenance and decommissioning of power plants, increases in all the scenarios from 117 jobs-years/TWh (24,600 jobs/yr) in 2010 to between 129 and 230 jobs-years/TWh (109,600-196,000 jobs/yr) in 2050 (Figure 18a). The lowest employment opportunities exist in BAU-1 which relies heavily on conventional coal and gas power, which in turn are highly mechanised. On the other hand, scenario C-4, with the highest penetration of renewables, provides the highest number of direct jobs, with the highest contribution from run-of river hydropower (Figure 18a) which provides 538 jobs-years/TWh, followed by biomass at 407 and solar with 254 jobs-years/TWh. By comparison, gas provides only 45 jobs-years/TWh (see Figure S4-1a in the Supplementary material). For immature renewable technologies, such as geothermal, offshore wind and solar PV, the employment factor decline rate is higher than for the others so that their employment rates are lower.

Figure 18: Employment for the current situation (2010) and future scenarios (2050)

Figure 19: Total injuries and fatalities for the current situation (2010) and future scenarios (2050)

3.3.2 Total employment

Similar to direct employment, all the scenarios show an increase in the total employment, which in addition to the direct, includes employment in fuel extraction and processing as well as in the manufacturing of plant components. As indicated in Figure 18b, the best option for this indicator is C-4 with 337 jobs-years/TWh (287,000 jobs/year) because of the high contribution of renewables in the electricity mix. The lowest job provision is in A-3, with 276 jobs-years/TWh (or 235,000 jobs/year) owing to the high contribution of nuclear power to the electricity mix; however, the total annual employment is still around four times higher than today.

3.3.3 Worker injuries

Under the assumptions made here, the number of worker injuries is expected to decrease in all the scenarios, reaching around 2 injuries/TWh (1835 per year) in the best case (C-3), compared to around 17 today (Figure 19a). Even for the worst option (BAU-1), the injury rate would still be reduced by 70%. As expected, the highest rate of injuries is found for coal power which largely occurs in mining (Figure S4-1c).

3.3.4 Large accident fatalities

A similar trend to worker injuries is found for large accident fatalities which decrease significantly in 2050 compared to today (Figure 19b). C-3 is also the best option for this indicator, causing 0.013 fatalities per TWh (11 per year). By comparison, the worst scenario (BAU-1) has 0.034 fatalities per

TWh (or 29 per year), half the current number. Like the worker injuries, coal power has the highest life cycle fatality rate, again because of mining. Geothermal, offshore wind and reservoir hydropower are the best technologies for this social impact (Figure S4-1d).

3.3.5 Imported fossil fuel potentially avoided

This indicator evaluates national energy security related to the imports of fossil fuels potentially avoided through the utilisation of technologies that do not rely on imported fossil fuels. It applies only to the operation of power plants rather than the whole life cycle as was the case for the other indicators (see Section S1 in the Supplementary material). The current fleet is estimated to avoid 72 tonnes of oil equivalent (toe) per GWh or around 15 Mtoe/yr. By comparison, the best scenarios (C-3 and C-4) would save 145 toe/GWh or 123 Mtoe/yr (Figure 20). In the worst case (BAU-1), only 52 toe/GWh (44 Mtoe/yr) would be avoided because of the high contribution of fossil fuel options.

Figure 20: Avoidance of fossil fuels potentially imported for the current situation (2010) and future scenarios (2050)

3.3.6 Summary

Overall, C-3 and C-4 could be considered the best scenarios for the social sustainability, with the former ranked top for the employment and the latter for worker safety; they also share first place for energy security as measured by the avoidance of imported fossil fuels. The worst option across all the social criteria is BAU-1, except for the total employment for which A-3 is least sustainable.

3.4 Multi-criteria decision analysis (MCDA)

As discussed in the previous sections, different scenarios have different advantages and disadvantages so identifying the most sustainable among them is not easy. Therefore, MCDA has been used to help analyse the results and choose the best options. The MCDA decision tree can be found in Figure S7-1 in the Supplementary material.

The MCDA has first been performed assuming an equal importance of all three sustainability aspects (environmental, economic and social) and assigning the same weighting to each ($w_i=0.33$). To test the robustness of the results, in a subsequent analysis it has been assumed in turn that each aspect has a much higher importance, chosen arbitrarily to be five times. However, it is assumed in all the analyses that the sustainability indicators have an equal importance within their respective sustainability aspect, assigning them following weights w_i (for the definition of weights, see eqn. [21] in the Supplementary material):

- 11 environmental indicators: $w_i=1/11=0.09$;
- three economic indicators: $w_i=1/3=0.33$; and
- five social indicators: $w_i=1/5=0.2$.

The MCDA results are discussed below. Note that the option with the highest total score is considered most sustainable. Further details on the MCDA results and the sensitivity analyses can be found in Section S7 in the Supplementary material.

3.4.1 Equal preferences for the sustainability aspects

Figure 21 presents the sustainability scores for the equal weighting on all the sustainability aspects. As indicated, all the scenarios are more sustainable than electricity at present. C-3 is ranked best with a total score of 0.69, followed by B-3 and C-4 with 0.66 and 0.65, respectively. By comparison, the current electricity mix scores only 0.22. Although C-4 is the third best overall, it is the worst option in terms of economic sustainability; however, it has the best score for the social aspect, nearly three times higher than the worst scenario for the social sustainability (BAU-1).

B-1 is the least sustainable, scoring only 0.47, but still twice as high as today's electricity mix. A-1 and C-1 follow closely with 0.51. Even though BAU-1 is the worst option for the environmental and social aspects, it has the best economic performance among the scenarios.

The sensitivity analysis suggests that the weight on the environmental aspect would have to change significantly, from the current 0.33 to 0.73, to incur a change in the scenario ranking (see Figure S7-3a in the Supplementary material). In that case, BAU-1 would become the worst option, after BAU-2 and B-1. Moreover, the rank of C-4 and B-3 would reverse and C-4 would become the second best option.

For the economic aspect, the ranking order of the scenarios would change if the weighting on this aspect almost doubled, from 0.33 to 0.60 (Figure S7-3b). In that case, the BAU-1 scenario would become the best option overall, scoring 0.70 while C-1 would be the least sustainable, with only 0.36.

A sensitivity analysis for the social aspect shows that the current weight of 0.33 would have to increase to 0.80 for the rankings to change (Figure S7-3c) in which case BAU-1 would be the worst scenario, after A-1 and B-1, and C-4 would be the best, followed by B-4 and C-3.

Figure 21: 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

Figure 22: Ranking of the scenarios with different preferences for the sustainability aspects

3.4.2 Different preferences for the sustainability aspects

As mentioned earlier, to find out if and how the choice of the best option would change with different preferences for the sustainability aspects, it has been assumed in turn that each aspect is five times more important than the other two. For these purposes, each aspect is assigned in turn a weight of 0.71 and each of the remaining two 0.145.

As indicated in Figure 22a, if the environmental aspect is considered most important, all the scenarios are still several times better than the current electricity mix; even the worst scenario (BAU-1) has a sustainability score four times higher. This is mainly because the impacts would be lower in the future than today per unit of electricity generated (except for the depletion of elements).

Among the scenarios, C-3 is the most attractive (scoring 0.83), followed by B-3 and C-4 with 0.79 owing to their renewable-intensive electricity mix. Although the remaining C scenarios have the same GHG emissions, they rank lower (C-2 is the 5th and C-1 the 9th) because of their worse performance on the other criteria. BAU-1 is least sustainable, scoring only 0.55, followed by BAU-2 with 0.60. However, these two scenarios perform better for the economic aspect than any other scenarios. The ranking of the scenarios would change if the weighting on the environmental aspect reduced from the current 0.71 to 0.57 (see Figure S7-4 in the Supplementary material). In that case, B-3 would be the second and C-4 the third preferred while B-1 would be the least sustainable scenario.

When the economic aspect is a priority, BAU-1 and BAU-2 are clear winners, scoring 0.75 and 0.71, respectively (Figure 22b). However, they perform poorly for the other two aspects. The scenario C-4 and C-1 are the least sustainable, scoring 0.31, lower than the current electricity mix which scored 0.41. B-2, B-3, B-4 and C-2 are also worse than the present mix. The sensitivity analysis suggests that this ranking would change if the importance of the economic aspect was lowered from 0.71 to 0.41 (Figure S7-5) in which case C-3 would be the best and B-1 the worst scenario.

In case the social aspect is five times more important than the other two (Figure 22c), C-4 would emerge as the most sustainable scenario with the score of 0.84. B-4 is ranked second best (0.77), followed by C-3 (0.75). BAU-1 and B-1 are the worst options (scoring 0.45 and 0.46, respectively). However, they are all still more than four times better than today's electricity generation. The sensitivity analysis suggests that the ranking of the scenarios would change at $w_i=0.4$, with the C-3 scenario becoming the best and B-1 the worst option (Figure S7-6).

3.4.3 Summary

The results discussed above are summarised in Table 5 to help guide the identification of the most sustainable option(s). Simple ranking has been used for these purposes, with the most sustainable scenario assigned a score of 1, the next best a 2 and so on, up to 15 which represents the least sustainable option.

As indicated in Table 5, the C-3 scenario is the most sustainable option if all the aspects are considered equally important as well as when the highest priority is given to the environment. C-4 scenario is ranked best if the social impacts are most important. However, C-4 becomes the least sustainable scenario (together with C-1) if the economic aspect is prioritised, in which case BAU-1 is ranked first. BAU and the other fossil fuel intensive scenarios (A-1, B-1 and C-1) are least sustainable after the current mix, except for a very high importance given to the economic criteria.

Overall, renewable or renewable-nuclear intensive scenarios are more sustainable than the other options considered here. However, the main drawback of these scenarios is their high costs. Generally, fossil and nuclear intensive scenarios are the middle ranking options. The fossil fuel based scenarios are least sustainable across the wide range of preferences for the sustainability aspects considered in this work. The exception to this is if the economic sustainability is considered most important, in which case renewable-intensive scenarios are least sustainable overall. Nevertheless, all the scenarios are more sustainable than electricity at present; the only exception is if the economic aspect is given priority, in which case it becomes a middle ranking option.

Table 5: Sustainability ranking of the scenarios with different weights on the environmental, economic and social aspects

Scenario	Equal weights	Aspect five times more important at a time		
		Environmental	Economic	Social
2010	15	15	9	15
BAU-1	8	14	1	14
BAU-2	6	13	2	11
A-1	12	11=	7	12
A-2	10	10	4	10
A-3	5	7	3	6
A-4	7	6	8	5
B-1	14	11=	13	13
B-2	11	8	10	8
B-3	2	2=	4	4
B-4	4	4	12	2
C-1	13	9	14=	8
C-2	9	5	11	7
C-3	1	1	6	3
C-4	3	2=	14=	1

4. Conclusions and policy recommendations

This paper has addressed the environmental, economic and social sustainability of potential electricity scenarios for Turkey to help identify the most sustainable pathways for future developments of the electricity sector. In total, 14 electricity scenarios have been developed considering different technologies, electricity mixes and GHG emission targets up to 2050. Each scenario has been assessed using 19 sustainability indicators, considering the whole life cycle of electricity generation, from extraction, processing and transport of fuels and raw materials, to plant construction, operation and decommissioning.

The findings suggest that, per unit of electricity generated, all the environmental impacts would be lower in the future than today across all the scenarios. The only exception is depletion of elements which would increase by 2-18 times, depending on the scenario. However, because of the expected significant increase in electricity demand, the annual impacts increase significantly for six categories across all the scenarios: depletion of elements, fossil fuels and the ozone layer, global warming potential, photochemical oxidants and terrestrial ecotoxicity. The other impacts are also higher for some of the scenarios, mostly those dominated by fossil fuels. The only impact that would be reduced in all the scenarios on today's value is acidification. Regarding the specific scenarios, BAU is environmentally least sustainable for seven out of 11 impacts. This includes the GWP which would increase up to four times on the current annual impact. On the other hand, choosing the best option instead (C-3) would halve the current GHG emissions from electricity. Generally, the scenarios with a higher contribution of renewables and nuclear power (A-3, A-4, B-3, B-4, C-3 and C-4) have lower annual impacts. However, the main drawback of the renewables-intensive scenarios is that they have the highest depletion of elements which in the worst case (C-4) would require around 70 times more resources annually than at present.

Regarding the economic sustainability, a huge investment will be needed to meet future electricity demand. The BAU-1 scenario is the most attractive option in terms of capital costs, requiring a total investment of US\$388 bn. In contrast, the most expensive option, C-4, would cost US\$760 bn; a 10-fold increase on today's costs. This is mainly because of the high contribution of renewable technologies (79%), which have higher capital costs than the fossil fuel options dominating in BAU-1. The BAU scenarios also have the lowest total annualised costs (US\$86-88 bn/yr) and C-4 the highest (US\$114 bn/yr); the latter are four-fold greater than at present. The levelised costs of electricity follow a similar trend although the difference between the current and projected future costs is not as dramatic as for the capital and annualised costs. For the most expensive C-4 scenario, the cost of electricity would be 10% higher than presently while for the best BAU-1 option, the electricity would be 18% cheaper. However, these estimates should be interpreted with care because of the uncertainties

associated with both current costs of fossil fuels and cost estimates over long timescales as well as due to a general lack of cost data for Turkey.

With respect to the social indicators, the direct and total employment increase in all the scenarios, with the latter being up to five times higher than the current level of employment in the electricity sector. Overall, the best option is C-4 in terms of job creation because of the high contribution from renewables which provide more jobs per unit of electricity than the fossil and nuclear options. The worst scenario from this perspective is A-3 (renewable-nuclear intensive) with a total of around 235,000 jobs in 2050, but still four times higher than at present. Injury and fatality rates are expected to decrease in the future. However, the annual worker injuries and large accident fatalities differ between the scenarios. The best option (C-3) would lead to around 1840 injuries and 11 fatalities per year. The BAU-1 scenario is the least sustainable for worker safety, with around 8625 injuries and nearly 30 fatalities per year; this is due to its heavy reliance on coal power. Energy security is clearly better in scenarios with a high penetration of renewable energy. By 2050, the C-3 and C-4 scenarios would avoid the imports of 145 toe/GWh, twice as much as at present. Only BAU-1 avoids less fossil fuel (52 toe/GWh) than today's electricity mix because it has the highest proportion of fossil fuels.

Multi-criteria decision analysis suggests that renewable and nuclear intensive scenarios outperform those that are dominated by fossil fuels, except for the very high preference for the economic criteria, in which case they are the best option. However, their poor environmental and social performances makes them least sustainable overall. Using the fossil fuel and nuclear power together leads to a better sustainability performance which is the case for the A-2, B-2 and C-2 scenarios. The renewable-nuclear intensive scenarios (A-3, B-3 and C-3) are the most sustainable options with respect to most of the environmental, economic and social impacts considered in this paper. Renewable-intensive scenarios (A-4, B-4 and C-4) perform very well for the environmental and social categories, but poorly for the economic categories. In all cases future scenarios can be considered more sustainable than today's electricity, except for a high preference for the economic criteria, in which case it becomes a middle ranking option.

Therefore, as these results suggest, some trade-offs will be needed between the sustainability aspects to identify the most sustainable pathways for a future development of the electricity sector in Turkey. Ultimately, the outcomes will depend on the importance that government and other stakeholders place on different sustainability criteria. Notwithstanding this, the following policy recommendations can be made on the basis of this work:

- Government should adopt a life cycle approach in decision and policy making to help identify hot spots and opportunities for reducing environmental, economic and social impacts of future electricity generation along the whole supply chain.
- Government should consider wider environmental, economic and social aspects rather than focusing solely on costs, energy security and climate change before deciding which electricity technologies to promote for the future.
- A more detailed assessment of resource potential should be carried out for all energy sources available in Turkey.
- As a signatory to the Kyoto Protocol, Turkey should set reduction targets for GHG emissions to help mitigate climate change.
- Turkey's energy strategy covers the period only up to 2023. A longer time frame should be considered to help plan future development of the electricity sector up to 2050.
- The results of this work shows 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, while also improving energy security. Therefore, future policies should be oriented towards reducing the contribution of fossil-fuel technologies and increasing the penetration of low-carbon options.
- The technical and economic feasibility of carbon capture, transport and storage in Turkey should be assessed.
- Increasing the proportion of renewable power in the electricity mix would significantly increase depletion of elements. This impact could be minimised through appropriate policies that encourage recycling, use of non-scarce and renewable materials as well as dematerialisation.

- Government should strengthen the financial support mechanisms and incentives to help renewable power become more competitive with fossil-fuels, particularly for technologies with high capital costs, such as geothermal, solar PV and hydropower.
- The use of nuclear power should be assessed considering further issues not included in this study, such as human health impacts from radiation, risks of accidents, earthquake-prone characteristics of the country and long-term storage of nuclear waste. These and other issues should be considered judiciously before making plans for further development of nuclear power in Turkey.
- Government should support research into improvements of electricity technologies as well as better legislation to limit environmental impacts in particular.
- Technological improvements are necessary but on their own will not be sufficient so they must be coupled with reducing the electricity demand, including through energy efficiency measures. Reducing the demand should be encouraged through appropriate policies and education programmes, engaging both electricity generators and the public.

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Appendix A. Supplementary Information

Supplementary information to this article can be found online.

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