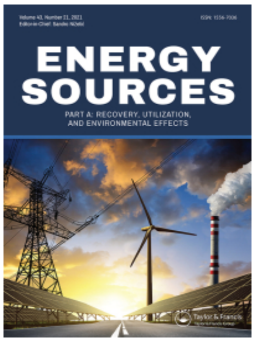

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ORIGINAL ARTICLE

Environmental performance of high-efficiency natural gas combined cycle plant

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ABSTRACT

The aim of this paper is to assess the environmental impact of electricity production from one of the best available gas-fired power plants and to compare it with the current mix of electricity and the supply of electricity from a typical gas plant. The scope of the paper includes gas field exploration, natural gas processing, pipeline transportation, and electricity generation as well as construction and decommissioning of the plant. The influence of efficiency of the plant and natural gas supply from different countries on the results is explored within the sensitivity analysis. The findings indicate that the global warming potential is estimated at 388 g CO_2 eq./kWh. The natural gas system described offers major improvements in all considered environmental impacts compared to the typical natural gas electricity generation system, ranging from 4.9% for abiotic depletion potential to 82.1% for acidification potential. Increasing the contribution of natural gas in the electricity mix would reduce only eutrophication, human toxicity, freshwater, and marine aqua ecotoxicity potentials. The lower environmental impacts in this paper are due to the different gas composition, relatively high efficiency assumed as well as the proximity of Turkey to Azerbaijan which reduces transport distances. The results of this study would be of benefit to the future energy market, as natural gas is one of the electricity-producing plants promoted in Turkey.

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KEYWORDS
Natural gas; energy technologies; life cycle assessment; environmental impact

Introduction

Natural gas is an important energy source for the Turkish energy market due to environmental, geographic, and economic reasons. Since the mid-1980s, natural gas has primarily been used for electricity generation, industrial energy supply, domestic and commercial heating in the country. Furthermore, Turkey is surrounded by the Middle East, Russia, and the Caspian Sea regions which together they hold the majority of the world's gas reserves. Turkey is also neighbor of Europe, which is the second-largest energy market in the world. The geographical location of the country makes it a very critical energy corridor as it is a natural bridge between countries rich in natural gas reserves and significant consumption markets. Turkey aims to become an energy hub to improve national and regional energy security (Demirbas 2010; Schulte and Weiser 2019).

As shown in Figure 1, Turkey's gas production is very low compared to its consumption levels. Around 45.7 billion m^3 of natural gas was consumed in Turkey in 2019 and around 1.1% of that amount was met by domestic production (EMRA 2020a). In 2020, Turkey discovered natural gas from the Black Sea. The reserve is 320 billion m^3 and is estimated to meet about 7–8 years of Turkey's natural gas needs (Shkurti and New 2020).

Gas transported through the pipelines must meet all the specifications of the country (BOTAS 2019). As shown in Figure 2, natural gas imports amounted to 45.2 billion m^3 in 2019, compared to

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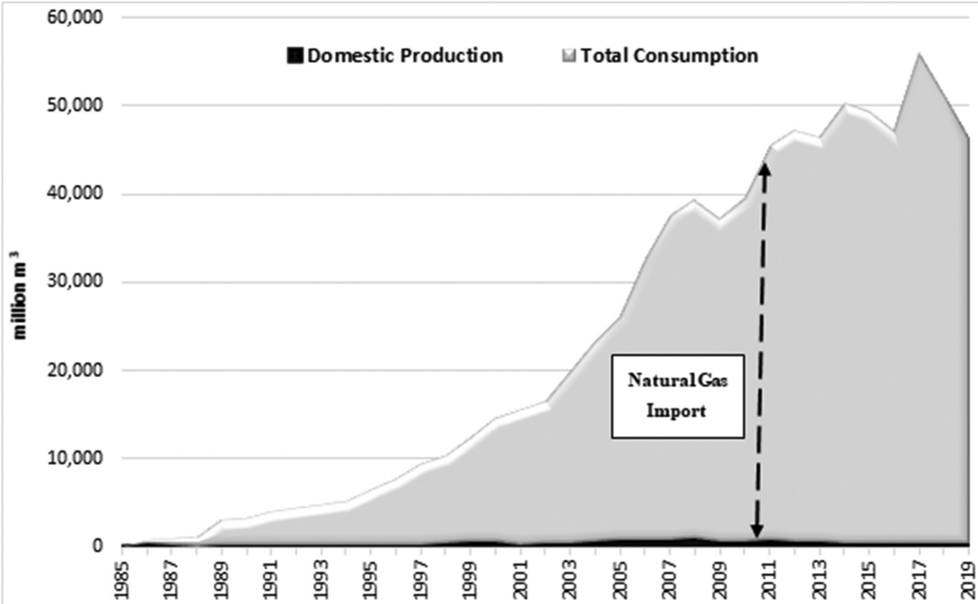

Figure 1. Natural gas supply in Turkey (EMRA 2020a).

50.3 billion m^3 of gas imports in the previous year. In the distribution of the country's natural gas imports by country in 2019, Russia's share decreased from 47.0% in 2018 to 33.6% in 2019. In 2019, Azerbaijan passed Iran with a 21.2% share, while Iran dropped to third with a 17.1% share, see Figure 2. In the same year, other countries where natural gas is imported are Algeria (12.6%), Qatar (5.4%), Nigeria (5.4%), and the United States (2.7%) (EMRA 2020a). This situation shows that energy security is a significant issue in Turkey.

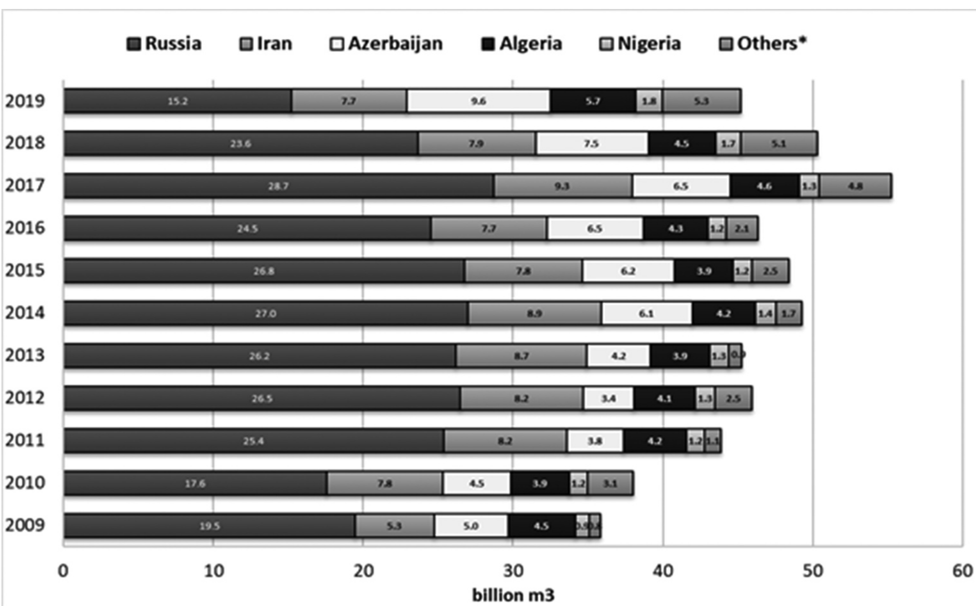

Figure 2. Natural gas imports by countries from 2009 to 2019 (billion m^3) (EMRA 2020a).

Turkey has sought to minimize its energy reliance on Russian energy sources by reducing the share of natural gas in the electricity production mix and increasing its downstream network to ensure alternate import sources. As presented in Figure 2, Azerbaijan's share of Turkish gas imports has increased in recent years. Turkey imports natural gas from Azerbaijan through the Southern Caucasus pipeline. This pipeline is part of the Southern Gas Corridor project aimed at transporting natural gas from Azerbaijan to Europe. The current geopolitical processes in the region, changes in the gas market and the implementation of energy projects between Azerbaijan and Turkey have gradually increased Azerbaijan's position in the Turkish gas supply (Rzayeva 2018).

Electricity is a vital need for the development of societies, and demand in Turkey has increased rapidly. The electricity production of the country reached the level of 294,251 GWh in 2019, compared with 292,595 GWh in 2018. The electricity generation is based on domestic and imported coal, natural gas, hydropower, geothermal, wind and others such as waste and solar energy. The most important source of renewable energy for the generation of electricity comes from the flow of water. According to 2019 data, electricity is produced from fossil fuels (58%), hydropower (30%), and other renewables (12%) (EMRA 2020b), see Figure 3.

As of 2019, the installed capacity of natural power plants was 25.9 GW in total which was around 31% of the total installed capacity of the country. In 2019, the natural gas-based power production was 56.5 TWh with nearly 19.2% share in the total generation (EMRA 2020b). In 2019, there were 327 natural gas power plants in Turkey (MENR 2020).

Natural gas electricity is produced mainly through combined-cycle natural gas (NGCC) systems. Because of their wide range of capabilities and high performance at full load (up to 64%) (VIRN 2017), NGCC is the most common gas-fired plant as an advanced energy generation technology (Wojcik and Wang 2018). As shown in **Figure 4**, NGCC systems are made of gas and steam turbines; waste heat recovery units for steam generation; condensers; and other auxiliary equipment. First, air passes through a compressor and it is mixed and burned with natural gas. In order to improve the overall performance of the power plant, steam and gas turbines are coupled at these types of generating facilities. Both gas and steam turbines generate the power to be transmitted (Kuehn et al. 2013). The gas turbine uses hot gasses from natural gas burning to turn the turbine and produce electricity. The exhaust gas turbine is linked to a heat recovery steam generator, where the exhaust gas produces energy from the waste heat. The steam generated is used for steam turbine

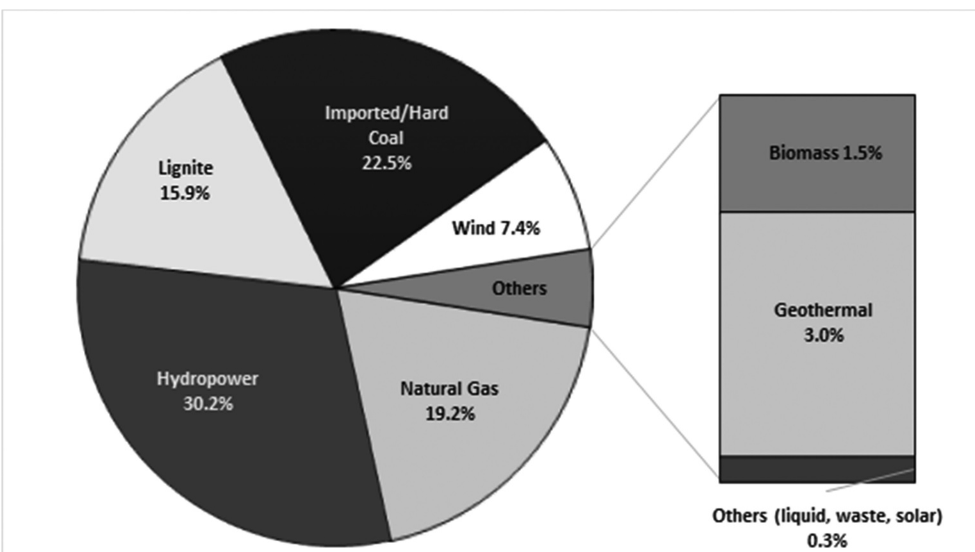

Figure 3. Turkey's electricity generation mix in 2019 (EMRA 2020b).

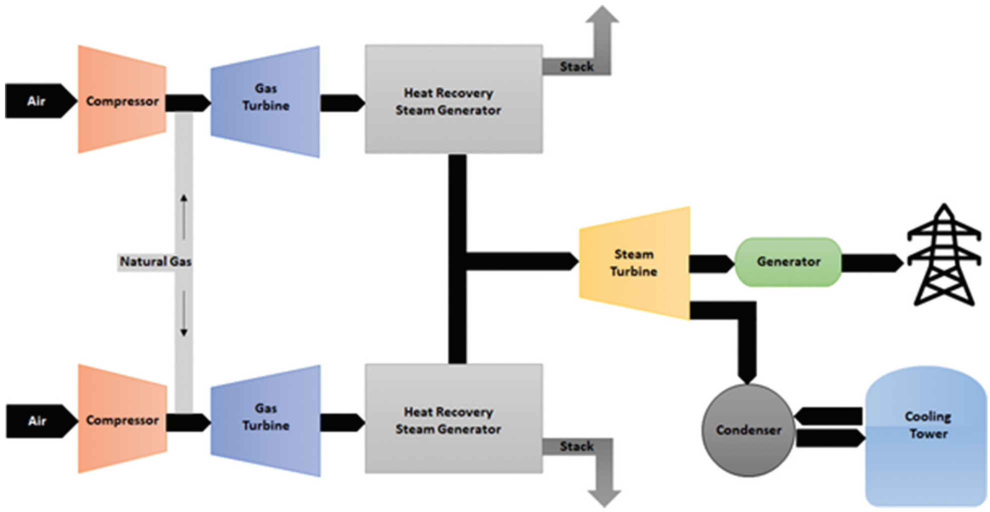

Figure 4. Flow diagram of natural gas combined cycle plant.

operation, which generates additional electricity (IEA 2012). The waste gasses are discharged into the atmosphere through the stack. The steam turbine's input temperature is about 540°C. The steam turbine's efficiency is about 40%. The temperature of input to a gas turbine can be as high as 1100°C while the output temperature can be reduced to around 550°C. The gas turbine's efficiency is around 33% (Hasan, Rai, and Arora 2014). NGCC systems play a significant role in Turkish power generation (MMO 2010).

Life Cycle Assessment (LCA) is a widely used method for determining the environmental effect of power systems. Several papers evaluated the environmental impacts of power production from natural gas plants from different countries. Examples of studies elsewhere include the United Kingdom (Stamford and Azapagic 2012), Mexico (Santoyo Castelazo 2012; Toscano et al. 2019), India (Agrawal et al. 2014), Thailand (Phumpradab, Gheewala, and Sagisaka 2009; 2016), Chile (Gaete-Morales et al. 2019), Norway (Riva, D'Angelosante, and Trebeschi 2006; Singh, Strømman, and Hertwich 2011), the United States (Jaramillo, Griffin, and Matthews 2007; Spath and Mann 2010), Portugal (Garcia, Marques, and Freire 2014), Tanzania (Felix and Gheewala 2012) and Spain (Navajas et al. 2019). LCA study of electricity generation from fossil fuel power plants in Turkey has also been carried out Atilgan, Azapagic (Atilgan and Azapagic 2015). The impact assessment methods vary across the papers as well as the scope and selected technologies. Most of the papers have been carried out for fossil and renewable electricity generation technologies (Atilgan and Azapagic 2015; Felix and Gheewala 2012; Gaete-Morales et al. 2019; Garcia, Marques, and Freire 2014; Jaramillo, Griffin, and Matthews 2007; Santoyo Castelazo 2012; Stamford and Azapagic 2012) including natural gas. Some of the papers considered only natural gas power plant (Agrawal et al. 2014; Phumpradab, Gheewala, and Sagisaka 2009; Riva, D'Angelosante, and Trebeschi 2006; Spath and Mann 2010; 2016), as opposed to natural gas power plants with carbon capture and storage (Navajas et al. 2019; Singh, Strømman, and Hertwich 2011; Toscano et al. 2019). Global warming potential (GWP) was considered in all studies. Most also considered acidification potential (AP) except three studies (Jaramillo, Griffin, and Matthews 2007; Singh, Strømman, and Hertwich 2011; Spath and Mann 2010). These three studies estimate only GHG emissions and GWP of natural gas-based power generation. Despite their importance of global energy supply, there is scant information on the environmental sustainability of the latest technology NGCC power plants. In order to improve knowledge about the new natural gas power generation and its impact on the environment, this paper considers the best available technology natural gas-based electricity generation.

The goal of this research is to apply the life cycle approach in analyzing the environmental impacts of electricity production from natural gas-based power generation with one of the best available technology gas plants in 2020. This paper evaluates for the first time the environmental sustainability of the new supply routes of natural gas and the best NGCC power plant in Turkey by using real and detailed data. A further novelty includes a comparison of the obtained results to the impacts from a conventional supply of gas-powered electricity and the current electricity mix in Turkey. The modeled NGCC power plant is one of the biggest and highest efficient power plants in Turkey in 2020. Environmental sustainability evaluation of the new supply routes of natural gas and the better power generation technologies is critical in helping to select the most environmentally friendly future options. It is important to perform a detailed environmental sustainability impact assessment of the electricity generation systems, assessing the impacts from all life cycle stages of the power generation to allow comparisons between the technologies. It is, therefore, important to provide reliable information to policymakers to ensure that new or improved energy options would not result in changes that will increase the environmental impacts.

The following sections present the data sources, methodology and estimated environmental impacts from the selected NGCC system in Turkey. This is followed by a discussion and validation of the findings.

Materials and methods

The methodology of this research is based on the Life Cycle Assessment (LCA) framework as defined by ISO 14040 and 14044 guidelines (ISO 2006a, 2006b). Global Emission Model for Integrated Systems (GEMIS) v4.95 and GaBi v9.5 software has been used for the assessment (Öko Institute 2018; Sphera 2020). According to ISO 14040 and 14044 guidelines, there are four main stages of LCA: goal and scope definition of the research, life cycle inventory analysis, impact assessment and interpretation steps. The first two steps of the LCA methodology are discussed below.

Goal and scope definition

The main aim of this life cycle assessment study is to quantify and analyze the environmental impacts of electricity generation from a natural gas power system in Turkey and compare the obtained results to the life cycle environmental impacts from a conventional supply of electricity from gas power and the current electricity mix in Turkey. The modeled power generation plant is a new NGCC power plant. It is one of the biggest and highest efficiency of NGCC power plants in Turkey in 2020.

Functional unit

The functional unit of this study is defined as '1 kWh of electricity generation' and all results in this paper are presented as per kWh electricity generation.

System description and boundaries

The electricity production process considered in this research contains the following stages: natural gas supply, pipeline transportation, plant operation, plant construction, and plant decommissioning. The natural gas supply stage comprises the extraction, production, and processing of natural gas. Thus, the electricity transmission and distribution steps are not included within the system boundary. All stages consider energy and material inputs and outputs, production wastes and construction of the infrastructure. The life cycle stages of the NGCC plant are detailed in **Figure 5**.

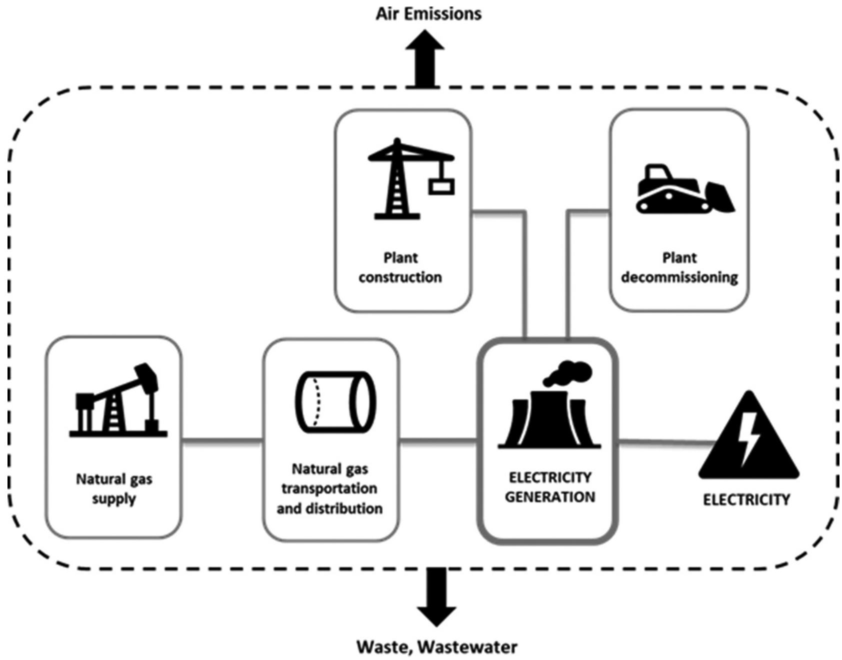

Figure 5. The life cycle of natural gas power plant.

Inventory data and assumptions

Inventory data were collected from websites, reports, literature, and private communications. Also, the Ecoinvent database, GEMIS 4.95 and GaBi v9.5 software packages were used to complete the life cycle inventory of the system due to a lack of primary data (Ecoinvent 2010; Öko Institute 2018; Sphera 2020). **Figure 6** illustrates the methodology and data sources used to assess the life cycle environmental sustainability of electricity production from NGCC technology in Turkey.

Due to the lack of background data for the supply of gas and raw materials, construction and decommissioning of plant and pipelines Ecoinvent database (Ecoinvent 2010) was used in this paper.

Data for natural gas composition and properties are specific to natural gas from the Caspian Sea, Azerbaijan. The specifications of the gas (see **Table 1**) are obtained from BOTAS (BOTAS 2020). The average higher calorific value of the natural gas used as fuel to power generation is 9,575 kcal/m (BOTAS 2020; EMRA 2020a).

To determine the potential environmental impacts from NGCC plants in Turkey, emission factors for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), sulfur dioxide (SO_2), nitrogen oxides (NO_x), nitrous oxide (N_2O), and particulates were estimated based on GEMIS 4.95 (Öko Institute 2018). The direct emissions from the NGCC plant obtained by GEMIS 4.95 have been used in the GaBi v9.5 full life cycle modeling. The main modeled process based on GaBi software is presented in **Figure 7**.

The inventory data are presented in **Table 2**. As detailed below, the operating parameters of the plant such as fuel type, technology, gas composition and NGCC power plant efficiency in Turkey were used to calculate emission factors. The NGCC power plant model described in the Ecoinvent database was adapted to Turkish conditions according to the inventory data.

The natural gas consumed for the electricity generation is from the Shah Deniz field in the Caspian Sea. This is the biggest field of natural gas in Azerbaijan. The gas production is offshore. The natural gas supply stage includes gas field exploration, gas production, and purification. The background data for natural gas supply are sourced from Ecoinvent database (Ecoinvent 2010). There is no process for the natural gas extraction and processing for the gas from the Shah

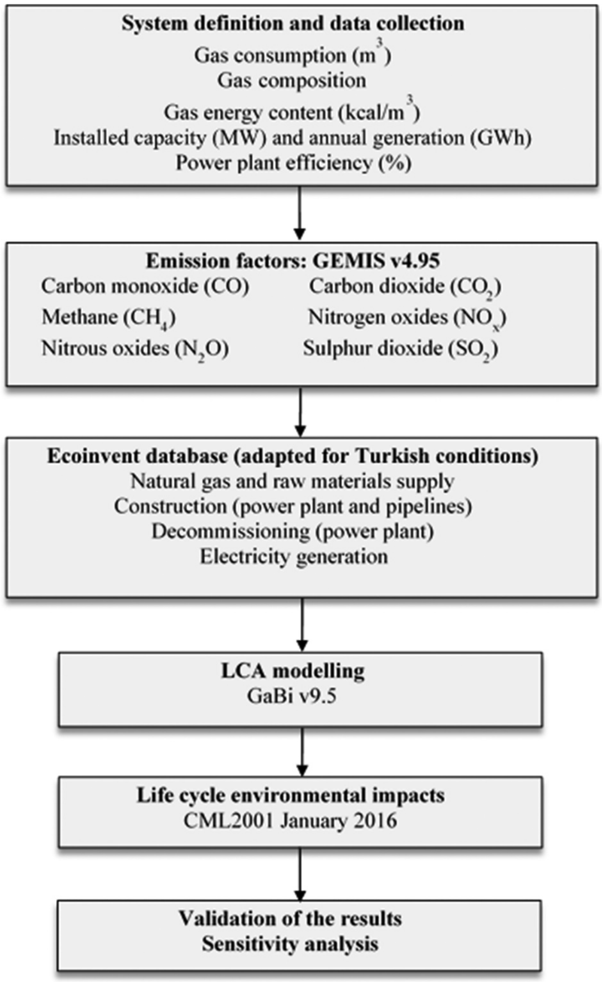

Figure 6. The data sources and methodology.

Table 1. Properties of natural gas (BOTAS 2020).

Parameter	Value
Higher calorific value (kcal/m^3)	9,575
CH_4 (mole %)	92.98%
C_2H_6 (mole %)	5.39%
C_3H_8 (mole %)	0.97%
C_4H_{10} (mole %)	0.16%
N_2 (mole %)	0.52%
CO_2 (mole %)	0.07%

Deniz field, the process of the extraction and processing of gas in the North Sea, Norway has been used instead. The effect of this assumption on the results is explored as part of a sensitivity analysis. In order to remove water and oil, higher hydrocarbons, and sulfur, natural gas is treated. Sulfur is extracted from the sour gas in the sweetening process to 99.9% (Dones, Bauer, and Bolliger et al. 2007).

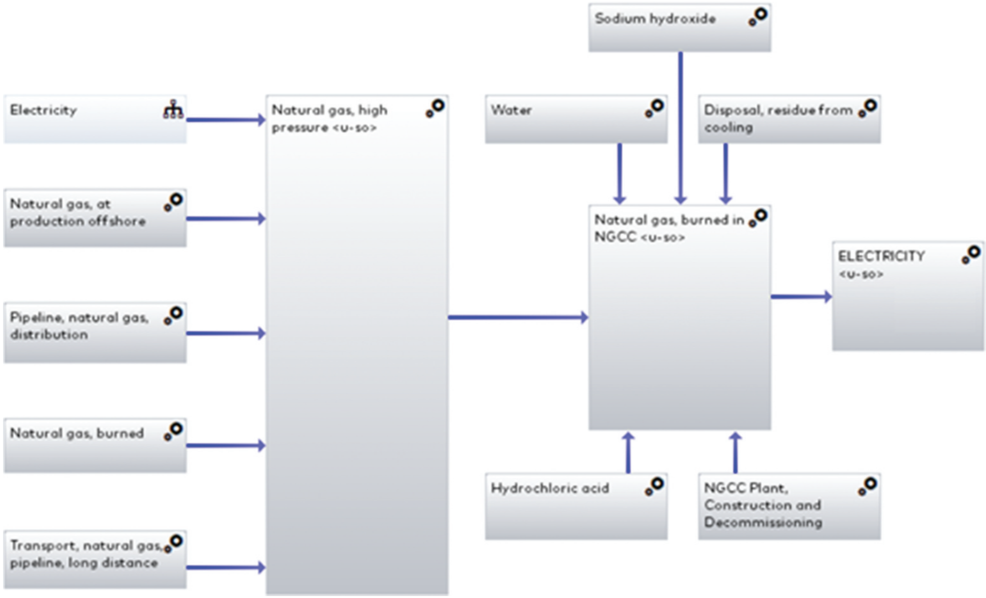

Figure 7. Basic LCA model based on GaBi.

Natural gas is transported only via pipeline. The South Caucasus pipeline and the Trans-Anatolian Natural Gas pipeline transport the gas from the Shah Deniz in Azerbaijan to Turkey. The natural gas used for the electricity production is supplied from BOTAS via Turkey-Greece Natural Gas Pipeline (DOKAY 2011). Gas is supplied by high-pressure pipeline over a distance of about 2000 km onshore pipeline (BOTAS 2019; DOKAY 2011) from the Azerbaijan Shah Deniz field. The length of the pipeline was used to calculate the t.km (transport unit). The onshore and offshore pipeline transportation and distribution background data are obtained from the Ecoinvent database (Ecoinvent 2010).

The size of the NGCC power plant model is 936 MW (two gas turbines with a capacity of 304 MW and one steam turbine with a capacity of 328 MW). The inventory data for natural gas plant construction are taken from a model for a 400 MW plant (Ecoinvent 2010). The size of the gas plant has been scaled up from 400 MW to 936 MW. The 'economies of scale' method (Coulson, Sinnott, and Richardson 1993) has been used for scaling the size of the gas power plant.

The efficiency of the modeled NGCC plant is 59% (DOKAY 2011). The power plant is located close to the Marmara Sea, using 3 kg/kWh of cooling water. The height of the stack is 70 meters (DOKAY 2011).

Construction of a typical NGCC plant generally takes 2–3 years (Spath and Mann 2010). The life cycle of the plant was assumed to be 25 years, after that the facilities need to be decommissioned (Dones, Bauer, and Bolliger et al. 2007). For the decommissioning stage, the recycling rate for metal and cement construction materials is assumed as 50% and for plastics 20%. The system is credited for recycled materials.

Impact assessment

In order to determine the possible environmental impacts of electricity generation from the selected NGCC system, the CML 2001 updated January 2016 (Guinée, Heijungs, Huppes, 2001) mid-point impact assessment methodology was used. The impact categories for the environmental sustainability assessment are presented in Table 3.

Table 2. Summary of data inventory.

Natural Gas Supply	
Gas extraction *	Offshore extraction North Sea (Norwegian production)
Leakage *	Production: 0.07 g/Nm^3
Water **	21% of the water re-injected 79% of the water discharged into the sea
Natural Gas Transportation and Distribution	
Transportation and distribution	Pipeline
Distance	2000 km
Leakage *	0.026% per 1000 km pipeline
Energy consumption, compressor *	1.8% of transported gas per 1000 km
Plant Construction	
Plant type	Combined cycle
Size	936 MW • Gas turbines: 304 MW x 2 • Steam turbine: 328 MW
Lifetime	25 years
Plant Decommissioning	
Recycling rate	50% cement 50% metals 20% plastics
Landfill	50% cement 50% metals 80% plastics
Electricity Generation	
Technology	Natural Gas Combined Cycle (NGCC)
Load factor	85%
Fuel share	100% natural gas
Efficiency	59%
Input	
Fuel consumption (m^3/kWh)	0.16
Water consumption (kg/kWh)	3
Output (based on GEMIS 4.95 and GaBi v9.5)	
Electricity (kWh)	1
CO_2 (g/kWh)	342
CO (g/kWh)	0.25
CH_4 (g/kWh)	0.02
NO_x (g/kWh)	0.1
N_2O (g/kWh)	0.02
SO_2 (g/kWh)	0.004

* Dones, Bauer, and Bolliger et al. 2007
** Schori and Frischknecht 2012

Table 3. Environmental impact categories.

Impact Category	Acronym	Units
Abiotic depletion elements	ADP	kg Sb-eq.
Abiotic depletion fossil	ADP fossil	MJ
Acidification potential	AP	kg SO_2-eq.
Eutrophication potential	EP	kg PO_4^{3-}-eq.
Freshwater aquatic ecotoxicity potential	FAETP	kg dichlorobenzene (DCB)-eq.
Global warming potential	GWP	kg CO_2-eq.
Human toxicity potential	HTP	kg DCB-eq.
Marine aquatic ecotoxicity potential	MAETP	kg DCB-eq.
Ozone layer depletion potential	ODP	kg R11-eq.
Photochemical ozone creation potential	POCP	kg Ethane-eq.
Terrestrial ecotoxicity potential	TETP	kg DCB-eq.

Results and discussions

A more detailed description of the environmental impact categories considered in this paper is given in Appendix 1. **Figure 8** illustrates the impacts of NGCC system per kWh and **Figure 9** shows the contribution of each step of the life cycle to the impact categories. In the following parts, first, the life

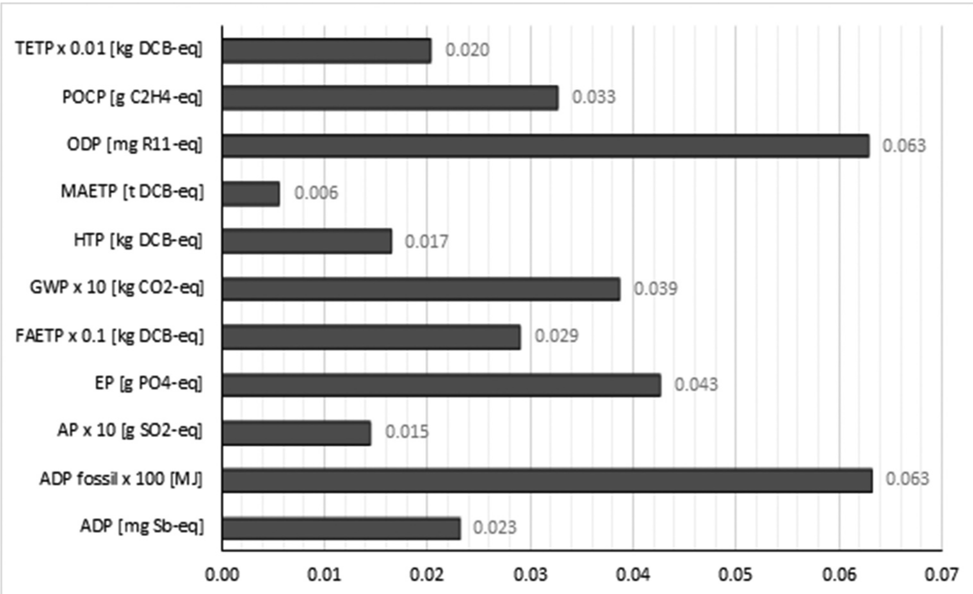

Figure 8. Environmental impacts per kWh generated electricity. [Some impacts have been scaled to fit.].

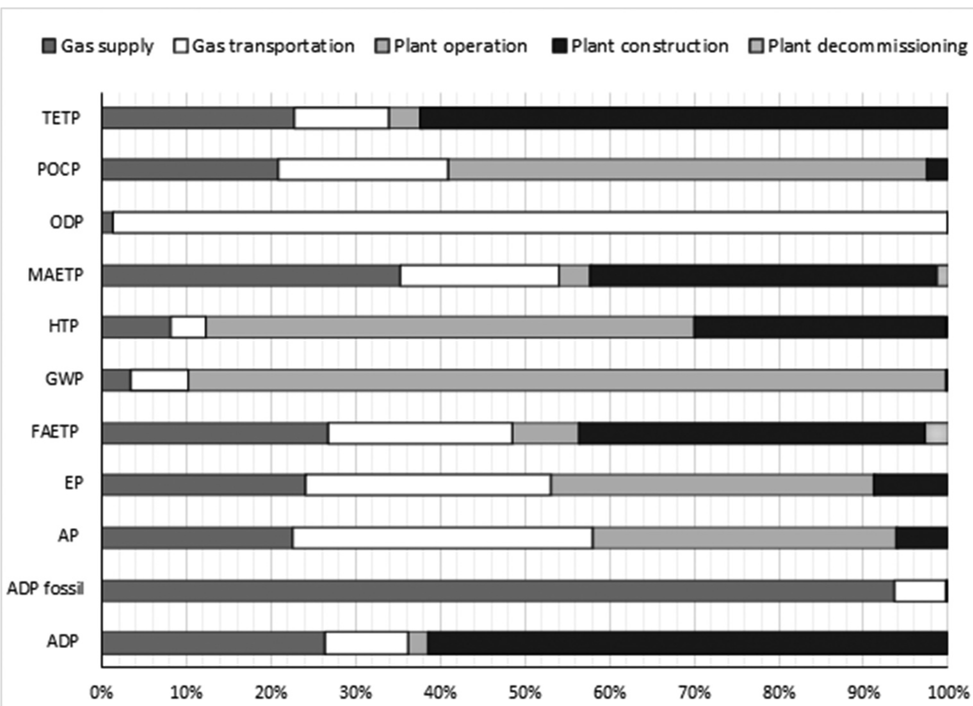

Figure 9. Percentage contribution of the considered stages to the total impacts.

cycle environmental impacts associated with the selected NGCC plant are discussed and compared with another NGCC plant in Turkey and the current electricity mix of the country.

Abiotic depletion potential (ADP)

This impact is estimated at 0.02 mg Sb-eq./kWh. As presented in **Figure 9**, power plant construction, gas supply and gas transportation due to pipeline construction contribute 61.3%, 26.5%, and 9.7% to the total ADP, respectively. Electricity generation from NGCC plants contains scarce elements, such as copper (25.6%), chromium (23.0%), and nickel (9.6%).

Abiotic depletion potential (ADP fossil)

As presented in **Figure 8**, the total ADP fossil is estimated at 6.3 MJ/kWh. The efficiency of the plant and heating value of the gas are important factors for this impact. Natural gas supply stage which includes gas extraction and processing accounts for almost all ADP fossil (~94%).

Acidification potential (AP)

Electricity generation from combined cycle system is responsible for an estimated at 0.15 g SO_2-eq./kWh (**Figure 8**). NO_x and SO_2 emissions contribute 77.7% and 21.6% of this impact, respectively. Plant operation accounts for nearly 36% of the total of this impact. The other major contributions are gas transportation (35.3%) and gas supply (22.7%) stages.

Eutrophication potential (EP)

The total EP of 0.04 g PO_4-eq per kWh (see **Figure 8**). NO_x emissions to air are the largest contributor to this impact accounting for 69.2% followed by phosphate emissions to freshwater (12.3%) and N_2O emissions to air (10.1%). Plant operation, gas transportation and gas supply contribute 38.2%, 28.8%, and 24.2% to the total EP, respectively.

Freshwater aquatic ecotoxicity potential (FAETP)

FAETP is estimated at 2.9 g dichlorobenzene (DCB)-eq. per kWh. Nickel (46.7%), vanadium (23.9%), cobalt (10.3%), and copper (3.5%) are the main heavy metals emitted to water. As presented in **Figure 9**, the biggest contributor to this impact is the power plant construction stage (41.0%). Activities conducted during the processing gas supply and gas transportation stages represent the other major contributors to the total FAETP, accounting for about 26.7% and 21.7%, respectively.

Global warming potential (GWP)

As presented in **Figure 8**, the total GWP over 100 years is calculated as 388.0 g CO_2-eq./kWh. The major contributors to GWP include CO_2 emissions (97.1%), CH_4 (1.9%), and N_2O (1.1%) emissions to air. Due to the gas combustion, the major source of GHG emissions is the power plant operation stage, contributing 89.3% to total GWP. The second-largest contributor is the natural gas transportation stage (6.8%) due to the leakages in the long-distance pipeline transport. Plant construction and decommissioning stages have a negligible contribution to this impact.

Human toxicity potential (HTP)

HTP is estimated at 16.5 g DCB-eq./kWh (see **Figure 8**). The emission of polycyclic aromatic hydrocarbons (61.5%) from gas combustion is a significant contributor to HTP. The other main burdens contributing the total HTP are the emission of heavy metals into the air include emissions of chromium (32.9%), arsenic (10.6%), and nickel (4.3%). Power plant operation and plant construction make a large contribution: 57.8% and 29.6%, respectively.

Marine aquatic ecotoxicity potential (MAETP)

Estimated at 5.7 kg DCB-eq. per kWh (Figure 8), this impact is mainly due to the plant construction (40.8%) and gas supply (35.4%) stages. Beryllium (30.5%), vanadium (11.6%), cobalt (5.8%), and selenium (3.7%) emissions to water and hydrogen fluoride (21.9%) emissions to air are the significant burdens contributing to MAETP.

Ozone layer depletion potential (ODP)

The system has an ODP of 0.06 mg R11-eq./kWh (see Figure 8) and 98.3% of this impact is from the gas supply due to halogenated gases (mainly halon 1211, 96.8%) used as fire retardants in natural gas pipelines.

Photochemical ozone creation potential (POCP)

This impact is calculated as 0.03 g Ethane-eq. per kWh (Figure 8) and it is also mainly due to the burning gas which contributes 56.6% to the total. The important burdens contributing to POCP include NMVOC, CO, and N_2O emissions which account for 46.0%, 26.2%, and 19.3%, respectively.

Terrestrial ecotoxicity potential (TETP)

As presented in Figure 8, the total TETP from the system is determined at 0.2 g DCB-eq. per kWh produced electricity. Nearly 63% of TETP is from the gas supply (Figure 9). Chromium (62.6%) and mercury (24.8%) released to air are the main burdens.

Validation of the results

To validate the results, the comparison of the results with the range obtained from database (Ecoinvent 2010) and the literature (Agrawal et al. 2014; Gaete-Morales et al. 2019; Santoyo-Castelazo and Azapagic 2014; Stamford and Azapagic 2012) for NGCC plants. Only papers that use the CML impact analysis methodology are considered for the comparison.

As presented in Figure 10, the results are within the lower range of the literature values. This is mainly due to the higher efficiency of the considered NGCC power plant. Only TETP obtained from this study is close to the average value reported in the literature.

The AP value in the literature is between 0.05 and 9.2 g SO_2-eq. per kWh electricity so the value of 0.15 g SO_2-eq./kWh obtained in this study is within the range. The calculated results in this work for the GWP of NGCC plants is 388 g CO_2-eq./kWh. This is very similar to the minimum value for NGCC plants in the literature: for example, 379 g CO_2-eq./kWh (Stamford and Azapagic 2012). It has been found that GWP is mainly contributed during the natural gas combustion stage compared to the natural gas supply, transport, plant construction and decommissioning phases. The study found that the overall efficiency of the NGCC plant modeled in this paper is higher than in other countries. It is, therefore, necessary to make efforts to increase the efficiency of NGCC plants to reduce the life cycle environmental impacts.

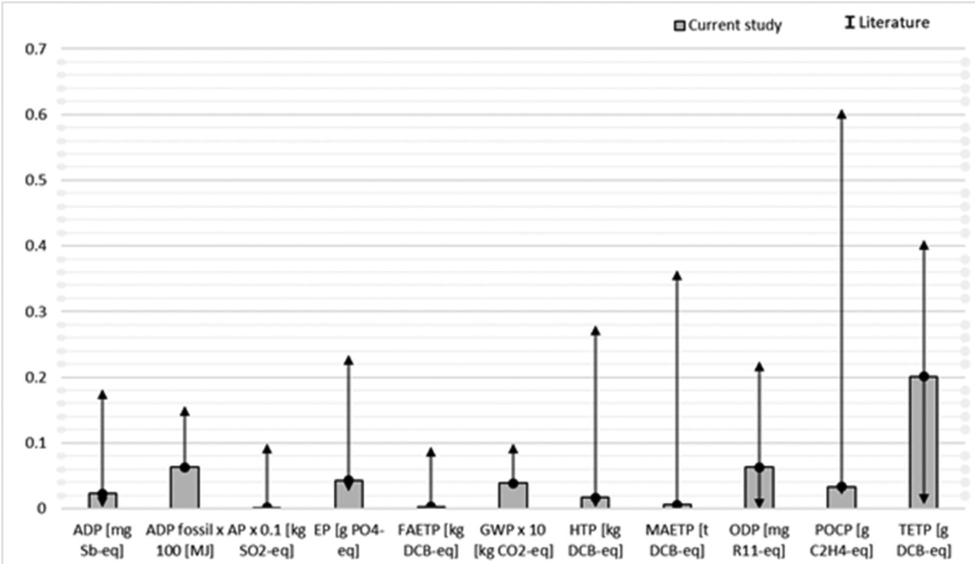

Figure 10. Comparison of the results from the current study with the literatüre. [Some impacts have been scaled to fit.].

Sensitivity analysis

The influence of natural gas extraction and processing in different countries on the results is explored within the sensitivity analysis. This parameter has been selected due to the assumption that has been made. As explained in Section 2.2, there is no process for the natural gas offshore extraction and processing for the gas from Azerbaijan in the database, the process of the extraction and processing of gas in Norway has been used instead. The effect of this assumption on the results is explored as part of a sensitivity analysis. The extraction and processing of gas in the Netherlands and Germany and the results are compared to the gas supplied from Norway in **Figure 11**. The results suggest that extraction and processing of natural gas from Germany affects significantly only EP, increasing the impact by nearly 60%. Another sensitive impact is ADP. This impact is increased by 40% when natural gas is extracted in the Netherlands. As presented in **Figure 11**, the effect of this parameter is small across the other environmental impacts.

Another sensitivity analysis identified changes in overall thermal efficiency. This parameter was selected because of its significant impact on the environmental sustainability of the considered power plant system. Figure 12 compares the results with the two different plants with an overall efficiency of 61% and 64% and the power plant in this study with an efficiency of 59%. Globally, the highest plant efficiency for NGCC system is 64% (VIRN 2017). The results show that the efficiency of NGCC plant affects all the environmental impacts. Although the modeled NGCC is currently the best technology available in Turkey, any increase in efficiency will reduce the environmental impact of the resulting life cycle.

Comparison to other studies

The results obtained from this paper for the NGCC technology in 2020 were compared with the supply of electricity from a typical NGCC power plant and the current electricity mix in Turkey.

Privatization of power stations is an important issue for the Turkish energy sector. Privatization of natural gas plants began in 2009. Privatization in the electricity sector will continue to create a competitive market structure, encourage investment in long-term plans and increase the efficiency of generation and distribution. Apart from this, Azerbaijan officially became Turkey's top gas supplier

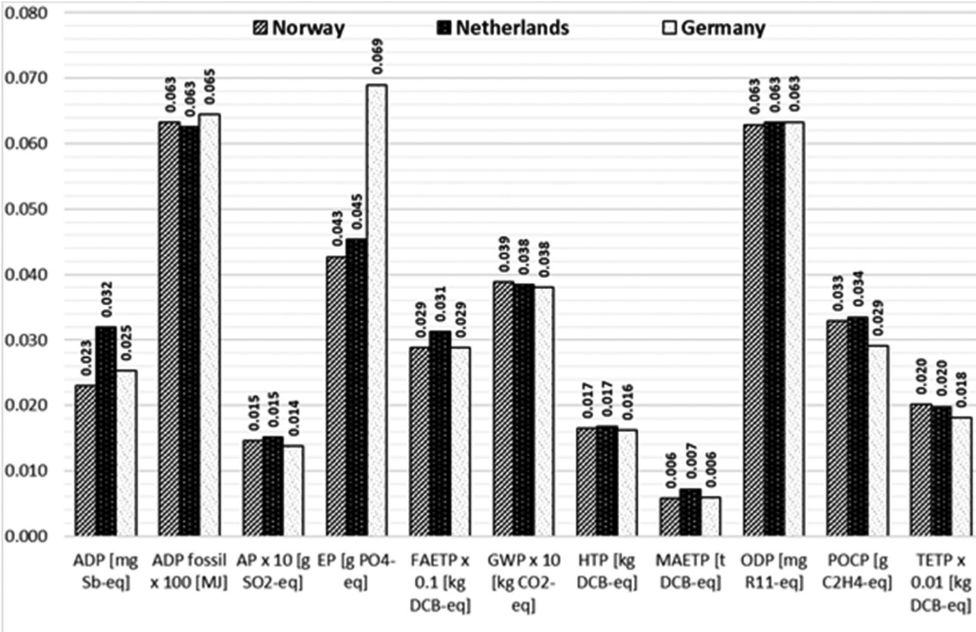

Figure 11. Sensitivity graphs for overall efficiency on the environmental impacts. [Some impacts have been scaled to fit.].

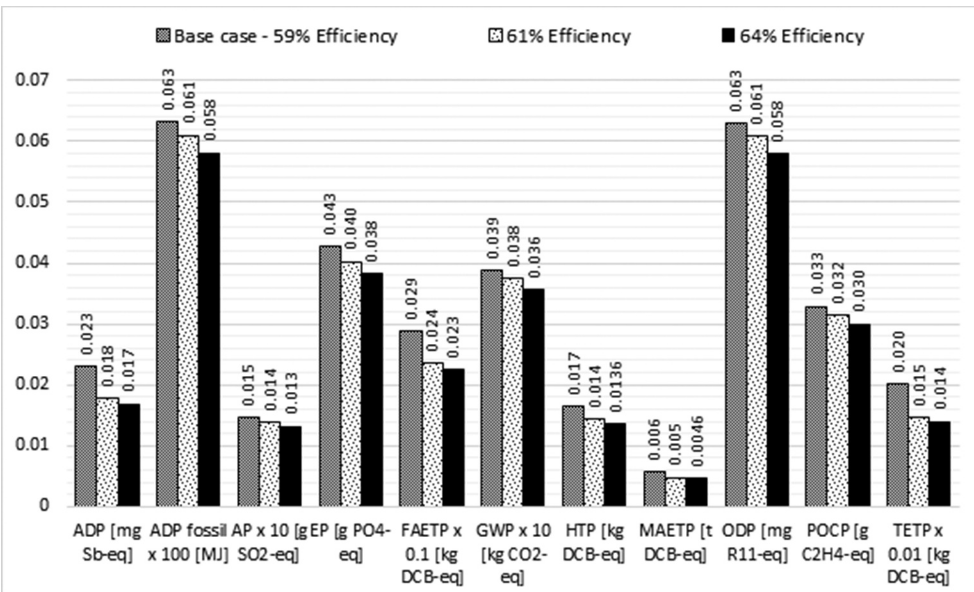

Figure 12. Sensitivity graphs for natural gas extraction on the environmental impacts. [Some impacts have been scaled to fit.].

in May 2020. This became possible after the launch of the new pipeline, Trans-Anatolian Natural Gas Pipeline (TANAP), at the end of 2019. As mentioned in the introduction, there is one paper, prepared by the author of this study, presenting the results of a typical NGCC power generation in 2010 (Atilgan and Azapagic 2015). The comparison of these two gas plants is also important from the point of privatization and a new gas supply route. The details of the inventory data and the impact assessment of the NGCC power plant in 2010 can be found in Atilgan and Azapagic (2015).

It is important for future energy policy to compare the environmental sustainability of the improved NGCC plant with the country's electricity mix. The grid mix of the country in 2019 has been used to estimate the life cycle environmental impacts of the electricity, with the electricity generation mix presented in Figure 3. Turkey's electricity mix has been modeled using the environmental impacts of each technology from Atilgan and Azapagic (2016).

The results for the NGCC power technology in 2010 were obtained from an LCA study of natural gas power in Turkey to identify the differences. As shown in Figure 13, the gas-based electricity generation system described in this paper provides significant improvements in all life cycle environmental impacts compared to a typical NGCC power generation system, ranging from 4.9% for ADP to 82.1% for AP. The only exception to this is HTP mainly due to the different version of CML impact assessment method used in these studies. The method for the calculation of HTP has been changed for the last updated CML impact methodology. In this paper, CML 2001 updated January 2016 has been used for the calculation of the results. The lower life cycle environmental impacts obtained from this study are due to the different gas composition, relatively high efficiency assumed as well as the proximity of Turkey to Azerbaijan which reduces transport distances.

As can be seen in Figure 13, electricity mix is environmentally more friendly with seven out of 11 impacts lower than for the NGCC plants in 2010 and 2020 due to the high share of renewable energy in the electricity mix. Increasing the contribution of natural gas in the electricity generation mix would reduce only four out of eleven environmental impacts. EP, FAETP, HTP, and MAETP for the electricity mix in 2019 are higher than for the NGCC plants. This is mainly a result of the coal power in the electricity mix.

Conclusions

Natural gas has a leading position in the Turkish energy sector. Azerbaijan's share of Turkish gas imports has risen due to the new supply opportunities. More amounts of natural gas from Azerbaijan will most likely be supplied to Turkey in the future. Furthermore, there are new highly efficient natural

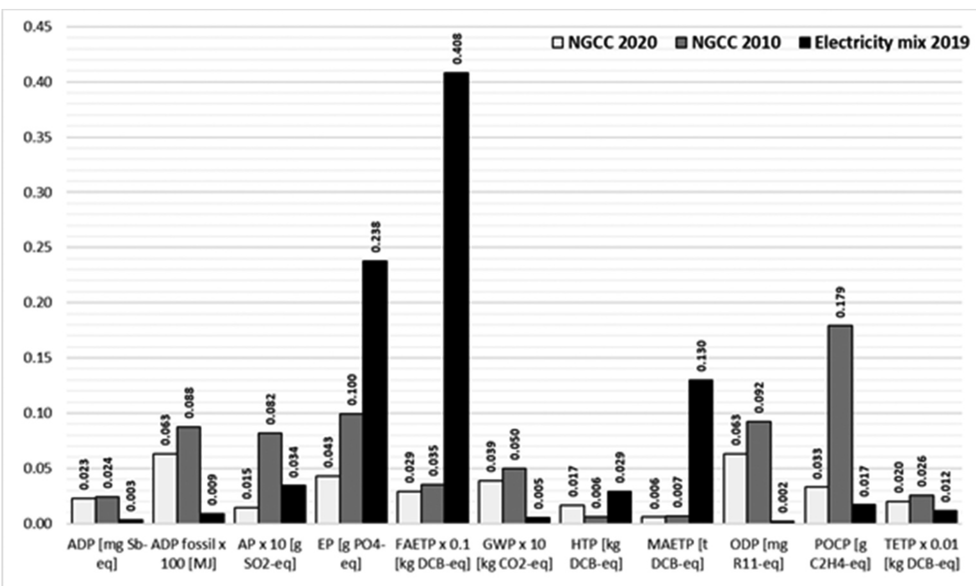

Figure 13. Comparison of the results with an NGCC plant and electricity mix in Turkey. [Some impacts have been scaled to fit.].

gas power plants operated by private sectors in Turkey. Environmental sustainability evaluation of changes in the gas market and technological development of NGCC plants in Turkey is critical in helping to select the most sustainable options for the country's future energy sector.

This study has presented the results of the LCA of one of the best available gas combined cycle power plants in Turkey. In total eleven impacts have been estimated and the main contributors to these impacts have been identified. For the validation, the obtained results are compared to the values reported in the literature for the NGCC plants. The influence of natural gas extraction and processing in different countries and different overall thermal efficiencies on the results are explored within the sensitivity analysis. The results are also compared with a typical natural gas power plant in Turkey and the electricity grid mix in 2019 to evaluate the differences.

The results of this paper help identify the environmental sustainability of electricity generation from NGCC plant. The findings indicate that GWP is estimated at 388 g CO_2 eq./kWh. The major contributors to GWP include CO_2 emissions (97.1%), CH_4 (1.9%) and N_2O (1.1%) emissions to air. Electricity generation from gas plant is responsible for an estimated at 0.15 g SO_2-eq./kWh. The EP of 0.04 g PO_4-eq. per kWh. The environmental impact assessment results from this study are compared with the values from the literature for gas-fired electricity generation technologies and show a good agreement.

In terms of life cycle stages, the electricity plant operation stage is the main hotspot (36–89%) for AP, EP, GWP, HTP, and POCP. Construction of power plants also plays a major role (30–62%) for ADP, TETP, FAETP, and MAETP. Natural gas pipeline transportation is an important hotspot for ODP. Extraction of fuels is significant for ADP fossil (94%) of natural gas power plants. Finally, plant decommissioning typically has a negligible contribution.

A sensitivity analysis has also been carried out to test the assumption related to the origin of natural gas extraction made in the study. Another sensitivity analysis has identified changes in the overall thermal efficiency of the plant. Natural gas extraction and processing in different countries have been selected due to the assumption that has been made. The extraction and processing of gas in the Netherlands and Germany and the results are compared to the gas supplied from Norway. Gas extraction and processing in Germany affects significantly only EP, increasing the impact by nearly 60%. And ADP is increased by 40% when natural gas extracted in the Netherlands. The effect of this parameter is small across the other environmental impacts. Efficiency was selected for a further sensitivity analysis due to its significant impact on environmental impacts. The results were compared with the two different plants with an overall efficiency of 61% and 64% and the power plant with an efficiency of 59%. This analysis shows that large environmental gains would be achieved by an increase in plant efficiency.

The gas-based electricity production system described in this paper provides significant improvements in all life cycle environmental impacts compared to a typical natural gas electricity generation system in Turkey. The biggest change was observed for AP (82.1%) while ADP was affected the least (4.9%). The lower environmental impacts in the present study are due to the different gas composition, relatively high efficiency assumed as well as the proximity of Turkey to Azerbaijan which reduces transport distances. Furthermore, increasing the contribution of natural gas in the electricity generation mix would reduce only EP, FAETP, HTP, and MAETP. This is mainly due to the high share of renewable energy sources such as hydropower and wind power in the country's electricity mix.

Although modeled NGCC is currently one of the best technologies available in Turkey, any increase in efficiency will reduce the environmental impact of the resulting life cycle. Developing technologies designed to increase efficiency is one of the most effective strategies for minimizing the impact on the environment from electricity generation. Technological improvements are important, but they are not enough on their own, so they must be combined with decreases in the electricity demand. Reducing demand should be promoted through policies and education programs, involving both energy generators and the public.

The environmental impacts of electricity from one of the best available NGCC plants have been discussed in this paper. This is a description of the entire gas plant life cycle, which will help to make decisions. The findings of this study will be useful for the future energy sector, as natural gas is one of the electricity-producing plants promoted in Turkey. These findings will also be used in further research to compare them with other energy technologies.

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

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