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Environmental Performance of Electricity Generation Based on Resources: A Life Cycle Assessment Case Study in Turkey

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Abstract: The aim of this paper was to determine how to change the environmental performance of electricity generation depending on the resources and their shares, in order to support decision-makers. Additionally, this paper presents an application of life cycle assessment (LCA) methodology to determine the environmental burdens of electricity generation in Turkey. Electricity generation data in Turkey for the years 2012 and 2023 were used as a case study. The functional unit for electricity generation was 1 kWh. The LCA calculations were carried out using CML-IA (v3.00) data and the results were interpreted with respect to Monte Carlo simulation analysis (with the Monte Carlo function built in SimaPro 8.0.1 software). The results demonstrated that the fossil fuel consumption not only contributes to global warming, but it also has effects on the elemental basis of abiotic depletion due to raw material consumption for plant infrastructure. Additionally, it was observed that the increasing proportion of wind power in the electricity mix would also increase certain life cycle impacts (such as the elemental basis of abiotic depletion, human ecotoxicity, and terrestrial ecotoxicity) in Turkey's geography compared to increasing the share of other renewable energy sources, such as hydropower, geothermal, as well as solar.

Keywords: electricity generation; fossil fuels; global warming; life cycle assessment; renewable energy

1. Introduction

Energy plays an important role in the realization of economic development and the improvement of living standards. Countries with high gross domestic product (GDP) tend to consume more primary energy per capita [1].

Two energy sectors produced nearly two-thirds of global CO_2 emissions in 2013: electricity and heat generation, by far the largest, which accounted for 42%, while transport accounted for 23%. CO_2 emissions from electricity and heat almost doubled between 1990 and 2013, driven by the large increase of generation from coal [2]. Climate change is dominantly caused by CO_2 emissions of the energy sector and they have recently been taken into account at the 21st Conference of Parties (COP21) in Paris from 30 November to 11 December 2015. As a decision of this Conference, parties made pledges to reduce global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C. This target would only be achieved by shifting from fossil fuels, especially coal, to renewable energy, especially wind, solar, and hydroelectric power. Table 1 shows CO_2 emission statistics of some Organization for Economic Co-operation and Development (OECD) European countries in 2012. CO_2 emissions given in Table 1 are the emissions only from fuel combustion. On the other hand, the Turkish Statistical

Institute (TUIK) records show that CO_2 emissions increased by 133.4 percent in 2012 compared to the level of 1990 [3]. For that reason, some actions should be taken to focus on cleaner investments.

Table 1. CO_2 emission statistics of some OECD European countries [4].

OECD European Countries	CO_2 Emissions [1] (tCO_2/Capita)
Norway	7.08
Sweden	4.13
Austria	7.74
Belgium	8.03
France	4.75
Germany	9.09
Netherland	9.36
Denmark	6.63
UK	7.24
Spain	5.57
Italy	6.08
Turkey	4.04 (4.14 [2])

[1] CO_2 emissions from fuel combustion; [2] Turkish Statistical Institute data.

Turkey is an energy-importing country, with more than 60% of energy consumption in the country being met by imports, and the share of imports continues to grow each year [5]. In 2012, the total electricity generation was 239,496 GWh and was shared by the public sector and the private sector with percentages of 38% and 62%, respectively [6]. Figure 1 shows Turkey's electricity generation by primary resources between 2008 and 2012. With focus on the year 2012, the electricity generation mix by resources was mainly based on natural gas (43.6%), lignite, hard coal, and imported coal (28.1%), and hydro-electric power (24.2%). The remaining part was shared by other resources: wind (2.4%) and geothermal power (0.4%) [7]. However, increasing demand for electricity has required the determination of new energy policies to decrease fossil fuel consumption and to increase renewable energy, in terms of environmental and economic factors. Within the framework of the Electricity Energy Marketing and Security of Supply Strategy Paper, by the year 2023, to reduce the environmental impacts, especially of CO_2 emission, reductions in the following areas have been targeted: the utilization of all domestic resources; the maximum use of renewable energy resources; an increase in the diversification of energy supply; the integration of nuclear energy into the electricity generation sector; and the redesigning of the energy sector, which has, so far, been based on three main sources (coal, natural gas, and hydroelectric), thereby reducing energy import dependence [8].

The life cycle assessment (LCA) can support the elaboration of policies to meet global or regional challenges. For example, environmental goals or targets at a regional level (e.g., 2020 or 2030 policy targets at the EU level) could be met by using the LCA as an instrument to distribute efforts required by each party involved, depending on its energy and societal landscape. At a national level, the LCA could support the definition and management of energy policies to set and control targets, while ensuring that potential environmental trade-offs are identified and future burden shifting is anticipated and prevented in time. It can also allow for the identification of hotspots and the refining of existing energy policies, e.g., supporting amendments in national emission standards and prioritizing or targeting specific energy sources and technologies identified as important causes of environmental impact in the countries considered. The LCA is a systemic tool and is, thus, highly relevant for evaluating long-term electricity trajectories, which can encompass all electricity supply systems and their interactions with other systems and society at large [9].

The LCA has been used to carry out environmental analyses of energy/electricity generation for countries (Table 2). In this context, this paper presents an application of LCA methodology to determine the environmental burdens of electricity generation in Turkey.

Table 2. LCA studies of different countries for electricity generation systems.

References	Country	Studied Electricity Generation Systems	Considered Environmental Parameters
Hondo [10]	Japan	Coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic.	Greenhouse gas emissions.
Peiu [11]	Romania	Lignite, brown coal (domestic and import), heavy oil (domestic, land), heavy oil (domestic and import), natural gas (domestic and import), hydropower, and nuclear energy.	CO_2, SO_x, NO_x, CH_4, non-methanic volatile organic compounds (NMVOC), CO, N_2O, particulate matter.
Turconi et al. [12]	Ireland	Combined cycle gas turbine, open cycle, gas turbine, coal, distillate oil, gas condensing, peat.	CO_2, NO_x, and SO_2.
Kannan et al. [13]	Singapore	Oil-fired steam turbine power plant, Natural gas-fired combined cycle plant, orimulsion-fired steam turbine power plant, Solar PV system, proton exchange membrane fuel cell.	CO_2, CH_4, and N_2O.
Messagie et al. [14]	Belgium	Nuclear combustible, oil, coal, natural gas, bio waste, blast furnace gas, and wood, photovoltaic cells, hydro installations, and wind turbines.	Global warming potential.
Garcia et al. [15]	Portugal	Coal, fuel, oil, natural gas, hydro, wind, waste incineration, biogas and photovoltaic.	Non-renewable fossil energy demand, global warming, abiotic depletion, acidification, eutrophication, photochemical oxidation, and ozone layer depletion.
Stamford and Azapagic [16]	UK	Shale gas, conventional gas, oil, nuclear, offshore, wind and solar photovoltaics.	Abiotic resources, eutrophication, and freshwater, marine and human toxicities.
Ou et al. [17]	China	Coal, natural gas, oil, diesel, gasoline.	Primary fossil energy consumption and greenhouse gas emissions (CO_2, CH_2, N_2O).
Foidart et al. [18]	Belgium and Spain	Lignite, solar, biogas, biomass, wind, hydraulic, derived gases, natural gas, fuel, coal, nuclear.	Acidification, global warming, eutrophication, photochemical oxidation, abiotic depletion, ozone layer depletion and human toxicity.
Felix and Gheewala [19]	Tanzania	Natural gas, coal, oil, hydropower.	Abiotic resource depletion potential, eutrophication potential, climate change potential, acidification potential.
Turconi et al. [20]	Denmark	Wind, hydro, thermal power plants, biogas, coal, gas oil, natural gas, refinery gas, residual oil, straw, waste, wood.	Global warming, ozone depletion, depletion of fossil and abiotic resources, photochemical oxidant formation, particulate matter, terrestrial acidification, marine eutrophication, freshwater eutrophication, human toxicity, ecotoxicity.
Gujba et al. [21]	Nigeria	Gas, coal, hydro, solar-PV, biomass, wind.	Global warming potential, abiotic depletion potential, ozone layer depletion, human toxicity potential, freshwater aquatic eco-toxicity potential, marine toxicity potential, terrestrial toxicity potential, photochemical oxidation potential, acidification potential, eutrophication potential, not including terrestrial, fresh water and marine ecotoxicity.
Santoyo-Castelazo et al. [22]	Mexico	Coal, oil, natural gas, hydro-power, geothermal, wind, nuclear.	
Brizmohun et al. [23]	Mauritius	Coal, fuel oil, bagasse, hydro-plants.	
Liang et al. [24]	China	Integrated gasification combined cycle, sub-critical coal power generation, super-critical coal power generation, super-critical coal power generation.	

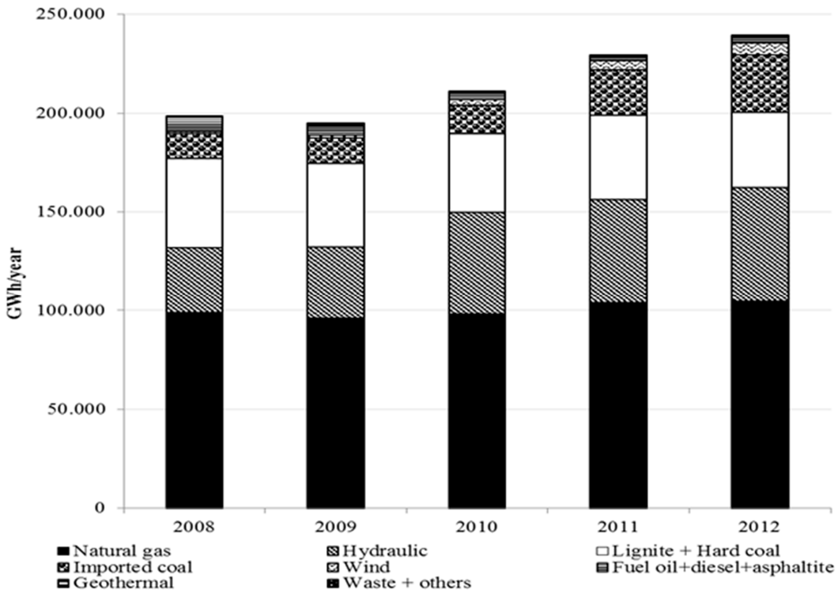


Figure 1. Turkey's electricity generation by primary resources (2008–2012).

2. Materials and Methods

The LCA methodology used in this study follows four phases; Goal and Scope, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation (Results) according to ISO 14040 [25] and ISO 14044 [26]. The data sources and the approach to estimating the environmental impact are discussed further in the following sections.

2.1. Goal and Scope Definition

The goal of this study is to make a comparative environmental assessment of electricity generation mixes for the years 2012 and 2023. The year 2012 is the best year for data availability and 2023 is the target year for improvements on electricity production in Turkey.

2.1.1. Functional Unit

The functional unit was applied as the production of 1 kWh electricity. All input (energy and material consumption) and output (emissions) are indicated based on this functional unit.

2.1.2. System Description

The electricity generation mix for the year 2012 is given in Table 3 with the 2023 values. Values for the year 2023 have already been estimated by the Ministry of Energy and Natural Resources based on the Long-Range Energy Alternatives Planning System (LEAP 3.0) application [27] according to targets indicated in the Electricity Energy Marketing and Security of Supply Strategy Paper [8]. The relatively low contribution of asphaltite, fuel oil, diesel, waste, and similar (1.3%) was beyond the scope of this study.

Table 3. The total electricity generation and mix for the reference years.

	2012 [6]	**2023 [1]**
Total electricity generation amount (GWh)	239,496	384,389
Electricity generation mix		
Natural gas (%)	43.6	14.77
Coal (%) [2]	28.1	18.64
Hydro (%)	24.2	39.26

Table 3. *Cont.*

	2012 [6]	2023 [1]
Wind (%)	2.4	15.95
Geothermal (%)	0.4	0.96
Solar (%)	-	0.23
Nuclear (%)	-	9.84
Others (%)	1.3 (ignored)	0.35 (ignored)
Total (%)	100.0	100.0

[1] The 2023 values were obtained from [27] based on a modelling with the LEAP 3.0 application; [2] The total of coal based fuels (lignite, hard coal, and imported coal).

2.1.3. System Boundary

The system boundary has been created based on the electricity generation resources and is illustrated in Figure 2. The scope of this LCA study consists of raw material extraction/acquisition for fuel production, fuel and materials transportation, construction, and the operation and decommissioning of power plants. The production of imported fuels (natural gas, imported coal, and uranium) was also considered, although they are beyond Turkey's geographical borders. Transmission of electricity to the national grid was not included in the system boundary.

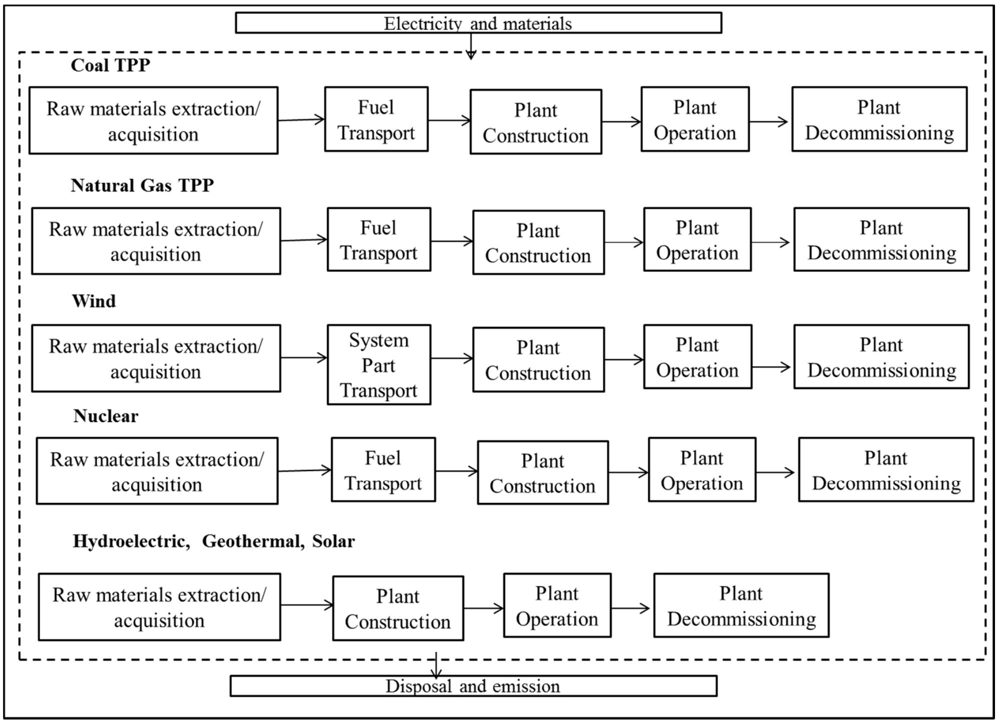


Figure 2. System boundaries of the LCA study.

2.2. Life Cycle Inventory

The data used to model the electricity generation systems are grouped into two categories: foreground and background. The foreground data (technologies, efficiencies, installed capacity, emissions, and so forth) have been obtained from strategy reports, technical reports, and literature. Background data regarding raw material extraction/acquisition, fuel transportation, construction and decommissioning of power plants was gathered from the ecoinvent (v.2.2–v.3.0.3) databases which is embodied in SimaPro 8.0.1 software (SimaPro: Amersfoort, The Netherlands). Seven different types of electricity generation systems were examined: coal-fired (lignite, hard coal, imported coal) thermal power plants (TPP), natural gas combined-cycle (NGCC), hydroelectric power plants, wind power, geothermal, nuclear power, and solar-photovoltaic. A detailed investigation of the systems is given in the following sections.

- Coal-fired TPPs

In 2012, the total electricity generation from coal-fired TPPs was shared by lignite, hard coal, and imported coal, in amounts of 51.6%, 5%, and 43.4%, respectively. Lignite and hard coal were domestically produced. The installed capacities of lignite-fired power plants range from 210 MW to 1440 MW. The weighted average installed capacity and the efficiency of lignite-fired thermal plants was calculated as to be 800 MW and 33.5%, respectively, using installed capacities, efficiencies, and individual contributions of the power plant to the total lignite-fired electricity generation. The hard coal-fired power plant (Çatalağzı) with a 300 MW installed capacity operates at an efficiency of 32.3%. The weighted average installed capacity of the imported coal-fired TPPs was calculated to be 1086.5 MW. The efficiency data was estimated at 40%, since the calorific quality of imported coal is higher than that of lignite. The data used to model the lignite, hard coal, and imported coal-fired TPPs in SimaPro are summarized in the Supplementary Materials (Table S1) with the calculation procedures explained in the footnotes.

- Natural gas-fired TPPs

Turkey does not have sufficient natural gas reserves, and natural gas is supplied by Russia (58%), Iran (18%), Azerbaijan (7%), Algeria (9%), and Nigeria (3%). Turkey is also exploring the importation of natural gas from Kazakhstan, Turkmenistan, and Egypt [28]. There are several existing gas pipelines in Turkey. The Eastern Anatolia Gas Pipeline bringing gas into Turkey from Iran is the main natural gas pipeline in Eastern Turkey. The pipeline presently extends as far west as Ankara. The 842 km Russia-Turkey Natural Gas Pipeline runs from Russia, through Ukraine, Romania, and Bulgaria, into Turkey. This pipeline enters Turkey at the Malkoçlar site at the Bulgarian border and then follows the Hamitabat, Ambarlı, Istanbul, İzmit, Bursa, Eskişehir route to reach Ankara [29]. The average installed capacity of natural gas-fired TPPs is 1360 MW and the efficiency is 51.3%. The data used to model the natural gas-fired TPPs in SimaPro are illustrated in the Supplementary Materials (Table S2).

- Hydroelectric power plants (HPPs)

There are two types of HPPs used for electricity production in Turkey; reservoir type and run-of-river type, with the shares of 96% and 4%, respectively. The installed capacities of the reservoir and river-based HPPs are given in the Supplementary Materials (Table S3), respectively. The data regarding HPPs (area, lubricating oil consumption, infrastructure and atmospheric emissions of methane and dinitrogen monoxide) were obtained from the ecoinvent database. The efficiencies of HPPs' reservoir and run-of-river types are 78% and 82%, respectively. The lifetime is assumed to be 150 years for the structural parts and 80 years for the turbines.

- Wind power

There are 56 wind power plants in Turkey with installed capacities ranging from 0.85 MW to 140 MW. The number of turbines in a power plant varies depending on the turbine power. There are approximately 933 turbines which comprise 3% for 0.5–0.6 MW, 23% for 0.8–0.9 MW, and 74% for 1.8–3 MW turbine power [30].

Ecoinvent data, including production of fixed and moving parts of wind turbines, maintenance with lubricating oil, electricity demand for start-up and disposal phases for 600 kW, 800 kW, and 2 MW (modified from offshore) capacity turbines were used as being representative of the three different turbine power ranges given above. It was assumed that all the components were produced in Denmark, since the most preferred wind turbine producer in Turkey is a Danish firm. It was assumed that the wind turbine parts were transported by specially-adapted ships to the Aegean region of Turkey, where most of the wind turbines are situated. After the arrival of the parts in port, it is necessary to transport them by using especially long vehicles to the wind farms. The wind turbines were assumed to have been assembled in Balıkesir, which has the highest wind power plant installed capacity. The distance between the manufacturer (in Denmark) and the end user site (at Balıkesir/Turkey) are taken as 3503 miles by oceanic freight (Copenhagen Port/Denmark)-Izmir Port/Turkey) [31] and 180 km by truck (Izmir Port-Balıkesir). The transport data was calculated using the distances and the weights of the turbine parts (Table 4). The ecoinvent data was amended with the calculated transport data.

Table 4. Weights of the wind turbine parts (tons).

Turbine Parts	600 kW [1]	800 kW [2]	2MW [3]
Nacelle	20.4	22	69
Rotor (blades and hub)	7.2	10	24.5
Tower	28.9	40	137
Total	56.5	72	230.5

[1] used for 0.5–0.6 MW turbine powers, Vestas V47-660 kW with 40.7 m tower height; [2] used for 0.8–0.9 MW turbine powers, Vestas V52-850 kW with 40 m tower height; [3] used for 1.8–3 MW turbine powers, Vestas V80-2MW with 60 m tower height.

The turbines are erected on concrete foundations. Each turbine foundation is established, connected to a road, working and turning area. The roads, working areas, and turning areas are not considered in this study.

- Geothermal

There are eight geothermal power plants in Turkey with installed capacities ranging from 7.35 to 47.4 MW [32]. Deep geothermal plant data given for Turkey conditions by ecoinvent was used.

- Nuclear power plants (NPPs)

There are plans to build two nuclear power plants in Turkey. The first nuclear power plant, Akkuyu NPP, will be built at Mersin on the Mediterranean Coast. Akkuyu NPP will have four power units (4800 MW) with VVER-1200 pressure water reactors (PWR). The second one, Sinop, will have 4480 MW with ATMEA-1 reactors. In this study, ecoinvent data regarding electricity generation from a PWR nuclear power plant was used.

- Solar-photovoltaic power

Solar-photovoltaic (PV) panels have not been used for electricity generation in Turkey to date, but it is planned to generate electricity from this power source. For this study, locally-produced 3 kW PV panels are considered. The data relating to the PV panels was obtained from the ecoinvent database.

2.3. Life Cycle Impact Assessment and Interpretation

LCA analysis was performed via licensed SimaPro 8.0.1 software (Amersfoort, The Netherlands) based on the CML-IA (v.3.00) method [33] for the impact categories of abiotic depletion (elemental ADe and fossil fuel ADff), global warming (GW), ozone depletion potential (OD), human toxicity (HT), fresh water aquatic ecotoxicity (FAET), marine aquatic ecotoxicity (MAET), terrestrial ecotoxicity (TET), photochemical oxidation (PO), acidification and eutrophication. A detailed explanation of these impact categories are given in the below:

- Depletion of Abiotic Resources

The abiotic depletion (AD) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and the rate of deaccumulation. Abiotic depletion of fossil fuels is related to the lower heating value (LHV), expressed in MJ per kg of m^3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitutable [34].

- Global Warming (GW)

The characterization model is developed by the Intergovernmental Panel on Climate Change (IPCC). Factors are expressed for global warming with a time horizon of 100 years (GW) in kg carbon dioxide equivalent/kg emission [34].

- Ozone Layer Depletion (steady-state)

The characterization model is developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gases (kg CFC-11 equivalent/kg emission) [34].

- Human Toxicity, Freshwater Aquatic Ecotoxicity, Marine Aquatic Ecotoxicology, and Terrestrial Ecotoxicity

Characterization factors are calculated with the Uniform System for the Evaluation of Substances (USES)-LCA, describing fate, exposure, and effects of toxic substances for an infinite time horizon. Each toxic substance are expressed as 1,4-dichlorobenzene equivalents/kg emission (1,4-DB eq./kg) [34].

- Photochemical Oxidation (high NO_x)

The model defines photochemical oxidation expressed in kg ethylene equivalents per kg emission [34].

- Acidification

Acidification potential is expressed in kg SO_2 equivalents per kg emission. The model was developed by Huijbregts [34].

- Eutrophication (fate not included)

Eutrophication potential was developed by Heijungs et al. and expressed in kg ${PO_4}^{3-}$ equivalents per kg emission [34].

2.4. Uncertainty of the Life Cycle Impact Assessment

A Monte Carlo simulation analysis was used to quantify and characterize uncertainty from the ranges of input data. This process was rule-based and incorporated probability distributions for variable data that reflected the knowledge and process uncertainty associated with the variable. The Monte Carlo analysis is indispensable for establishing defensible metrics for evaluation, providing a quantified measure of what is known and what is unknown, as well as the inherent variability of a process. The life cycle impact assessment results were interpreted with respect to a Monte Carlo simulation analysis (with the Monte Carlo function built in SimaPro 8.0.1 software) which was performed to identify the effects of data variation on the results. In the analysis, 1000 fixed runs were carried out at a significance level $\alpha = 0.05$, and the number of comparison runs for 2012 and 2023 were counted by the software for the entire inventory result. The simulation results are shown with a graphic distribution of electricity generation for both 2012 and 2023.

3. Results and Discussions

This section presents the LCA performance results of Turkey's electricity generation in 2012 and 2023, and the uncertainty of the results determined by the Monte Carlo Simulation.

3.1. Life Cycle Impact Assessment

The LCA characterization results are presented in Table 5. The environmental impact in 2012 was greater than that of 2023 per kWh for all of the impact categories, except HT and TET.

Table 5. Characterization results.

Impact Categories	2012	2023
ADe (g Sb eq./kWh)	2.83×10^{-4}	2.42×10^{-4}
ADff (MJ/kWh)	6.67	4.44
GW (g CO_2 eq /kWh)	802	468
OD (g CFC-11 eq./kWh)	1.29×10^{-5}	6.06×10^{-6}
HT (g 1,4-DB eq./kWh)	49.5	61.9
FAET (g 1,4-DB eq./kWh)	3.46	2.51
MAET (g 1,4-DB eq./kWh)	24.2×10^3	18.2×10^3
TET (g 1,4-DB eq./kWh)	0.226	0.247
PO (g C_2H_4 eq./kWh)	2.26	0.873
Acid. (g SO_2 eq./kWh)	9.79	6.23
Eutroph. (g ${PO_4}^{3-}$ eq./kWh)	0.569	0.317

The ADe is mainly generated by copper and molybdenum in 2012, in addition to this order chromium takes the second place in 2023. Infrastructure processes of power plants play an important role for the consumption of these elements. Natural gas has a dominant effect on copper consumption and, for that reason, a decrease in the share of natural gas would also decrease the copper consumption from 2012 to 2023. On the other hand, chromium consumption would increase in 2023 because of the increased share of electricity generation from wind power plants. Molybdenum mainly resulted from natural gas in 2012 and from wind power in 2023, but its share on the total ADe amount would not change from 2012 to 2023.

Most of the total fossil fuel-based AD (ADff) occurs at the resource extraction stages of coal mining (approximately 90% in both of 2012 and 2023). The impact of natural gas is quite low (3.78%) compared to coal.

The total GW includes carbon dioxide and methane. Carbon dioxide and methane account for approximately 95% and 5%, respectively, of the total impact for both years. The emissions from burning of imported coal and lignite are the main contributors to the total GW, with average percentages of 64% and 34%, respectively.

The major contributing burden to OD is bromochlorodifluoromethane (Halon 1211) (96% for 2012 and 86% for 2023, respectively) resulting from transporting natural gas over long distance via a pipeline.

The emissions of selenium, chromium (IV), molybdenum, nitrogen oxides, and arsenic are the major burdens contributing to the total HT. The high carbon ferrochromium production process that takes place in the construction of wind power and hydropower plants is mainly responsible for this impact. Wind power, especially, would constitute 79% of HT in 2023. Coal ash (hard coal and lignite) disposal at thermal power plants and spoils from coal mining are also responsible for the HT impact.

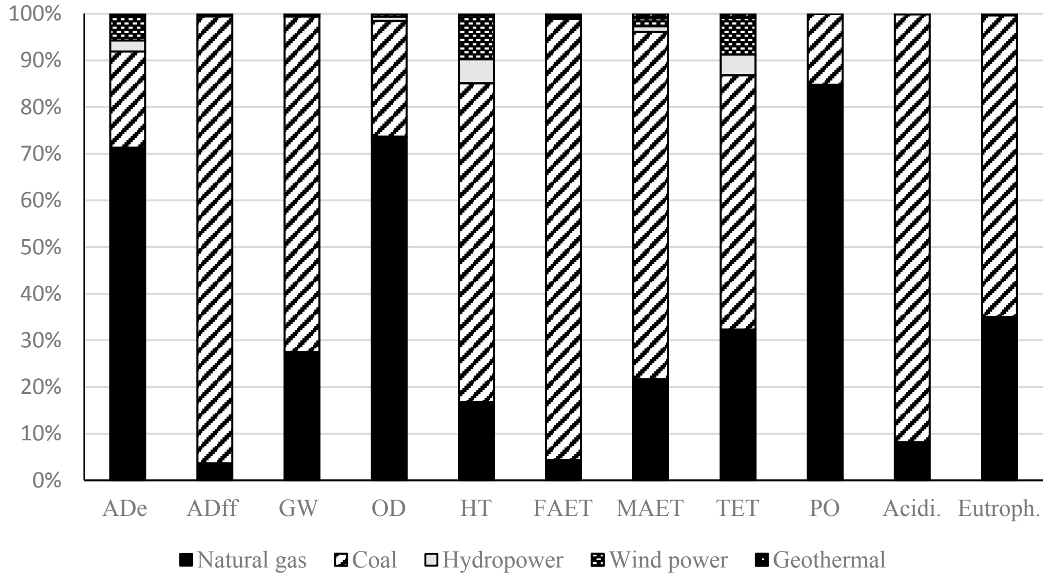
The total FAET includes emissions in the water of arsenic, molybdenum, nickel, vanadium, selenium, and beryllium, with the same percentages for 2012 and 2023. These emissions mainly result from coal ash (hard coal and lignite) disposal at thermal power plants and spoils from coal mining, with the exception of vanadium. Uranium mining is the most responsible for vanadium in the FAET impact.

Hydrogen fluoride, selenium, molybdenum, and beryllium emissions in water are the major burdens contributing to the total MAT with contributions range between 55%–58%, 15%–17%, 11%–12%, and 4%, respectively. Coal ash (hard coal and lignite) disposal at thermal power plants and spoils from coal mining processes are responsible for these emissions.

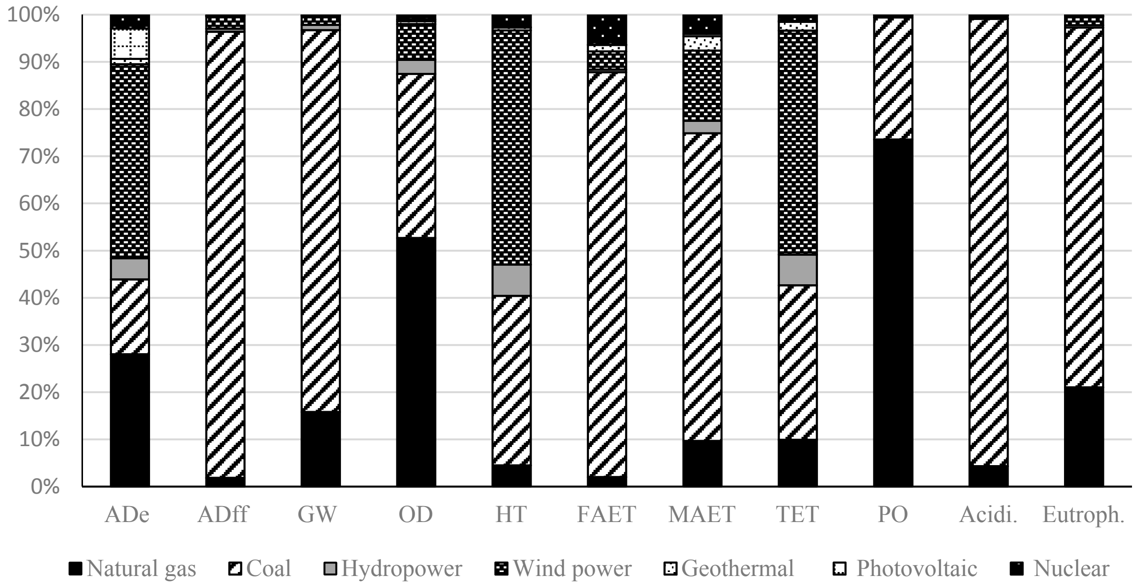
TET is mainly generated by mercury, chromium VI, and nickel emissions. Mercury emissions in water constitute about 70% of the total TET for both of the years, but sources of the emissions and their shares show a difference between 2012 and 2023. Mercury emissions mainly resulted from imported coal, lignite, and natural gas in 2012, whereas they would result from wind power (dominantly) and imported coal in 2023. The high carbon ferrochromium production process of wind power is also responsible from this impact in 2023.

The main burdens contributing to the total PO are carbon monoxide and sulfur dioxide for both of the years mainly resulted from the burning of natural gas and lignite, respectively. Sulfur dioxide and nitrogen oxides generated from the burning of lignite, coal, and natural gas are the cause of acidification for 2012, as well as 2023. The eutrophication impact is mainly contributed by NO_x emissions in the air and phosphate emissions in the water for both of the years. Burning natural gas is responsible for NO_x emissions, while disposal of spoils from lignite mining is responsible for phosphate emissions.

Figure 3a,b shows the share of electricity generation resources in the environmental impacts of the years under review. As can be seen from Figure 3a, coal and natural gas are the dominant resources causing environmental impacts in 2012. On the other hand, in 2023 (Figure 3b), in addition to coal and natural gas, wind power also has noticeable effects on ADe, HT, MAET, and TET.



(**a**)



(**b**)

Figure 3. Share of electricity generation resources on the environmental impacts (**a**) for the year 2012 (**b**) for the year 2023.

3.2. Uncertainty Analysis of Life Cycle Impact Results

Figure 4 shows the results of the uncertainty assessment in terms of the probability. In this figure, A represents 2012 and B represents 2023. A ≥ B shows the probability of an electricity generation mix in 2012 having higher impact than 2023 (or equal) and vice versa for A < B. For all indicators, except HT, TET, and ADe, electricity generation impact values in 2023 are almost certainly lower than those of 2012. There are probabilities of approximately 40% for TET and ADe that 2012 has higher values than those of 2023. However, for HT, the probability of having a smaller value in 2012 than in 2023 is only 0.6%. This result shows that the actual HT value in 2012 is not smaller than 2023. Figure 4 also displays that the results of life cycle impact are not random.

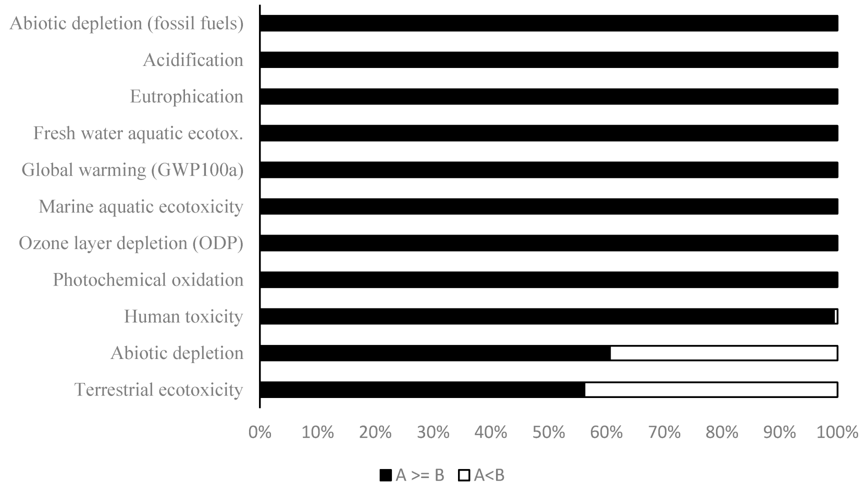


Figure 4. Monte Carlo simulation results of the comparison of the uncertainties between the electricity generation in 2012 (A) and electricity generation in 2023 (B).

3.3. Comparison of the Results with the Literature

GW, acidification, and eutrophication results of this study were compared with the findings of other LCA studies that were based on the electricity generation mix of a country. In this context, GW, acidification, and eutrophication values of the electricity generation mix in Turkey (for 2012 and 2023) are given with those of Portugal, Spain, Belgium, Tanzania, Nigeria and Mexico in Table 6. In this table, GW and eutrophication values, in the case of 2012, are higher than those of European countries (Portugal, Spain, and Belgium) but in the case of 2023, values are close to the average GW and eutrophication values of these three countries. Acidification values in the cases of 2012 and 2023 are higher than the European countries, but in the range of the values for Mexico. If it is considered that the acidification impact is mainly the result of the burning of fossil fuels (lignite, coal, and natural gas), then having higher acidification values in Turkey's electricity mix than those of European countries is remarkable.

Table 6. Comparison of the results with the literature.

Country	Impact Assessment Method	GW (g CO_2 eq/kWh)	Acidification (g SO_2 eq/kWh)	Eutrophication (g PO_4^{3-} eq/kWh)
This study (2012)	CML-IA (v.3.00)	802	9.79	0.57
This study (2023)	CML-IA (v.3.00)	468	6.23	0.32
Portugal [15]	CML 2 v2.05	456	1.22	0.86
Spain [18]	CML2 Baseline 2000	542	4.93	0.248
Belgium [18]	CML2 Baseline 2000	320	1.00	0.09
Tanzania [19]	CML 2001	560	4.53	0.70
Nigeria [21]	CML 2 Baseline 2001	370	0.22	0.06
Mexico [22]	CML 2 Baseline 2001	571	6.59	0.30

4. Conclusions

Assessment of the sustainability of any energy system should be investigated based on the environmental indicators. Global Warming is the first environmental impact indicator coming to mind while talking about electricity generation. However, other impacts should also be considered. For this reason, in this study eleven impact categories, including global warming, have been comprehensively assessed for the mix of electricity generation in Turkey. Whereas the contribution of fossil fuels to electricity generation was almost 72% in 2012 (base year), it will have reached nearly 34% by the end of the 2023 (future year) with some targets. The findings of the study show that the fossil-fuel options are mainly responsible for all environmental impacts for base and future situations of electricity generation in Turkey. However, the consumption of fossil fuels not only contributes to global warming, but it also has effects on the elemental basis of abiotic depletion due to raw material consumption for plant infrastructure. The government may improve more efficient fossil-fuel electricity technologies compared to conventional options.

Turkey has potential for diverse renewable sources, including wind, hydroelectric, solar, and geothermal. It is clear that wind energy will play a key role in Turkey's energy market over the next decade. However, the establishment of renewable energy sources have limitations in Turkey, since most of the equipment is supplied from foreign countries. This is both a cost and environmental-impact increasing factor. For these reasons new policies are needed for the promotion of equipment manufacturing, especially for wind. On the other hand, as an observation of this study, increasing the proportion of wind power in the electricity mix would also increase certain life cycle impacts (such as the elemental basis of abiotic depletion, human ecotoxicity, and terrestrial ecotoxicity) in Turkey's geography compared to increasing the share of other renewable energy sources, such as hydropower, geothermal, as well as solar.

Considering all of the impact categories, the hydropower energy option is the third lowest option in electricity generation after the geothermal and solar energy options. However, geothermal and solar energy, which will only supply small portions (nearly 1.2%) of Turkey's remarkable total energy demand in 2023, will also have the smallest share in renewables. The contribution of planned hydroelectric power for electricity generation will be approximately 40% (154,000 GWh) of all natural resources by the end of 2023. As a result, geothermal and solar energy should be considered as a local source rather than a nationwide energy supply.

Additionally, if the government of Turkey wants to supply 30% of the country's electricity demand in 2023 from renewables, it also needs to use nuclear power to supply its increasing electricity demand and accommodate problems related to wind and solar energy. The findings of life cycle impact assessment show nuclear power also has relatively low impacts on the elemental basis of abiotic depletion compared to wind power, and nuclear energy also has higher impacts on human and terrestrial ecotoxicity by comparison with geothermal and solar energy options.

Finally, for the future energy policy of Turkey, the government should consider a life cycle approach (with economic features, such as the fixed and annual costs of these technologies, as well as the social aspects: direct employment, worker injuries, etc.) in the decision-making process.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/8/11/1097/s1, Table S1: Data used to model coal fired TPPs in SimaPro with calculation details, Table S2: The data used to model the natural gas-fired TPPs in SimaPro, Table S3: Hydroelectric power plants operated in 2012.

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