

# Assessing the Environmental Sustainability of Electricity Generation in Turkey on a Life Cycle Basis

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Article

# Assessing the Environmental Sustainability of Electricity Generation in Turkey on a Life Cycle Basis

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**Abstract:** Turkey's electricity mix is dominated by fossil fuels, but the country has ambitious future targets for renewable and nuclear energy. At present, environmental impacts of electricity generation in Turkey are unknown so this paper represents a first attempt to fill this knowledge gap. Taking a life cycle approach, the study considers eleven impacts from electricity generation over the period 1990–2014. All 516 power plants currently operational in Turkey are assessed: lignite, hard coal, natural gas, hydro, onshore wind and geothermal. The results show that the annual impacts from electricity have been going up steadily over the period, increasing by 2–9 times, with the global warming potential being higher by a factor of five. This is due to a four-fold increase in electricity demand and a growing share of fossil fuels. The impact trends per unit of electricity generated differ from those for the annual impacts, with only four impacts being higher today than in 1990, including the global warming potential. Most other impacts are lower from 35% to two times. These findings demonstrate the need for diversifying the electricity mix by increasing the share of domestically-abundant renewable resources, such as geothermal, wind, and solar energy.

**Keywords:** electricity generation; environmental impacts; life cycle assessment; Turkey

## 1. Introduction

With its young population, fast growing economy and industrialisation, Turkey has become one of the fastest growing energy markets in the world. Its energy demand has been increasing rapidly over the past few decades, rising almost six-fold in the period between 1970 and 2010 [1,2]. The demand for electricity has also followed this trend. In 2010, the total installed capacity of 49,524 MW generated 211,208 GWh of electricity, four times more than in 1990 [3]. However, only 43% of the demand is met by domestic energy resources (lignite, hydropower, geothermal and wind) with the rest of electricity generated by imported fuels (hard coal and natural gas) [4]. As a result, Turkey has become dependent on other countries for the supplies of fuels, particularly natural gas, which provides 46.5% of electricity (see Figure 1). In 2010, around 98% of the country's natural gas demand was met through imports, mainly from Russia [5]. At current production levels (730 million m<sup>3</sup> in 2010), Turkey has the equivalent of only nine years of domestic gas reserves remaining [5]. There are currently 187 gas power plants with 18,213 MW of installed capacity, which, in 2010, generated 98,144 GWh [4]. The majority of the installations are combined cycle power plants [6].

The next most significant fuel is coal which supplies 26% of electricity [4]. Turkey has significant coal reserves with lignite being much more abundant than hard coal: 10.8 billion tonnes *vs.* 515 million tonnes of proven reserves, respectively [7]. However, most of Turkish lignite is of low quality with poor calorific value and high sulphur content. Hard coal is also of low grade, but of cokeable or semi-cokeable quality. In 2010, total coal production reached 73.4 Mt of which 69.7 Mt was lignite,

2.5 Mt hard coal and 1.2 Mt asphaltite [7]. By comparison, 24.3 Mt were imported, of which 60% from Russia and Colombia and 40% from the USA and South Africa [7]. There are 16 lignite and eight hard coal plants in Turkey, with the total installed capacity of 11,891 MW, which generated 55,046 GWh of electricity in 2010 [4]; the majority (65%) of this was from the lignite plants. Around 85% of the capacity is based on pulverised coal and the rest on circulating fluidised bed installations.

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 [6].

The contribution of hydropower is close to that of coal, providing around a quarter of electricity (Figure 1). The theoretically-viable hydroelectric potential of Turkey is estimated at 433 TWh/year [8]. Almost half of this is technically and nearly 30% economically exploitable [8]. Currently, there are 55 reservoir and 205 run-of-river plants with the total installed capacity of 15,831 MW, generating on average 51,795 GWh per year.

The only other sources of renewable energy available present in the electricity mix in Turkey are wind and geothermal, providing 1.4% and 0.3% of the total, respectively. Turkey has a good wind potential, estimated at 48,000 MW with an annual production capacity of 130 TWh/year [9]. There are currently 39 onshore wind power plants with an installed capacity of 1320 MW that produced 2916 GWh in 2010. The capacity of the individual turbines varies from 0.85 to 3 MW. At present, there are no offshore wind turbines in Turkey.

Located on the Alpine–Himalayan tectonic belt, Turkey is one of the richest countries in the world in terms of geothermal energy resources, with an estimated capacity of 31,500 MW [9]. However, the majority of this (88%) has the temperature below 200 °C, which is less suitable for electricity generation (unless an organic Rankine cycle system is used) but is still useful for direct use as heat [10]. Thus, there are only six geothermal power plants in Turkey with the installed capacity of 94.2 MW which generated 668 GWh in 2010 [3].

As a result of the high share of fossil fuels, the direct greenhouse gas (GHG) emissions from electricity (largely from burning fossil fuels) reached 99 Mt CO<sub>2</sub>-eq. in 2010, a quarter of the total national emissions in that year [11]. Since Turkey is a signatory to the Kyoto Protocol (Annex I), it is important that it identifies sustainable energy technologies suitable for the country to reduce the GHG emissions and other environmental impacts from the electricity sector. However, environmental impacts from the electricity sector in Turkey are currently unknown and there is no baseline to help the country identify the best way forward.

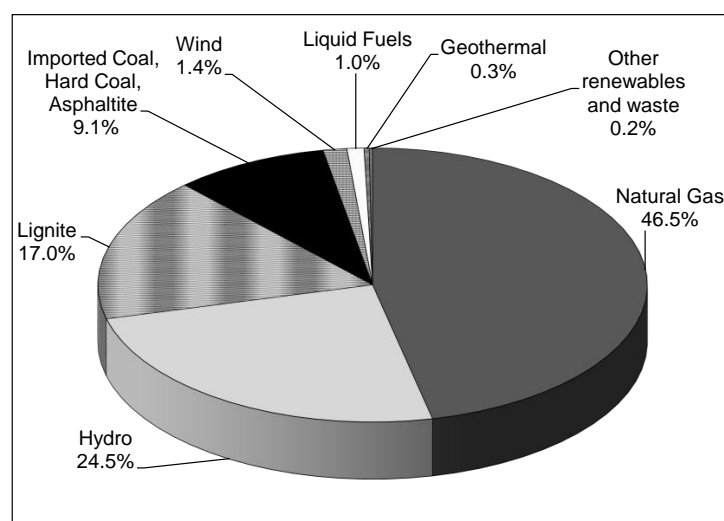


Figure 1. Share of different fuels in electricity generation in Turkey in 2010 [4].

Therefore, this paper sets out to estimate the environmental impacts of electricity in Turkey on a life cycle basis over the last 25 years (1990–2014). Although many life cycle assessment (LCA) studies of different electricity technologies have been carried out elsewhere, as far as the authors are aware, there are no such studies for Turkey. The only exception is the previous work by Atilgan and Azapagic [12,13], but that only considered electricity from individual technologies rather than the whole electricity supply mix which is the focus of this work. Therefore, this is the first study of its kind for Turkey and the findings will provide an insight into the past trends and current environmental impacts of electricity generation, helping to identify opportunities for improving the environmental sustainability of the sector. A further feature is that each of the 516 plants currently present in the Turkish electricity system have been considered individually. This has seldom been the case in other studies, which typically use average values for different technologies.

Some of the existing LCA studies relevant to the technologies present in Turkey's electricity mix are summarised in Table 1. The results from these studies are compared to the current study later in the paper (Section 3.1). As can be seen in the table, the scope varied across the studies, including the type of technologies and environmental impacts considered. All studies, however, considered GHG emissions and the related global warming potential. Most also considered eutrophication, acidification and photochemical smog, except Kannan, *et al.* [14] who considered the global warming potential and energy and Weisser [15] who focused on the global warming potential alone. Most studies used the Institute of Environmental Sciences (CML) 2001 method [16] to estimate the impacts. The same method has been applied in the current study, which considers 11 environmental categories, as discussed in the next sections.

## 2. Methods

The study has been carried out according to the LCA methodological guidelines in the International Organization for Standardization (ISO) 14040 and 14044 standards [17,18]. The LCA modelling has been carried out in GaBi v.6 [19].

**Table 1.** Some life cycle assessment (LCA) studies of electricity generation.

Aim and Scope of the Study	Technologies	Country	Environmental Impacts	Reference
Life cycle energy use, GWP and cost assessment of gas fired combined cycle plant	Natural gas	Singapore	Global warming, energy use	[14]
Life cycle greenhouse gas emissions from electric supply technologies	Lignite, hard coal, oil, natural gas, nuclear, CCS, hydro, wind, solar PV, biomass, energy storage	Not specified	Global warming	[15]
Setting up life cycle models for the environmental analysis of hydropower generation, considering technical and climatic boundary conditions	Run-of-river, storage and pumped storage hydro	Germany	Global warming, acidification, eutrophication, photochemical smog, energy demand	[20]
LCA of carbon dioxide capture and storage from lignite power plants	Pulverised coal (PC), PC with CO <sub>2</sub> capture, Integrated gasification combined cycle (IGCC), IGCC with CO <sub>2</sub> capture, oxyfuel plant with CO <sub>2</sub> capture	Germany	Global warming, energy demand, photochemical smog, eutrophication, acidification	[21]
LCA of a 2 MW rated power wind turbine	Onshore wind	Spain	Global warming, resource depletion, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity	[22]
LCA of mini-hydropower plants	Run-of-river hydro	Thailand	Global warming, resource depletion, acidification, human toxicity, photochemical smog, water ecotoxicity	[23]

Table 1. Cont.

Aim and Scope of the Study	Technologies	Country	Environmental Impacts	Reference
LCA of electricity generation	Nuclear, coal, natural gas, oil, renewables	Mexico	Global warming, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion	[24]
LCA of the wind turbines	Onshore wind	Spain	Global warming, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion	[25]
LCA of a hydroelectric power	Run-of-river hydro	Thailand	Global warming, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, resource depletion	[26]
Life cycle sustainability assessment of electricity generation	Nuclear, coal, natural gas, offshore wind, solar PV	UK	Global warming, ozone layer depletion, acidification, eutrophication, photochemical smog, land use, ecotoxicity, human toxicity, resource depletion	[27]
LCA of 1 kWh generated by a Gamesa onshore wind farm	Onshore wind	Europe	Cumulative energy demand, global warming, summer smog, ecotoxicity, eutrophication, acidification, human toxicity, land use	[28]
Life cycle data for hydroelectric generation at Embretsfoss 4 power station	Run-of-river hydro	Norway	Global warming, acidification, eutrophication, photochemical smog, ozone layer depletion, waste	[29]
Life cycle data for hydroelectricity from Trollheim power station	Reservoir hydro	Norway	Global warming, acidification, eutrophication, photochemical smog, ozone layer depletion, waste	[30]
Life cycle assessment of electricity from an onshore V90-3.0 MW wind plant	Onshore wind	Not specified	Global warming, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion	[31]
Life cycle assessment of wind power	Onshore wind	Not specified	Global warming, ecotoxicity, ozone layer depletion, acidification, eutrophication, photochemical smog, human toxicity, resource depletion	[32]
LCA of a wind plant	Onshore wind	France	Resource depletion, acidification, eutrophication, global warming, photochemical smog	[33]

The CML 2001 method [16], November 2010 update, has been used to estimate the following impacts: abiotic depletion potential (ADP elements and fossil), acidification potential (AP), eutrophication potential (EP), fresh water aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

The goal of the study, key assumptions and data sources are detailed in the following sections.

### 2.1. Goal and Scope Definition

The goal of the study has been to estimate life cycle environmental impacts of electricity generation in Turkey and to identify improvement opportunities for the future. To enable that, the impacts of the

individual power plants had to be estimated first. For these purposes, 2010 has been chosen as the base year because most complete data were available for the individual plants for that year. In addition to this, the impacts have been estimated for electricity generation over the past 25 years, covering the period from 1990 to 2014, to identify the impact trends and find out whether the electricity sector is becoming more or less environmentally sustainable.

The study is based on two functional units. The first is defined as “generation of 1 kWh of electricity” to enable comparisons of the impacts for individual electricity technologies as well as for different electricity mixes for over the period. The second functional unit is defined as the “total annual electricity generation” to estimate the total annual impacts from electricity over the last 25 years.

As indicated in Figure 2, the study considers all the options present in the Turkish electricity mix: coal, gas, hydro (large- and small-scale reservoir, run-of-river), wind and geothermal. The scope is from “cradle to grave”, comprising the extraction, processing and transport of fuels (where relevant) and raw materials as well as the construction, operation and decommissioning of power plants. Since the focus of the work is on electricity generation, its transmission, distribution and consumption are outside the system boundary.

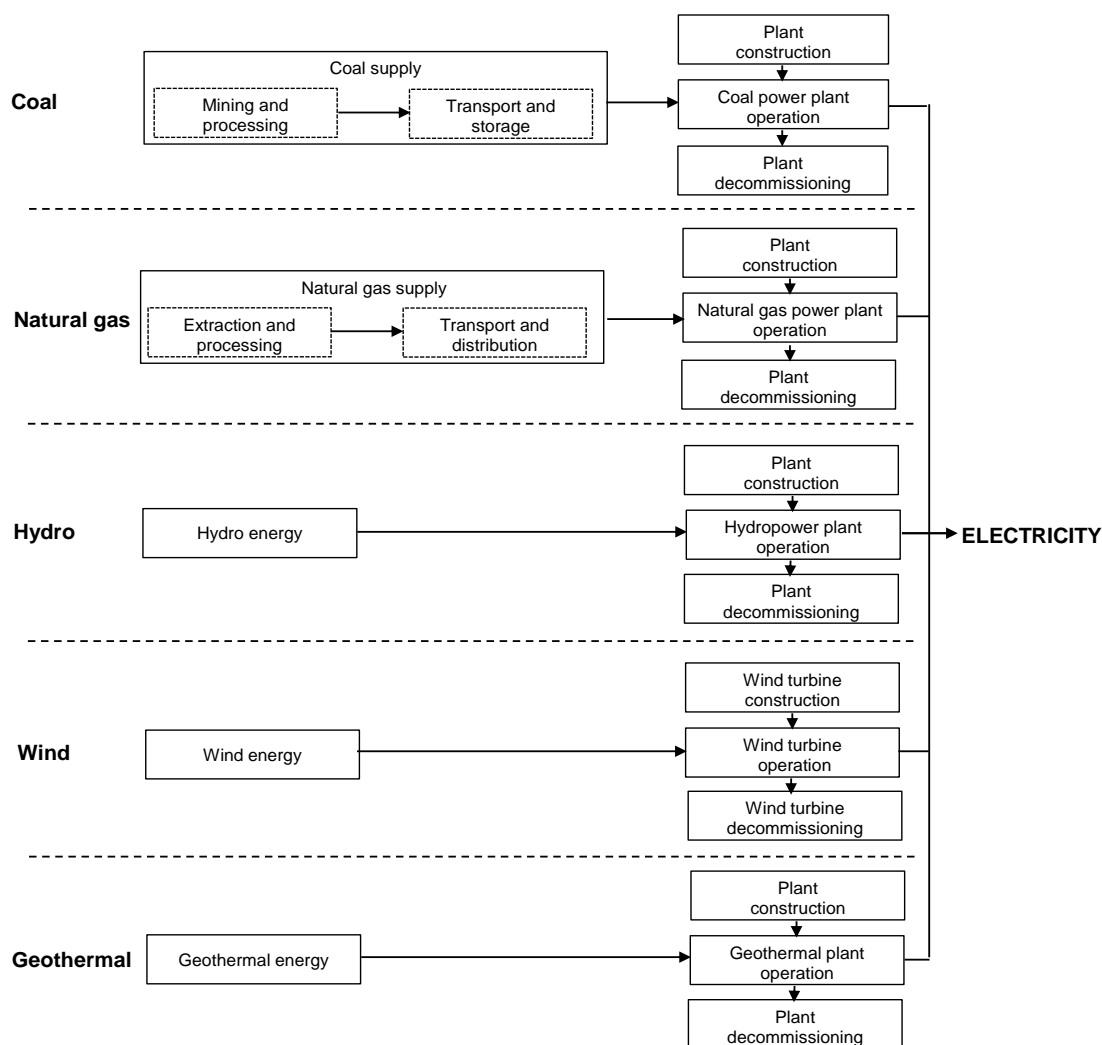


Figure 2. The life cycles of electricity from coal, natural gas, hydro, wind and geothermal power.

## 2.2. Inventory Data

In 2010, 211,208 GWh of electricity were generated by a total of 516 power plants, specifically, by 16 lignite, eight hard coal, 187 gas, 55 reservoir and 205 run-of-river hydropower, 39 wind and six geothermal installations. All of these plants are considered in this study (see Table 2 and Supplementary information). The key assumptions are summarised in Tables 3 and 4 with further details provided below.

**Table 2.** Power plants in Turkey (2010).

Type of Power Plant	Number of Plants	Installed Capacity (MW)	Annual Generation (GWh/yr)
Lignite	16	8140	35,942
Hard coal <sup>a</sup>	8	3751	19,104
Natural gas	187	18,213	98,144
Large-reservoir hydropower (capacity > 500 MW)	8	8459	30,583
Small-reservoir hydropower (capacity < 500 MW)	47	4608	13,885
Run-of-river hydropower	205	2764	7327
Onshore wind	39	1320	2916
Geothermal	6	94	668
Total	516	47,349 (49,524) <sup>b</sup>	208,569 (211,208) <sup>c</sup>

<sup>a</sup> Hard coal type power plant includes hard coal, imported coal and asphaltite power plants in Turkey. <sup>b</sup> 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. <sup>c</sup> 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.

**Table 3.** The amount of fuels used for electricity generation in 2010 [12].

	Natural Gas (million m <sup>3</sup> )	Hard Coal (million tonnes)	Lignite (million tonnes)	Transport Distances (km) Gas <sup>a</sup> Hard Coal <sup>b</sup>	
Domestic fuel	-	0.20	55.89	-	-
Imported fuel					
Russia	9921	4.45 <sup>c</sup>	-	5750	5000
Iran	4383	-	-	2700	-
Azerbaijan	2551	-	-	1150	-
Algeria	2205	-	-	4000	-
Nigeria	671	-	-	4500	-
USA	-	1.48	-	-	10,500
South Africa	-	1.48	-	-	13,000
Other	1738	-	-	1750	-
Total	21,469	7.61	55.89	19,850	28,500

<sup>a</sup> Transport by pipeline. Total weighted average distance of 4000 km used for LCA modelling, taking into account the amounts of gas imported from each country as listed in the table. <sup>b</sup> Russia: 4500 km by rail, 500 km by shipping; USA: 1000 km by rail, 9500 km by shipping; South Africa: 500 km by rail, 12,500 km by shipping. <sup>c</sup> 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.

### 2.2.1. Electricity from Fossil Fuels

Detailed data have been available for each lignite and hard coal power plants so that each has been modelled separately based on the data in Tables S1 and S2 in Supplementary information. For the



natural gas plants, data availability has been more limited. Therefore, an average efficiency of 55% has been assumed for all the gas plants; this matches the average efficiency of the combined cycle gas turbine (CCGT) plants for which the data have been available but also the efficiency of the plants in Turkey reported by IEA and NEA [34] as well as some other sources [35]. Specific data have not been available for the auto-producer plants; as mentioned earlier, they are not connected to the grid but generate electricity for own consumption. However, the total generation from these plants has been considered.

The data for the coal and natural gas power installations (Tables S1–S3 in Supplementary information) have been used together with the fuel composition data (Table 4) to estimate the emissions from each plant using GEMIS 4.8 software [36]. These have then been combined with the other inventory data in Tables 3 and 4 to estimate the life cycle impacts from the power plants in GaBi. The background life cycle inventory data have been sourced from Ecoinvent v2.2 [37] but have been adapted as far as possible to Turkey's conditions.

### 2.2.2. Electricity from Renewables

The data for the hydropower plants and onshore wind turbines are summarised in Tables 2 and 4; for details for the individual plants see Tables S4–S7 in Supplementary information. The background inventory data for hydropower have been sourced from the Ecoinvent v2.2 [37,38] and ESU [39] databases. Since the data for construction materials for reservoir plants in the databases correspond to a different size to the ones considered here, it has been necessary to apply some scaling of the impacts to reflect the difference in the size of the installations. Typically in LCA, this is carried out by assuming a linear relationship between the size of the plant and its impacts. However, in reality, the relationship is non-linear. To account for this, the “six-tenths” approach has been applied [40]. This method is typically used to estimate costs of different plant sizes accounting for the “economies of scale”, *i.e.*, larger plants cost less to build per unit of capacity than smaller installations. The same analogy has been applied to the impacts, which would also be lower per unit of installed capacity for bigger than smaller plants. Thus, the impacts have been scaled according to the following relationship:

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

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: the “six-tenths” scaling factor.

The construction materials for the hydro plants are assumed to be transported for 200 km by rail and 100 km by lorry (see Table 4). At the end of its service life, the plants are dismantled and components are recycled using the assumed recycling rates given in Table 4.

The inventory data for onshore wind turbines have been sourced from [41] based on the Vestas V80 2 MW turbine. The size of the turbine has been scaled down from 2 MW using Equation (1) to match the average turbine size in Turkey of 1.94 MW (see Table 4). The construction materials are assumed to be transported 100 km by lorry and 100 km by rail. The turbines are imported into Turkey from Europe, assuming an average distance of 2000 km by rail and a further 150 km by lorry to the installation locations in Turkey. At the end of life, the turbine construction materials are recycled as specified in Table 4.

Detailed data for the geothermal plants have not been available so that the LCA data have been taken directly from the GaBi database [19]. The only dataset available is for a 30 MW flash-steam plant with an annual electricity generation of 250 GWh. The data are aggregated so that it has not



been possible to adapt them to Turkey-specific conditions. However, as geothermal power contributes only 0.3% of the total electricity (see Figure 1), this limitation is not deemed significant. Moreover, the database model is representative of the standard, widely-used type of geothermal plant.

The total annual environmental impacts for the base year have been calculated based on the impacts of all the options present in the Turkish electricity mix, their share in the electricity mix and the total electricity generation in 2010. The same approach has been applied across all the other years considered in this work.

To model the electricity mix in Turkey over the period, the following assumptions have been made:

- the contribution of the liquid-fuel power plants to the total generation of electricity is small and for simplicity 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 small, they have been substituted by small-reservoir hydropower.

It has also been assumed that there were no technology changes over the period considered, using the characteristics of technologies in 2010 to model the impacts for the previous years. This is arguably a reasonable assumption as fossil and hydro-technologies are well established and have long lifetimes so that no technological changes would be expected over the period. Wind and geothermal are less well established, but their contribution to the total generation in the earlier years was negligible (<0.03% and <0.1%, respectively).

### 3. Results and Discussion

The results are given in Figures 3–9 and are discussed in the following sections, first for different electricity technologies, then for electricity in the base year (2010) and finally for electricity generation from 1990 to the present.

#### 3.1. Environmental Impacts of Different Electricity Technologies

The life cycle environmental impacts of different electricity generation options in Turkey are compared in Figure 3 and in Tables S8–S18 in Supplementary information. The results show that coal is the worst performer for all the impact categories, except for the ODP, which is lower than for gas power because of leakages of halon 1211 and halon 1301 used as fire suppressants and coolants in the life cycle of gas. Wind power has the highest impacts among the renewable options, with nine out of 11 impacts higher than for hydropower and geothermal power. This is due to the impacts from the extraction and processing of the construction materials. Wind power also has the second highest ADP elements, after hard coal. On the other hand, its GWP is 88% lower than for geothermal power and 11% smaller than for large-reservoir hydropower. The AP of geothermal electricity is lower than lignite power and higher than any other power options considered in this study: almost all of the impact is due to the hydrogen sulphide emissions from geothermal steam to air.

#### Comparison of Results with the Literature

As far as the authors are aware, there are no other LCA studies of electricity technologies in Turkey, except the previously mentioned studies [12,13]. However, as discussed in the introduction, there are many studies of electricity technologies in other countries, which are compared to the results from the current study in Figures 4 and 5. As can be seen, a wide range of values has been reported in the literature across different impacts. This is primarily due to different assumptions, such as capacities and efficiencies, pollution control measures, fuel origin, plant lifetimes and, in the case of hydropower and wind, local water and wind characteristics and plant design.

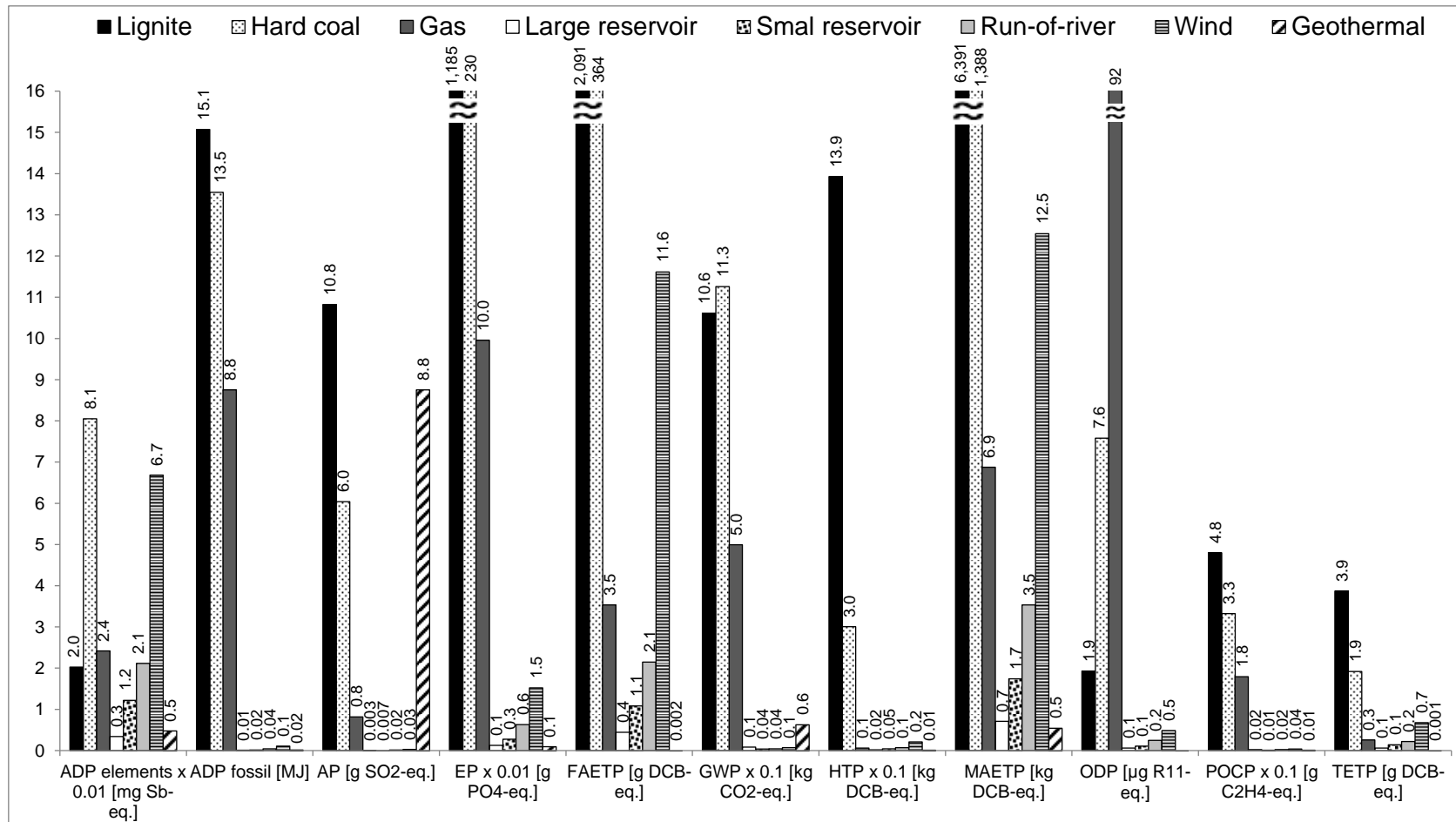
Table 4. Assumptions and summary of inventory data.

Coal	Gas	Hydropower	Wind
<b>Mining and Processing</b>			
<p>Lignite:</p> <ul style="list-style-type: none"> <li>Domestic lignite, open pit and underground mining</li> <li>Composition (% w/w)<sup>a</sup>: sulphur: 0.8%–4.5%; ash: 19%–40%; water: 20%–50%</li> <li>Net heating value (NHV): 7.2–13.9 MJ/kg</li> </ul> <p>Hard coal:</p> <ul style="list-style-type: none"> <li>Domestic and imported, open pit and underground mining</li> <li>Composition (% w/w)<sup>a</sup>: sulphur: 0.5%–0.9%; ash: 7%–11%; water: 4%–7%</li> <li>NHV: 27–27.5 MJ/kg</li> </ul>	<ul style="list-style-type: none"> <li>Composition (% vol.)<sup>a</sup>: C<sub>1</sub>: 94.7%–97.3%; C<sub>2</sub>: 1–3.4%; C<sub>3</sub>: 0.3%–0.6%; C<sub>4</sub>: 0.1%–0.4%; C<sub>5+</sub>: 0.02%–0.1%; CO<sub>2</sub>: 0.06%–0.6%; N<sub>2</sub>: 0.1%–4.6%</li> <li>NHV: 36.5–40.4 MJ/kg</li> <li>Leakage during extraction: 0.38%</li> </ul>		
<b>Transport<sup>b</sup></b>			
<p>Lignite:</p> <ul style="list-style-type: none"> <li>Power plants adjacent to the mine</li> </ul> <p>Hard coal:</p> <ul style="list-style-type: none"> <li>Russia: Freight train (4500 km); freight ship (500 km)</li> <li>USA: Freight train (1000 km); freight ship (9500 km)</li> <li>South Africa: Freight train (500 km); freight ship (12,500 km)</li> </ul>	<ul style="list-style-type: none"> <li>Pipeline: Russia: 5750 km; Iran: 2700 km; Azerbaijan: 1150 km; Nigeria: 4000 km; Other: 4500 km</li> </ul>	<ul style="list-style-type: none"> <li>Construction materials<sup>c</sup>: Freight train: 200 km; Lorry &gt; 16 tonne: 100 km</li> </ul>	<ul style="list-style-type: none"> <li>Construction materials: Freight train: 100 km; Lorry &gt; 16 tonne: 100 km</li> <li>Turbine: Freight train: 2000 km; Lorry &gt; 16 tonne: 150 km</li> <li>Maintenance: Passenger car: 100 p.km/year</li> </ul>

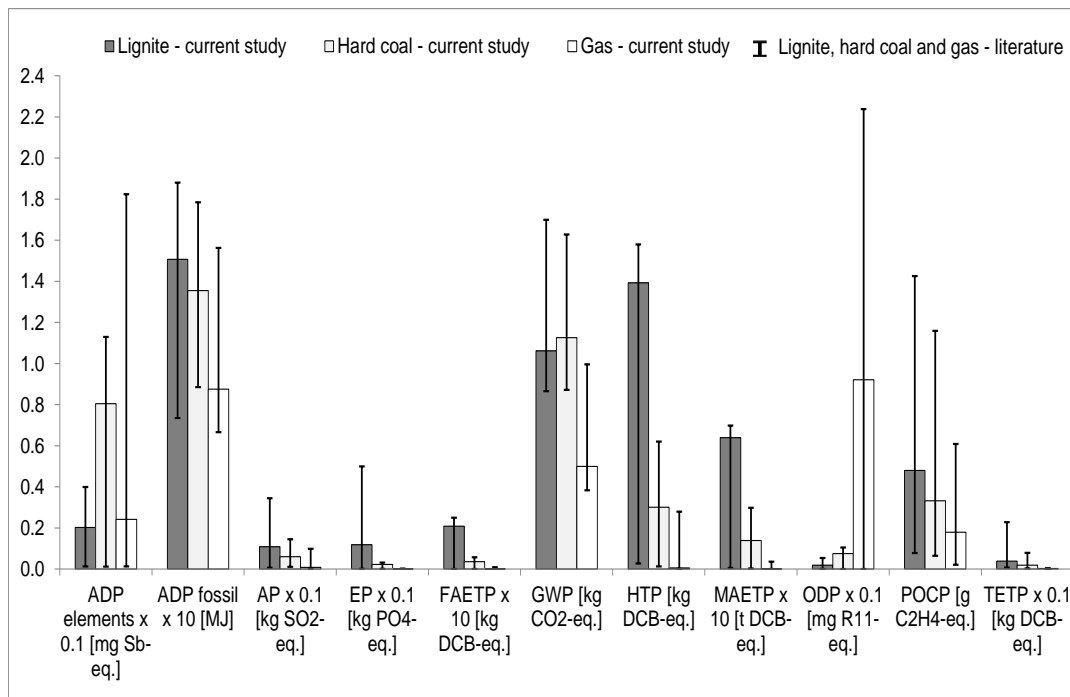
Table 4. Cont.

Coal	Gas	Hydropower	Wind
<b>Plant Construction</b>			
<ul style="list-style-type: none"> <li>Lifetime: 30 years <sup>d</sup></li> </ul> <p>Lignite:</p> <ul style="list-style-type: none"> <li>Data from Ecoinvent <sup>e</sup> based on average size of the plant of 380 MW (a mix of 500 MW and 100 MW plants in a 70:30 ratio)</li> </ul> <p>Hard coal:</p> <ul style="list-style-type: none"> <li>Data from Ecoinvent <sup>e</sup> based on average size of the plant of 460 MW (a mix of 500 MW and 100 MW plants at the 90:10 ratio)</li> </ul>	<ul style="list-style-type: none"> <li>Lifetime: 25 years <sup>d</sup></li> <li>Data from Ecoinvent assuming 400 MW plant</li> </ul>	<p>Large reservoir:</p> <ul style="list-style-type: none"> <li>Life time: 150 years <sup>e,f</sup></li> <li>Large reservoir</li> <li>Data based on Ecoinvent <sup>e,g</sup> with average size of 175.6 MW plant and scaled up to 1057 MW plant</li> </ul> <p>Small reservoir:</p> <ul style="list-style-type: none"> <li>Data based on ESU <sup>f</sup> with average size of 95 MW plant and scaled up to 98 MW plant</li> </ul> <p>Run-of-river:</p> <ul style="list-style-type: none"> <li>Life time: 80 years <sup>e,f</sup> Data based on ESU <sup>f</sup> for the average size of 8.6 MW plant and scaled up to 13.5 MW plant</li> </ul>	<ul style="list-style-type: none"> <li>Lifetime: 40 years for fixed parts and 20 years for moving parts <sup>e</sup></li> <li>Number of turbines: 682</li> </ul> <p>Data based on the average size of 2 MW turbine <sup>h</sup> and scaled down to the average size of 1.94 MW</p>
<b>Plant Operation</b>			
<ul style="list-style-type: none"> <li>See Table 3 for details</li> </ul> <p>Lignite:</p> <ul style="list-style-type: none"> <li>Average water use: 37.3 kg/kWh</li> </ul> <p>Hard coal:</p> <ul style="list-style-type: none"> <li>Average water use: 32.7 kg/kWh</li> </ul>	<ul style="list-style-type: none"> <li>All plants assumed to be CCGT with efficiency of 55%</li> <li>Average water use: 3.4 kg/kWh</li> </ul>	<p>Large reservoir:</p> <ul style="list-style-type: none"> <li>Lubricating oil: 7 mg/kWh</li> </ul> <p>Small reservoir:</p> <ul style="list-style-type: none"> <li>Lubricating oil: 0.03 mg/kWh</li> </ul> <p>Run-of-river:</p> <ul style="list-style-type: none"> <li>Lubricating oil: 0.12 mg/kWh</li> </ul>	<ul style="list-style-type: none"> <li>Lubricating oil: 43.1 mg/kWh</li> </ul>
<b>Plant Decommissioning <sup>i</sup></b>			
<ul style="list-style-type: none"> <li>Metals: 50% recycled, 50% landfilled</li> <li>Concrete: 50% recycled, 50% landfilled</li> <li>Plastics: 20% recycled, 80% landfilled</li> </ul>	<ul style="list-style-type: none"> <li>Metals: 50% recycled, 50% landfilled</li> <li>Concrete: 50% recycled, 50% landfilled</li> <li>Plastics: 20% recycled, 80% landfilled</li> </ul>	<ul style="list-style-type: none"> <li>Metals: 50% recycled, 50% landfilled</li> <li>Concrete: 50% recycled, 50% landfilled</li> <li>Plastics: 20% recycled, 80% landfilled</li> </ul>	<ul style="list-style-type: none"> <li>Metals: 50% recycled, 50% landfilled</li> <li>Concrete: 50% recycled, 50% landfilled</li> <li>Plastics: 20% recycled, 80% landfilled</li> </ul>

<sup>a</sup> Based on data from different mines and countries. <sup>b</sup> Estimated by using online mapping. <sup>c</sup> It is assumed that gravel is extracted at the construction site. <sup>d</sup> Source: [42]. <sup>e</sup> Source: [37]. <sup>f</sup> Source: [39]. <sup>g</sup> Source: [38]. <sup>h</sup> Source: [41]. <sup>i</sup> The system has been credited for recycling. The recycling rates are assumed due to a lack of data.



**Figure 3.** Environmental impacts for different electricity options 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. 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; HTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone layer depletion potential; POCP: Photochemical oxidants creation potential; TETP: Terrestrial ecotoxicity potential.].

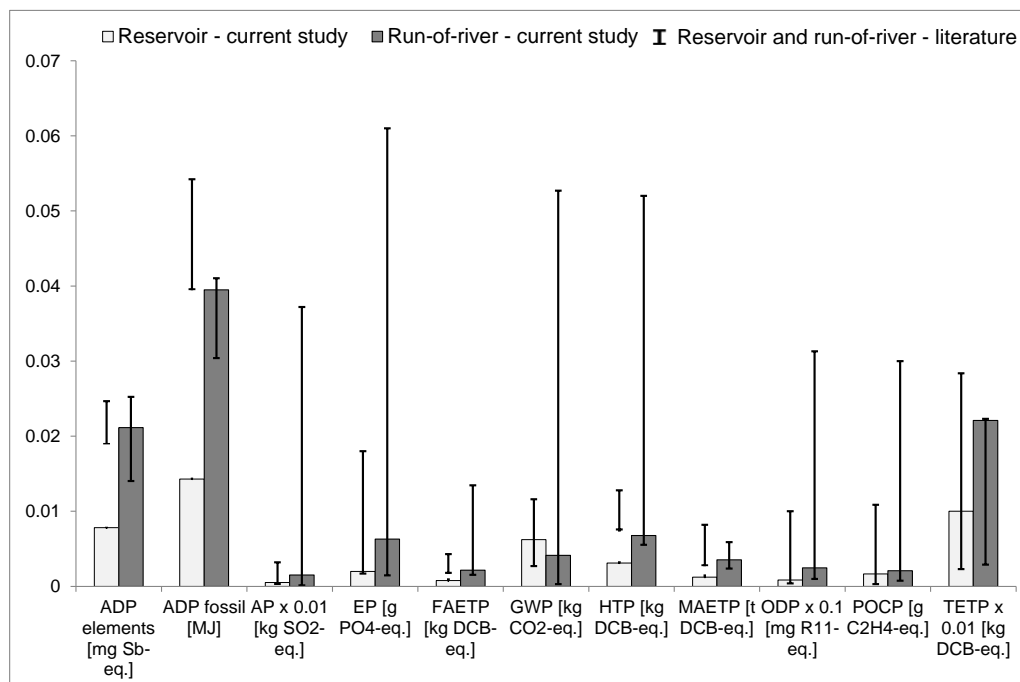


**Figure 4.** Comparison of the results from current study with literature for coal and gas. [All impacts expressed per kWh of electricity generated. Literature data for lignite from [15,19,21,43]; for hard coal from [19,27,43]; for natural gas from [14,15,19,24,27,43]. All impacts estimated using the CML 2001 method. For impacts nomenclature, see Figure 3.]

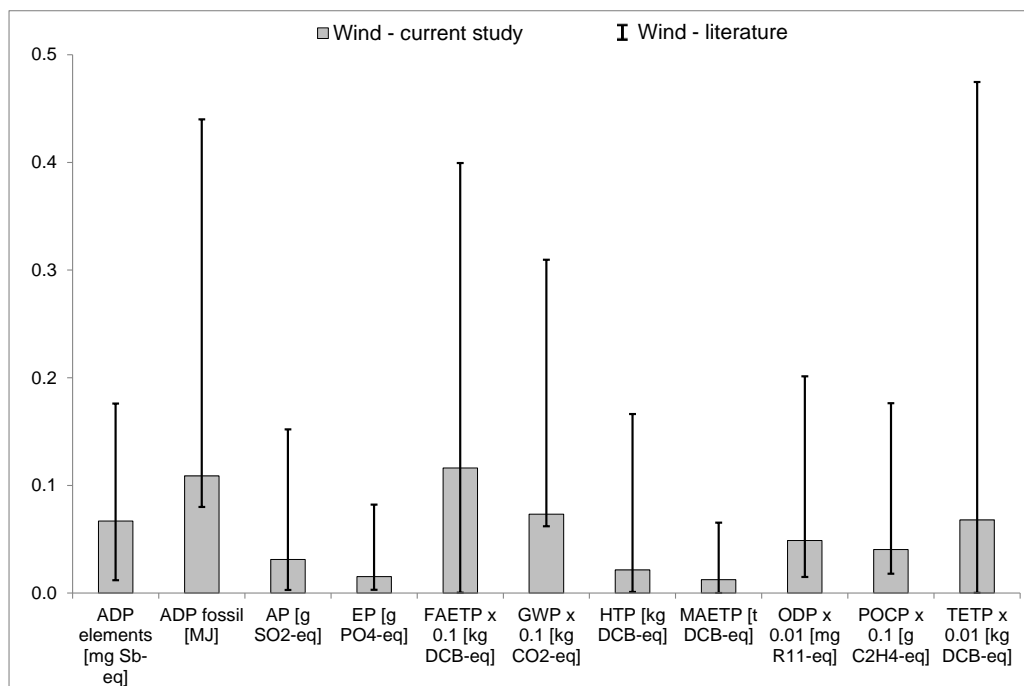
Nevertheless, all the impacts estimated in this study for lignite and hard coal power are well within the ranges reported in the literature (Figure 4). For example, for lignite electricity, the GWP falls between 866 and 1700 g CO<sub>2</sub>-eq./kWh, which compares well with the estimate in this study of 1062 g CO<sub>2</sub>-eq./kWh. For hard coal, the GWP in the literature ranges between 872 and 1628 g CO<sub>2</sub>-eq./kWh so that the value of 1126 g CO<sub>2</sub>-eq./kWh obtained in the current study is around the middle of the range. A good agreement of the results is also found for gas electricity. For instance, the GWP reported in the literature is between 383 and 996 g CO<sub>2</sub>-eq./kWh, and, in this work, it is estimated at 499 g CO<sub>2</sub>-eq./kWh.

There are only four LCA studies of reservoir hydropower plants so that comparison with the literature is limited. As shown in Figure 5, the results for the GWP, AP, EP, ODP, POCP and TETP are comparable to the lower values reported in the literature. For example, the GWP falls between 2.7 and 11.6 g CO<sub>2</sub>-eq./kWh in the literature, which compares well to this study's estimate of 6.9 g CO<sub>2</sub>-eq./kWh for reservoir hydropower. On the other hand, the results for the ADP elements and fossil, FAETP, HTP and MAETP are below the range of values in the literature. One of the reasons for this could be the very different size of large and small scale plants which are not distinguished in the literature.

All the impacts estimated in this study for run-of-river hydropower and wind electricity are well within the ranges reported by other authors (Figure 5). For example, the GWP for run-of-river hydropower is between 0.3 and 5.2 g CO<sub>2</sub>-eq./kWh, which compares well to the value of 4.1 g CO<sub>2</sub>-eq./kWh obtained in the current study. For onshore wind, the GWP ranges from 6.2 to 31 g CO<sub>2</sub>-eq./kWh, and the estimate in the present work is 7.3 g CO<sub>2</sub>-eq./kWh.



(a)



(b)

**Figure 5.** Comparison of the results from current study with literature for hydropower and wind power. (a) Reservoir and run-of-river hydropower. (b) Onshore wind. [All impacts expressed per kWh of electricity generated. The current study results for the reservoir hydropower present the average value for large and small reservoir. Literature data for reservoir from: [30,43,44]; for run-of-river from: [20,23,26,29,43–45]; for onshore wind from [22,25,28,31,33,43]. All impacts estimated using the CML 2001 method. For impacts nomenclature, see Figure 3.]

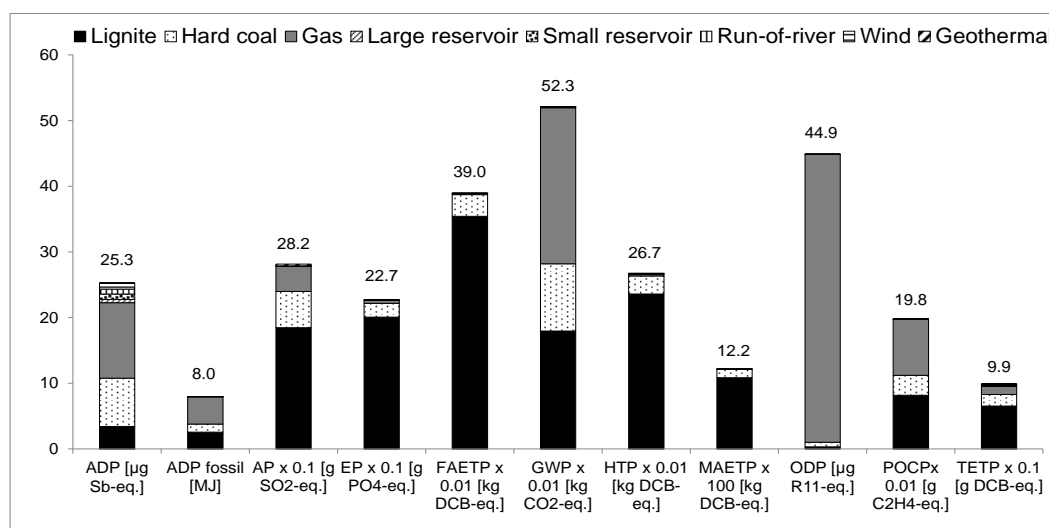
### 3.2. Environmental Impacts of Electricity Generated in the Base Year

Since the base year is used as a basis for the estimates of impacts in the other years, these results are discussed in more detail than for the rest of the period. Thus, the impacts for the base year are first presented for the functional unit of “1 kWh of electricity”, followed by the “total annual generation of electricity”.

#### 3.2.1. Impacts per kWh

The impacts per kWh of electricity generated in 2010 are given in Figure 6. The results suggest that fossil fuels cause the majority of the impacts, with coal contributing 43%–54% to the depletion of elements and fossil resources as well as the GWP; it also causes 84%–99% of the toxicity related impacts. The exception is ozone layer depletion, 98% of which arises from gas power.

These results are discussed for each impact in more detail below. Note that all the results incorporate the credits for material recycling after decommissioning of the plants.



**Figure 6.** Environmental impacts per kWh of electricity for the base year (2010). [For impacts nomenclature, see Figure 3].

#### Abiotic Depletion Potential

The depletion of elements from electricity generation is estimated at 25.3  $\mu\text{g Sb-eq./kWh}$  (Figure 6). Lignite, hard coal and natural gas power contribute 14%, 29% and 46% to the total, respectively. The high contribution of hard coal, despite its small share in the electricity mix (9.1%) is due to its long-range transport, which contributes 63% to the ADP of hard coal. By contrast, lignite is sourced domestically, so there are no impacts from transport.

The remaining contributions are from hydropower (8%) and wind power (4%); the impact from geothermal power is negligible (0.1%). This impact is primarily due to the use of chromium, copper, molybdenum and nickel during the construction of the plants and fuel supply infrastructure. Coal and gas also account for the majority (99.9%) of fossil resource depletion, equivalent to 8 MJ/kWh (Figure 6).

#### Acidification and Eutrophication Potential

The AP of 2.8 g SO<sub>2</sub>-eq./kWh is mainly due to SO<sub>2</sub> (82%) and N<sub>2</sub>O (14%) emissions. The biggest contributor is the electricity from lignite (66%) because of the high sulphur content and a lack of desulphurisation systems at some of the plants. The second biggest contributor is hard coal power (20%).



Lignite is also the main cause of the EP, estimated at 2.3 g PO<sub>4</sub>-eq./kWh, with the majority (87%) related to the emissions of phosphates during mining. As for the AP, the next biggest contributor is hard coal (9%).

#### Ecotoxicity Potential

All ecotoxicity related impacts (freshwater, marine and terrestrial) are also caused mainly by lignite power. For the FAETP, equivalent to 0.39 kg DCB-eq./kWh, 91% is due to the emissions of nickel, beryllium, cobalt and vanadium during mining. In the case of the MAETP, estimated at 1.2 t DCB-eq./kWh, the emissions to water of beryllium (40%) and hydrogen fluoride to air (33%) are the main burdens contributing to this impact. Finally, lignite contributes 66% to the TETP of 0.1 g DCB-eq./kWh, mainly because of the emissions of mercury (~75%).

#### Global Warming Potential

The global warming potential for the electricity mix in Turkey is estimated at 523 g CO<sub>2</sub>-eq./kWh. Emissions of CO<sub>2</sub> account for 92% of the total, with CH<sub>4</sub> contributing 7% and N<sub>2</sub>O 1%. The main source of the GHG emissions is the combustion of coal and natural gas in power plants. The renewables contribute only 0.4% to the total GWP (Figure 6).

#### Human Toxicity Potential

Like ecotoxicity, this impact is also mainly due to lignite mining (88%). The main burdens contributing to the HTP of 267 g DCB-eq./kWh include emissions of selenium (36%) and hydrogen fluoride (11%).

#### Ozone Layer Depletion Potential

The ODP is estimated at 45 µg R11-eq./kWh. The single largest contributor (98%) is electricity from gas. As mentioned earlier, it is mainly due to leakages of halon 1211 and halon 1301 used as fire suppressants and coolants in the life cycle of gas.

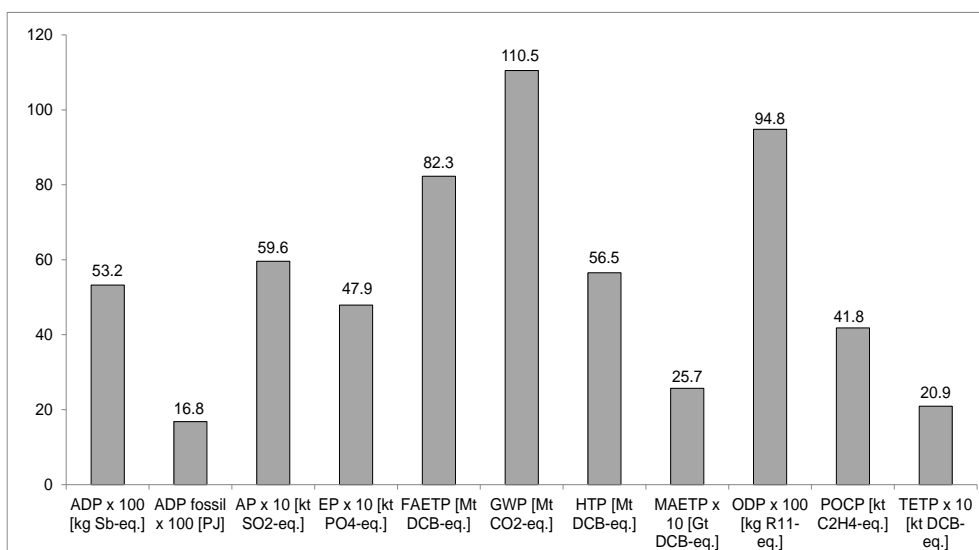
#### Photochemical Oxidants Creation Potential

This impact is equal to 198 mg C<sub>2</sub>H<sub>4</sub>-eq./kWh with 41%, 15% and 43% arising from lignite, hard coal and gas power plants, respectively. The main contributing burdens include SO<sub>2</sub> (47%), non-methane volatile organic compounds (32%) and N<sub>2</sub>O (11%).

#### 3.2.2. Total Annual Impacts

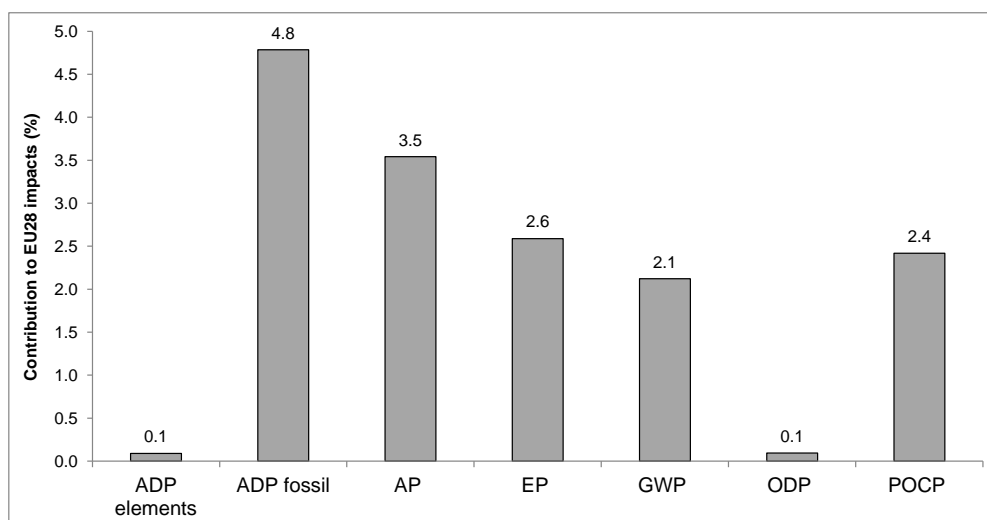
As can be seen from Figure 7, lignite and hard coal power contribute together more than 40% to most of the impacts in the base year, despite providing only a quarter of the total electricity. The exception is ozone layer depletion which is almost entirely (98%) from gas power, which generates 46.5% of electricity. The renewables, which supply around 27% of the demand, add 0.04%–12% to the impacts, mainly related to hydropower because of its high share in the mix (24.5%).

The total GWP is estimated at 111 Mt CO<sub>2</sub>-eq., 54% of which is due to coal and 46% to gas power. The estimated direct CO<sub>2</sub> emissions (emitted from the power plants as opposed to the life cycle emissions) are equal to 92 Mt CO<sub>2</sub>-eq. This is in good agreement with the total direct emissions of 99 Mt CO<sub>2</sub>-eq. from the whole Turkish electricity sector in 2010 [11]. The slight difference between the two estimates stems from different assumptions, including plant efficiencies and the amount of fuel used in different power plants.



**Figure 7.** Total annual environmental impacts for the base year (2010). [For impacts nomenclature, see Figure 3.].

To put these results into context, they have been normalised to the annual impacts in the European Union comprising 28 countries (EU28). As indicated in Figure 8, Turkish electricity sector contributes almost 5% to the depletion of fossil fuels and 2% to the GWP relative to these impacts in the EU28 countries. The contribution to the AP, EP and POCP is also significant, ranging from 3.5% for the former to 2.4% for the latter. The contribution of the ADP elements and ODP is small (0.1%). However, these results should be interpreted with care for at least two reasons: first, the base year for the EU28 impacts is 2000 (the latest available in the CML 2001 method) while the base year here is 2010; secondly, all impacts but the GWP for the EU28 are associated with high uncertainty and are likely underestimated, particularly the toxicity-related categories [46,47], which is the reason why they have not been considered in the normalised results.



**Figure 8.** Annual impacts from electricity generation in Turkey in the base year (2010) normalised to the annual EU28 impacts. [EU28: the European Union with 28 countries. All data for the EU28 impacts are for the year 2000, the latest available data in the CML 2001 method. For impacts nomenclature, see Figure 3.].

### 3.3. Environmental Impacts from Electricity Generation from 1990–2014

The total annual environmental impacts from the electricity mix in Turkey over the period have been calculated based on the impacts of different technologies presented in Section 3.1, their contribution to electricity generation in a particular year and the total electricity generation in that year. The results are summarised in Figure 9; for brevity, they only show the impacts for selective years in five-year intervals: 1990, 1995, 2000, 2005, 2010 and 2014 (data for 2015 were not available at the time of writing).

Figure 9 also shows the generation mix for each of the years considered. In 1990, total generation was 57 TWh and in 2014 it reached 250 TWh, representing a four-fold increase over the period. During this time, the electricity mix has also changed. In the past, it was mainly based on lignite, gas and reservoir hydropower but, over time, the contribution of other sources grew. For example, the share of hard coal (mainly imported) increased from 0.6 TWh in 1990 to 36.7 TWh in 2014. Since 2005, there has also been an increase in the share of renewables, mainly run-of-river hydropower (to 5% in 2014) and onshore wind (to 3%). The reservoir hydropower generation was reduced by almost a half in 2000 compared to 1995 and by another half in 2014 compared to 2010 because of severe drought; the shortfall in electricity generation was made up by gas power.

It can be noticed from Figure 9 that the annual impacts have been going up steadily over the period, increasing from two times (EP, HTP, FAETP and MAETP) to nine-fold (ODP). The GWP increased by five-fold, from 28.7 Mt CO<sub>2</sub>-eq. in 1990 to 143 Mt CO<sub>2</sub>-eq. in 2014. This is largely due to a growing electricity demand, although for some impacts the rate of increase is higher than the demand growth, including the GWP, because of the higher rate of growth of fossil-fuel electricity. The only exception to the trend are the reductions in the EP, FAETP, HTP and MAETP in 2005 on the previous period as a result of a decrease in the share of lignite power. The latter, together with hard coal and gas dominate all the impacts because of their dominance in the generation mix, with coal providing 26%–35% and gas 18%–48% of electricity across the years.

The impact trends per kWh are less uniform than for the total annual impacts because they depend on the electricity mix only. On the other hand, the annual impacts also depend on the amount of electricity generated and increase proportionally to the demand. Although, in general, most impacts are higher for the fossil fuel options, some impacts are also high for the renewables (e.g., ADP for wind power; see Figure 3) so that their contribution to the total impacts from the electricity mix may be disproportionate to their share in the mix. The upward trend is found for four impacts: ADP elements and ODP, which are two times higher in 2014 than in 1990, and ADP fossil and GWP, which increased by 13% in the same period. The increase in the depletion of elements is due to the growth in renewable electricity generation because wind and hydropower have high resource requirements per kWh of electricity generated. The other three impacts have increased because of the increasing share of fossil fuels; for example, the share of gas increased from 25% in 1990 to 50% in 2014, leading to the significant increase in the ODP. Some impacts were also affected by the low hydropower generation during the drought in 2000 and 2014, with the GWP, ADP fossil, ODP and POCP having the highest values per kWh in these two years. For example, the GWP in 2000 was 550 g CO<sub>2</sub>-eq./kWh, 13% higher than in 1995. In 2014, it was 570 g CO<sub>2</sub>-eq./kWh or 8% higher than in 2010, despite an overall 4% increase in the share of other renewables.

However, the opposite trend is found for the remaining impacts, with the EP, FAETP, HTP and MAETP being two times lower, the TETP 40% and AP 34% smaller at the end of the period than in 1990. This is a result of the increase in natural gas and renewables in the mix. The only exception is the POCP, which remained more or less unchanged over the period. This is because of the cancelling effects of the change over time of the share of coal and gas in the mix and the difference in their respective POCP: lignite and hard coal have 1.8–2.7 times higher impact than gas but their contribution to power generation reduced by 20% from 1990 to 2014 while the contribution of gas doubled.

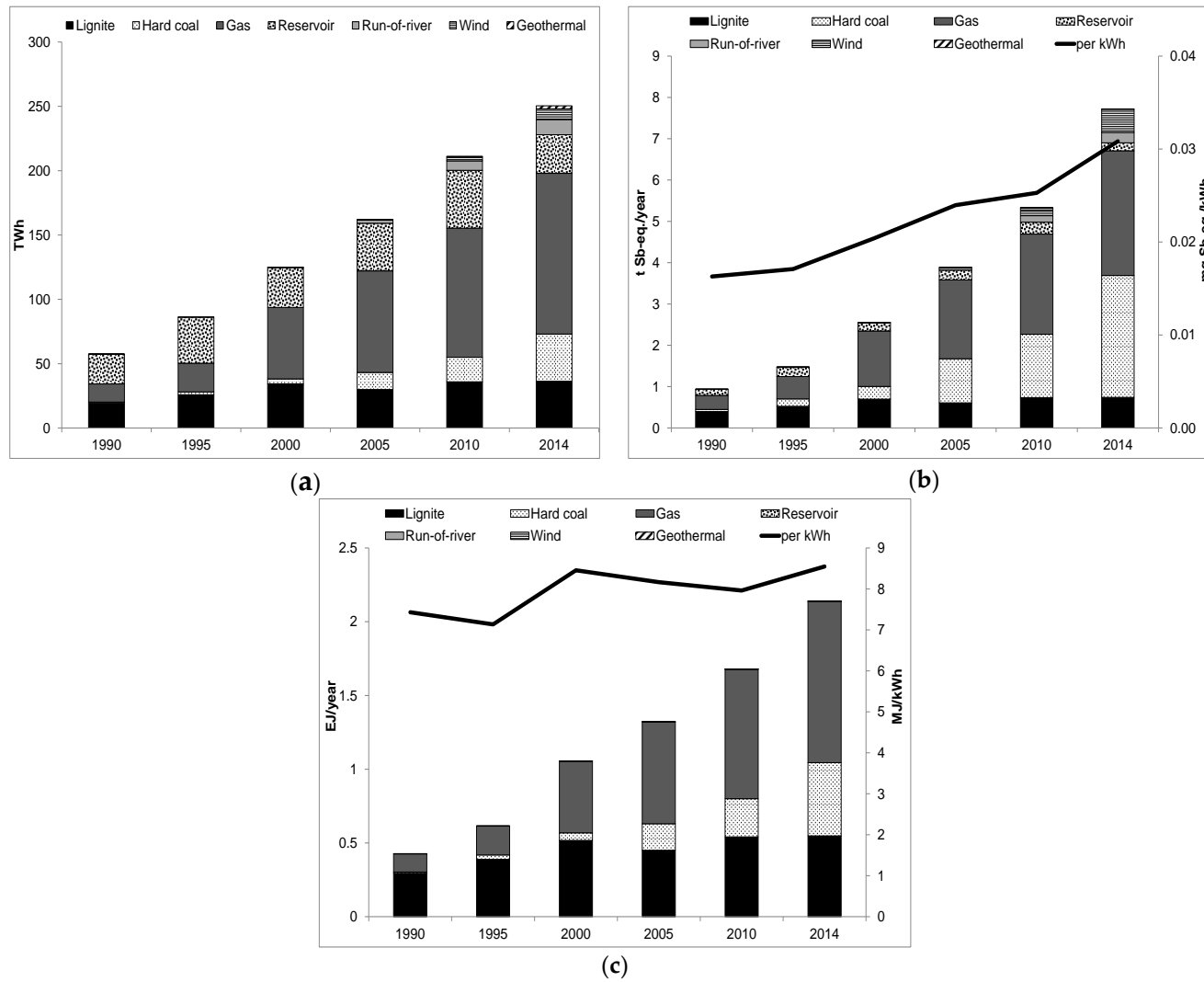


Figure 9. Cont.

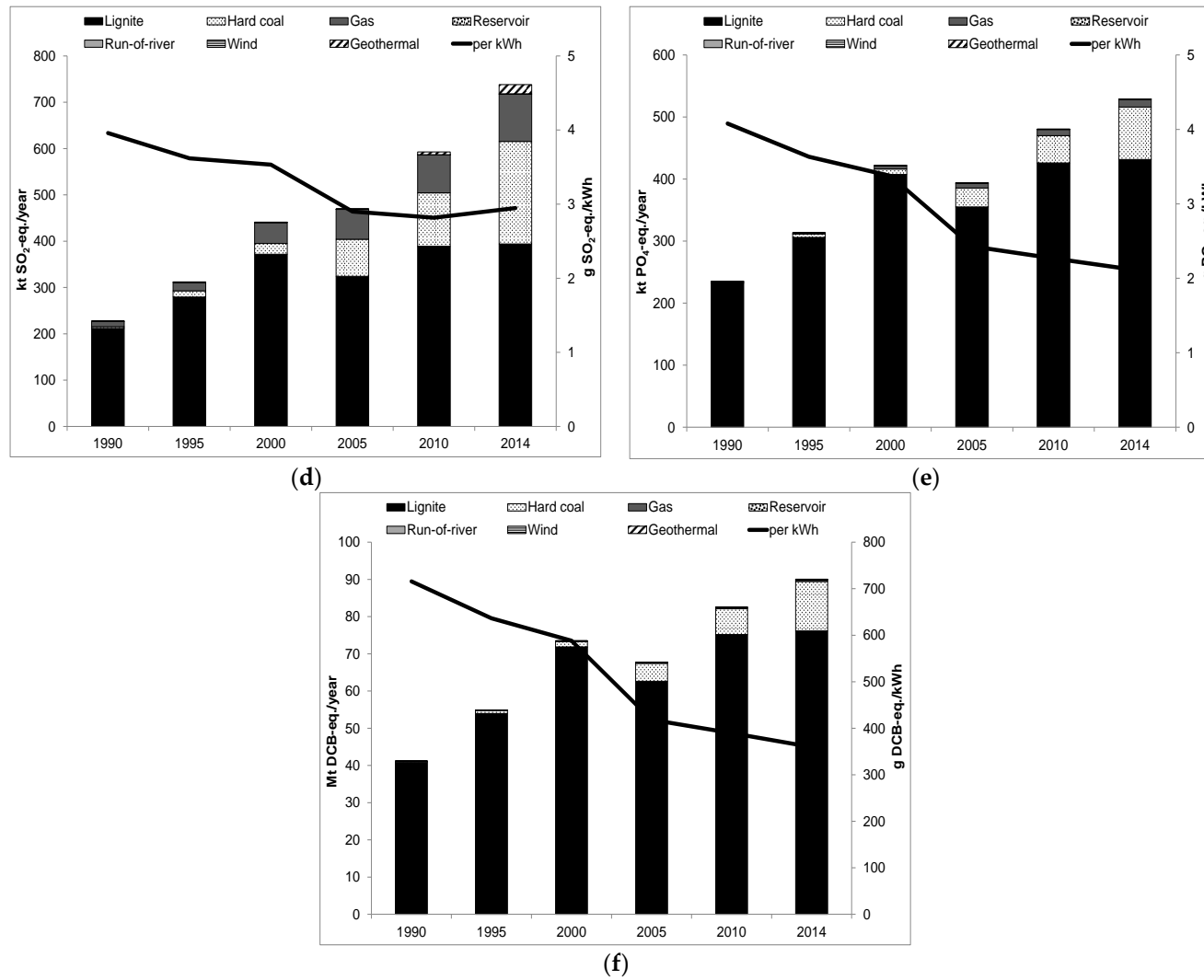


Figure 9. Cont.

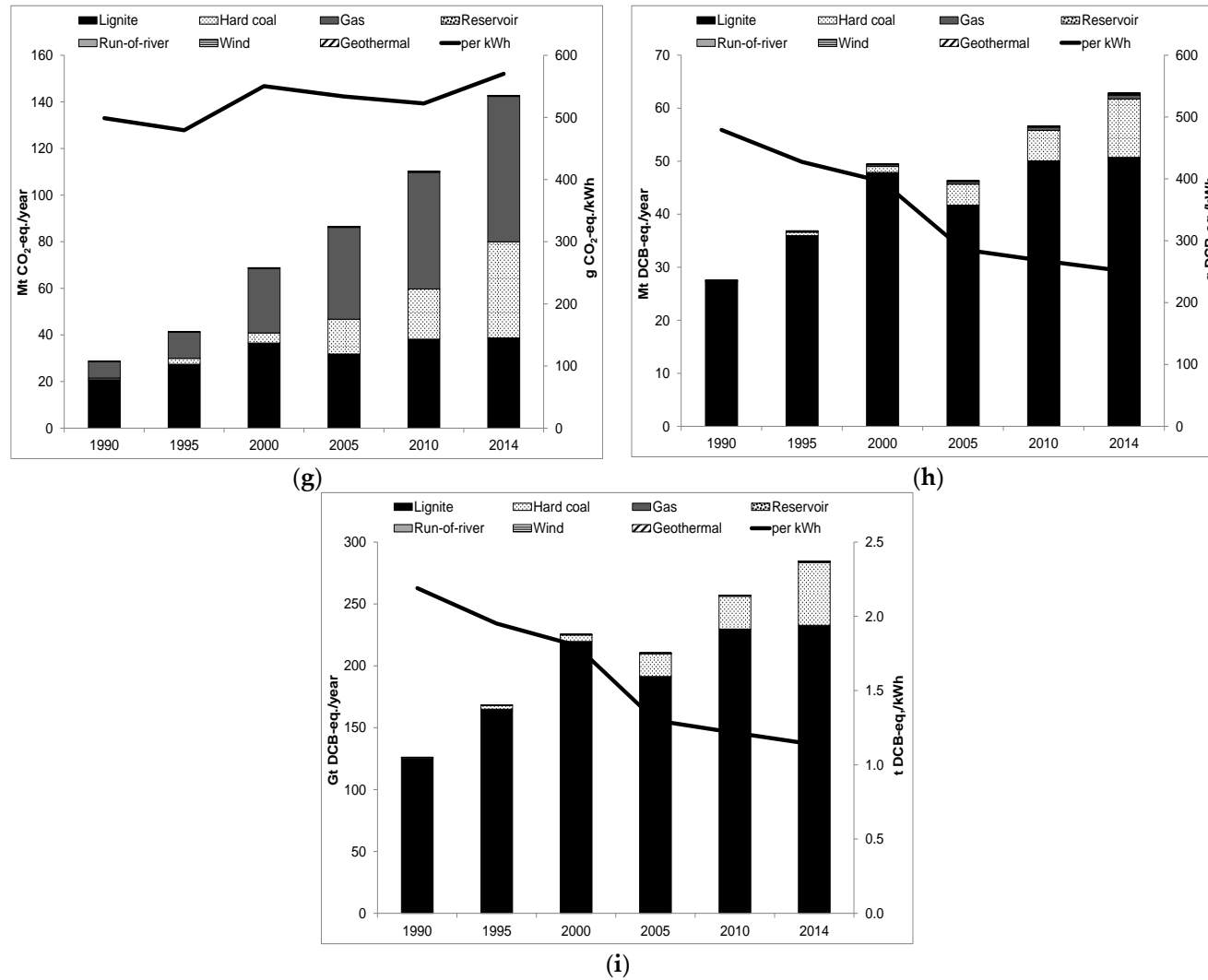
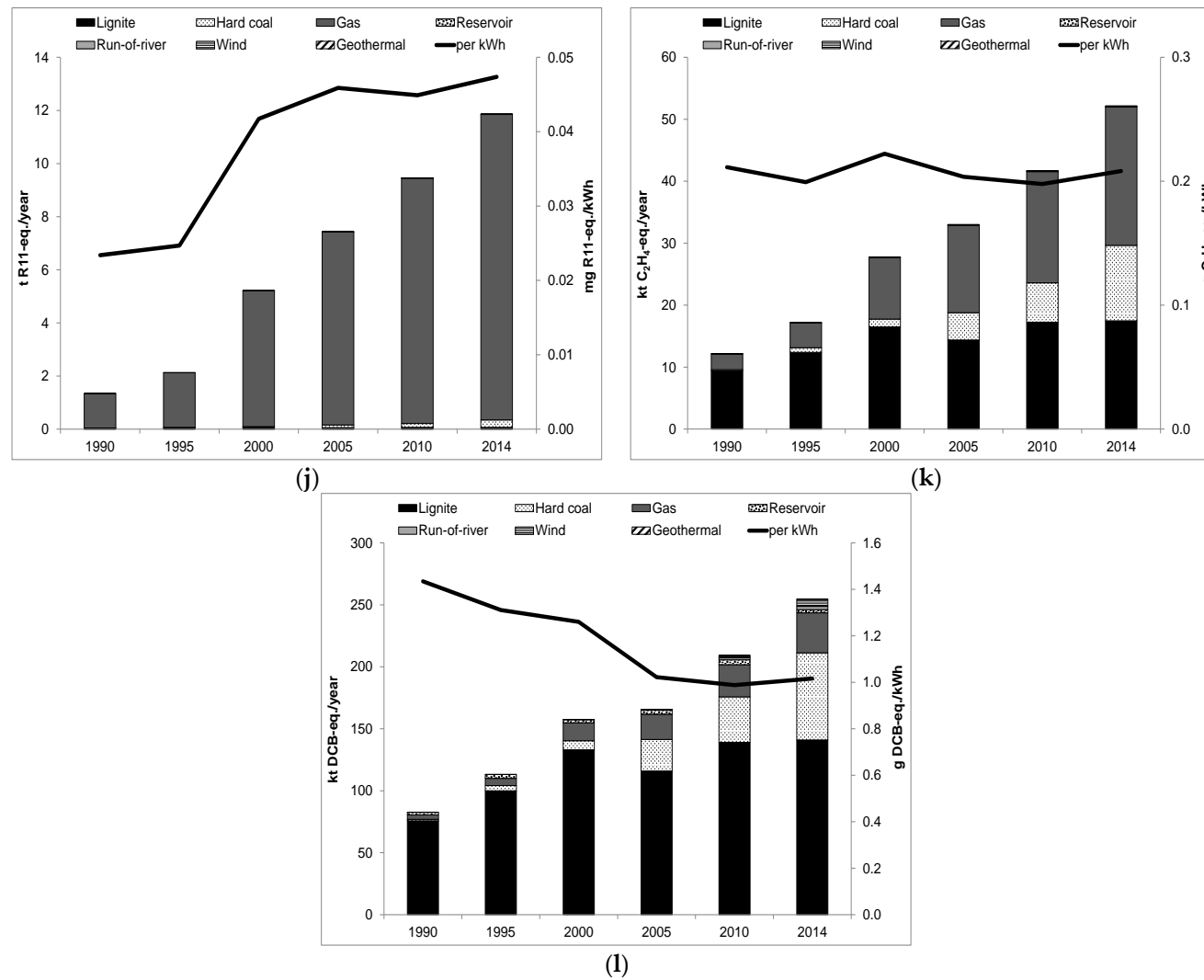


Figure 9. Cont.



**Figure 9.** Environmental impacts of electricity in Turkey in the period 1990–2014 for total annual generation and per kWh. (a) Electricity generation mix in Turkey; (b) ADP elements; (c) ADP fossil; (d) AP; (e) EP; (f) FAETP; (g) GWP; (h) HTP; (i) MAETP; (j) ODP; (k) POCP; (l) TETP. [For impacts nomenclature, see Figure 3].



#### 4. Conclusions

This study has estimated for the first time the life cycle environmental impacts of electricity generation in Turkey for the period 1990–2014. Eleven impacts have been considered for 516 power plants using lignite, hard coal, natural gas, hydro (large and small scale reservoir hydro and run-of-river), onshore wind and geothermal energy. The impacts have been estimated per kWh and for the total amount of electricity generated annually over the period.

The results suggest that, in comparison to the other options, lignite power has the highest impacts for eight out of eleven categories. Gas power is the worst option for ozone layer depletion. Geothermal electricity scores the best for six 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.

The annual impacts have been going up steadily over the period, increasing from two times (EP, HTP, FAETP and MAETP) to nine-fold (ODP); the GWP increased by a factor of five. This is due to meeting the growing demand by fossil fuels. The trends per unit of electricity generated are less uniform than for the annual impacts. The upward trend is found for four impacts only: ADP elements and ODP, which are two times higher in 2014 than in 1990, and ADP fossil and GWP, which increased by 13% in the same period. However, the opposite trend is found for the other impacts, with the EP, FAETP, HTP and MAETP being two times lower, the TETP 40% and AP 34% smaller at the end of the period than in 1990. The only exception is the POCP, which remained more or less unchanged.

As a signatory to the Kyoto Protocol, it is important that Turkey identified more sustainable pathways for future electricity supply. Being a developing country, it is likely that the demand will continue to grow. Therefore, the key question is how to decouple the expected demand growth with the environmental impacts. The results of this work show that reducing the share of coal in the electricity mix would lead to significant reductions in GHG emissions as well as the other impacts such as acidification, eutrophication and all the toxicity categories. This could be achieved in the short term by expanding the natural gas capacity; however, both ozone layer depletion and energy dependency on other countries would increase. Given the great potential of renewable energies in Turkey, the expansion of renewables should be pursued more aggressively in the medium to long term. Among the renewable energy sources, hydro, onshore wind and geothermal power are well established in Turkey and have a large potential for development. However, increasing the proportion of onshore wind power in the electricity mix would increase depletion of elements while increasing the share of geothermal power would increase acidification. As the results show, hydropower options would lead to a reduction in the environmental impacts; however, that would be at the expense of some other impacts not included in this study, such as biodiversity and land use. Other renewables such as solar power could play a role in the future given that solar energy is abundant in Turkey. The country is also trying to introduce nuclear power, which would help to reduce GHG emissions, but it raises various other concerns, such as human health impacts from radiation, risk of accidents and long-term storage of nuclear waste.

The findings from this work have provided an insight into the previously unknown environmental impacts of electricity generation in Turkey, helping to identify opportunities for future improvements. However, in addition to the environmental sustainability evaluated here, it is also important to understand various economic and social aspects to help the industry and policy makers in Turkey identify and implement most sustainable electricity options for the future. This is the subject of a forthcoming paper by the authors.

**Supplementary Materials:** The following are available online at [www.mdpi.com/1996-1073/9/1/31/s1](http://www.mdpi.com/1996-1073/9/1/31/s1).

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**Author Contributions:** Adisa Azapagic conceived and supervised the research. Burcin Atilgan collected the data and carried out the LCA study. Adisa Azapagic and Burcin Atilgan co-wrote the paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

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