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Life cycle assessment of electricity generation in two thermal power plants: environmental impacts and carbon footprint

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Abstract

This research was conducted to assess the environmental impacts and carbon footprint of the electricity production of the Zahedan gas power plant (ZGPP), and the Iranshahr combined cycle power plant (ICPP) using life cycle assessment and the intergovernmental panel on climate change. Data was collected annually for a functional unit of 1 kWh of electricity generation. The analysis of the impacts index at the midpoint level showed that the primary environmental impact from the electricity production included the consequences of human carcinogenic toxicity with 58% for ZGPP and 52% for ICPP. Damage to human health was the worst consequence in the endpoint level index with 86% for the two power plants. Based on the outcomes of the sensitivity analysis, natural gas was the most important factor contributing to the impacts. Also, the analysis of IPCC results showed that the consumption of fossil fuels that have the largest share in global temperature potential were 97% and 63% in ZGPP, and ICPP, respectively. The highest amount of CO_2 emissions per 1 kWh of electricity produced were obtained at the rates of 0.971 and 0.636 kg for ZGPP, and ICPP, respectively. According to the results, although the environmental consequences of the combined cycle power plant were less compared to the gas power plant, but still entails high level of liquid fuel usage in the combined cycle power plant. Therefore, it is suggested to reduce the use of this type of fuel in this power plant in order to reduce the environmental impact.

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Introduction

Electricity is one of the most widely used and high-level energy carriers, which also plays a significant role in promoting economic growth in the development process. It also increases the quality of human life through an increase in the use of related products and services (Wang, 2020). The ever-increasing demand for electricity consumption has caused the increase of electricity production plants with greater acceleration in recent years; but electricity production is dependent on other energy sources, especially fossil fuels. On the other hand, fossil fuels are an important source of greenhouse gas emissions and the main cause of global warming. The increase in electricity production can be associated with more use of fossil fuels, followed by an increase in the global concentration of greenhouse gases (Saint Akadiri et al., 2020). More than 60% of the environmental effects related to this industry are caused by the electricity generation sector. In contrast, electricity transmission sector has 70 to 90% less impact than the electricity generation sector (Orfanos et al., 2019). The percentage of environmental consequences of electricity production may differ among countries depending on the type of scenario used in its production. Using the renewable energy scenario may reduce the global environmental effects caused by fossil fuel energy consumption and greenhouse gas emissions, but it can increase local environmental consequences such as human toxicity. Also, a change in the type and amount of fossil fuel consumed can cause the release of different amounts of carbon. For example, changing the fuel from coal to natural gas can reduce carbon dioxide emissions in the electricity generation sector by 22%. In electricity production, regardless of the forms or sources of energy used, there are always potential impacts on the environment (Quek et al., 2019). Therefore, it is necessary to evaluate the environmental effects of power plants.

The life cycle assessment (LCA) method is the most comprehensive and extensive method to evaluate the environmental effects of systems and products, which is designed step by step based on various standards, including ISO 14040 and ISO 14044 (Yang et al., 2018). The basic concept of LCA is to identify and quantify the energy and materials used to produce a product and by-products that are discarded or released into the environment. The first step in the field of reducing the adverse environmental consequences of greenhouse gas emissions during the electricity production process is to estimate the exact amount of these emissions, which is termed "carbon footprint" in scientific terminology. It is possible to identify the most important processes with the highest amount of greenhouse gas release and to implement coherent planning to reduce the amount of these emissions (Odeh, 2008; Hosseini-Fashami et al., 2019). In this field, various methods have been presented, among which the method of the International Panel on Climate Change (IPCC) is one of the most reliable and common methods for determining the carbon footprint resulting from industrial activities. The IPCC method is developed based on international standards ISO 14040 and ISO 14044 and uses a series of legislations, processes, and calculation methods to determine the carbon footprint (Technical Committee ISO, 2006).

So far, various studies have been conducted in the field of evaluating the environmental consequences of the carbon footprint of power plants, among which we can mention the research of Hosseini-Fashami et al. (2019) who focused on electricity from solar power plants in Iran. Their results showed that the production of electricity from solar power plants causes a significant reduction in greenhouse gas emissions and can be used as a suitable solution to reduce the carbon footprint in Iran. The evaluation of the carbon footprint in steam and combined cycle power plants and its comparison with the coal-burning power plants has been carried out in a case-by-case basis in South Khorasan Province of Iran (Moosavian et al., 2022). They acknowledged that the carbon footprint of the coal-burning power plant per kilowatt-hour of electricity production is higher than other fossil power plants. In another study conducted by Dalir et al. (2018) a comprehensive model was presented for calculating the carbon footprint of fossil power plants in Iran. They calculated different effects on the emission of greenhouse gases as well as the amount of electricity production in all types of power plants, the amount of carbon released per kilowatt-hour of energy production, and compared the power plants from this point of view. In this regard, Ozcan (2016) investigated the emissions of different fuels used in power plants in Turkey. The results of this research, which focused only on the emission of greenhouse gases resulting from combustion processes, showed that reducing the emission of greenhouse gases resulting from fossil fuels can be achieved by replacing fossil fuels with renewable sources of wind energy. On the other hand, Malode et al. (2022) conducted a systematic review of LCA studies conducted on coal-fired power plants in India, emission reduction strategies, and transmission and distribution. In Iran, more than 91% of electricity is produced through thermal power plants that use diesel fuel, natural gas, and fuel oil (Jorli et al., 2017). Since there is no comprehensive information about the environmental impacts of Zahedan gas power plants (ZGPP), and Iranshahr combined cycle power plant (ICPP), which can be a challenging issue, the aim of this study was life cycle assessment of these power plants using the LCA method to determine and compare their carbon footprints. The results of this research can provide solutions to reduce possible negative effects in addition to clarifying their environmental consequences.

Materials and methods

Studied power plants

The studied power plants are located in the southeast of Iran, in the Sistan and Baluchistan Province, in the cities of Zahedan and Iranshahr. Table 1 shows the general characteristics of the studied power plants.

Table 1. General characteristics of the studied power plants

Power plant	Geographical location	Number of units	Capacity of units (MW)	Launch year	A (he)	Site weather information			Manufacturer company
						h%	P(kPa)	T(℃)	
ICPP	27° 13′ 32″ N, 60° 29′ 51″ E	3	310	2013-2014	50	25.6	93	38	Tuga, Mago, Pars generator, Siemens
ZGPP	29° 28′ 38.99″ N, 60° 48′ 21.37″ E	9	267	1986-2007	48	35	85	30	Hitachi, Broun, AEG

T: Temperature; **P**: Pressure; **h**: humidity; **A**: Area

Goal and scope

LCA includes the stages of goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (Zuffi et al., 2022). In the goal and scope definition stage, according to ISO 14040 and ISO 14041, the execution process, the goal and scope, the functional unit, and the resource flow are defined. The LCI stage includes the collection and, organization of all relevant data, such as the amount of input materials, production waste, released compounds and energy consumption. The level of accuracy and details of the collected data will be reflected in other LCA processes (Kazemi et al., 2018). Determining the boundaries of the study and the boundary of the system are expressed according to the purpose of the study and also the determination of the operational unit for the registration of the operational unit (Tabesh et al., 2019). In this research, the system boundaries were ZGPP, ICPP and ISPP. The boundary was the gate-to-gate system, which includes only the stage of power generation in power plants. The functional unit was 1 kWh of electricity produced in these power plants.

Life cycle impact assessment analysis

In the LCIA stage, the assessment of potential environmental effects and potential health effects is considered (Liu et al., 2020). This stage includes preparing a list of all input data to the system to quantify the necessary resources in the system, for product production and all outputs (emissions) to the environment based on what is determined in the research objective (Abyar and Nowrouzi, 2020). The information needed in this research was prepared by referring to the database of each power plant and Iran's energy balance sheet (Detailed Statistics of Iran Power Industry, 2021) for one year. The list of lists collected in this research is given in Table 2.

Environmental impacts assessment

Finally, there is the life cycle interpretation stage, which is a systematic technique for identifying, quantifying, checking, and evaluating the information obtained from LCI and LCIA results and establishing effective communication between them (Liu et al., 2020). In research related to life cycle assessment, different methods are used for impact assessment or LCIA. In this research, SimaPro (version 9.3) software, the ReCePi method, and the ecoinvent database (version 3.4) were used. The ReCePi method presents the results at the midpoint and endpoint levels. The midpoint level index shows the consequences of a product or process in 18 categories, including terrestrial acidification, stratospheric ozone depletion, global warming, fresh water toxicity, terrestrial ecosystems toxicity, human carcinogenic toxicity, and etc. While the endpoint level index reveals the environmental consequences in three higher cumulative levels, including destructive impacts on human health, ecosystems, and resource degradation (Hootmirdoosti et al., 2024).

Table 2. Inventory used in the LCA analysis of the electricity generation power plants systems (functional unit: 1 kWh of electricity production)

Amount per 1 kWh electricity produced per year		**Unit**	**LCA inventory**		
ZGPP	**ICPP**				
0.027	0.020	m^3	Tap water	Water consumed	Input parameters
0.037	0.031		Well water		
0.417	0.304	m^3	Natural gas	Fuel consumed	
0.008	-	kg	Diesel fuel		
-	0.011	l	Oil fuel		
0.014	0.008	kWh	Electricity		Energy
837.844	540.076	g/m^3	CO_2	Output to air	
0.017	0.012		CH_4		
2.224	2.797		NO_x		
0.309	0.447		SO_2		
0114	0.086		SPM[1]		
228.503	147.293		C[2]		
0.037	0.02	m^3	Wastewater	Output to water	

[1] Suspended particulate matter

[2] Carbon

Sensitivity analysis

Sensitivity analysis is a management strategy that is used to prioritize operating parameters for control and decision-making (Hootmirdoosti et al., 2024). In this research, natural gas was identified as the most important parameter. Therefore, to assess the effects of changes, a variation of -10% in the value of this parameter was implemented to evaluate its impact on other parameters.

Carbon footprint assessment

The analysis of the relationship between the calculated consequences and the processes of power generation plants, as well as the determination of the most important processes and materials with the greatest impact on the carbon footprint, and the amount of greenhouse gas emissions of power generation plants was carried out using the IPCC method.

Results

Midpoint impact assessment and sensitivity analysis

The classification of the environmental impacts of 1 kWh of electricity produced in ICPP and ZGPP which has been investigated using the ReCiPi Midpoint H (2016) method, is given in Tables 3 and 4, respectively.

Based on the outcomes of the sensitivity analysis, the most important factor affecting the results was the amount of natural gas, which was reduced by 10% from the initial value, and the result of the midpoint level index was re-checked. The results are given in Tables 3 and 4. For this purpose, by reducing the value of this parameter by 10%, the scope of reducing the consequences in the ICPP was between 0.07-9.67%. The greatest reduction impact of natural gas was also related to the fossil resource scarcity (9.67%), followed by the mineral resources' scarcity (9.40%). In the case of ZGPP, with a 10% reduction in natural gas consumption, the range of environmental consequences ranged from 0.05-9.66%. The largest reduction was related to the fossil resource scarcity (9.66%), and the next rank was the result of the mineral resources' scarcity (9.18%).

Table 3. Results of environmental impacts of 1 Kwh of electricity produced in ICPP and sensitivity analysis

Impact category	Unit	Characterization	Normalization	Sensitivity analysis Natural gas
Global warming	kg CO2 eq	0.708961	1.2054	2.11%
Fossil resource scarcity	kg oil eq	0.294812	0.000301	9.67%
Terrestrial ecotoxicity	kg 1,4-DCB	0.136816	0.0672	6.89%
Human non-carcinogenic toxicity	kg 1,4-DCB	0.092801	0.0584	2.39%
Human carcinogenic toxicity	kg 1,4-DCB	0.012353	0.001199	9.35%
Terrestrial acidification	kg SO2 eq	0.005368	0.0242	0.51%
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.003291	0.000185	1.34%
Ozone formation, Human health	kg NOx eq	0.003173	0.000154	1.03%
Land use	m2a crop eq	0.002894	0.00000046	8.72%
Marine ecotoxicity	kg 1,4-DCB	0.002667	0.000061	6.77%
Freshwater ecotoxicity	kg 1,4-DCB	0.001898	0.000075	6.71%
Ionizing radiation	kBq Co-60 eq	0.001242	0.0000025	6.30%
Fine particulate matter formation	kg PM2.5 eq	0.000565	0.000022	1.87%
Mineral resource scarcity	kg Cu eq	0.000552	4.5×10^{-9}	9.40%
Marine eutrophication	kg N eq	0.000111	0.000024	0.07%
Freshwater eutrophication	kg P eq	5.67E-05	0.000087	1.64%
Stratospheric ozone depletion	kg CFC11 eq	5.98E-08	9.9×10^{-7}	3.11%
Water consumption	m^3	0.0000001	0.0000002	0.08%

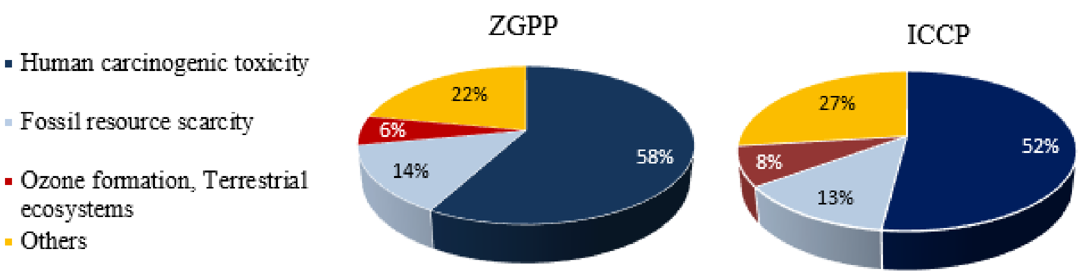


Figure 1. Distribution diagram of the most important impacts of electricity produced based on the midpoint level index in ICPP and ZGPP

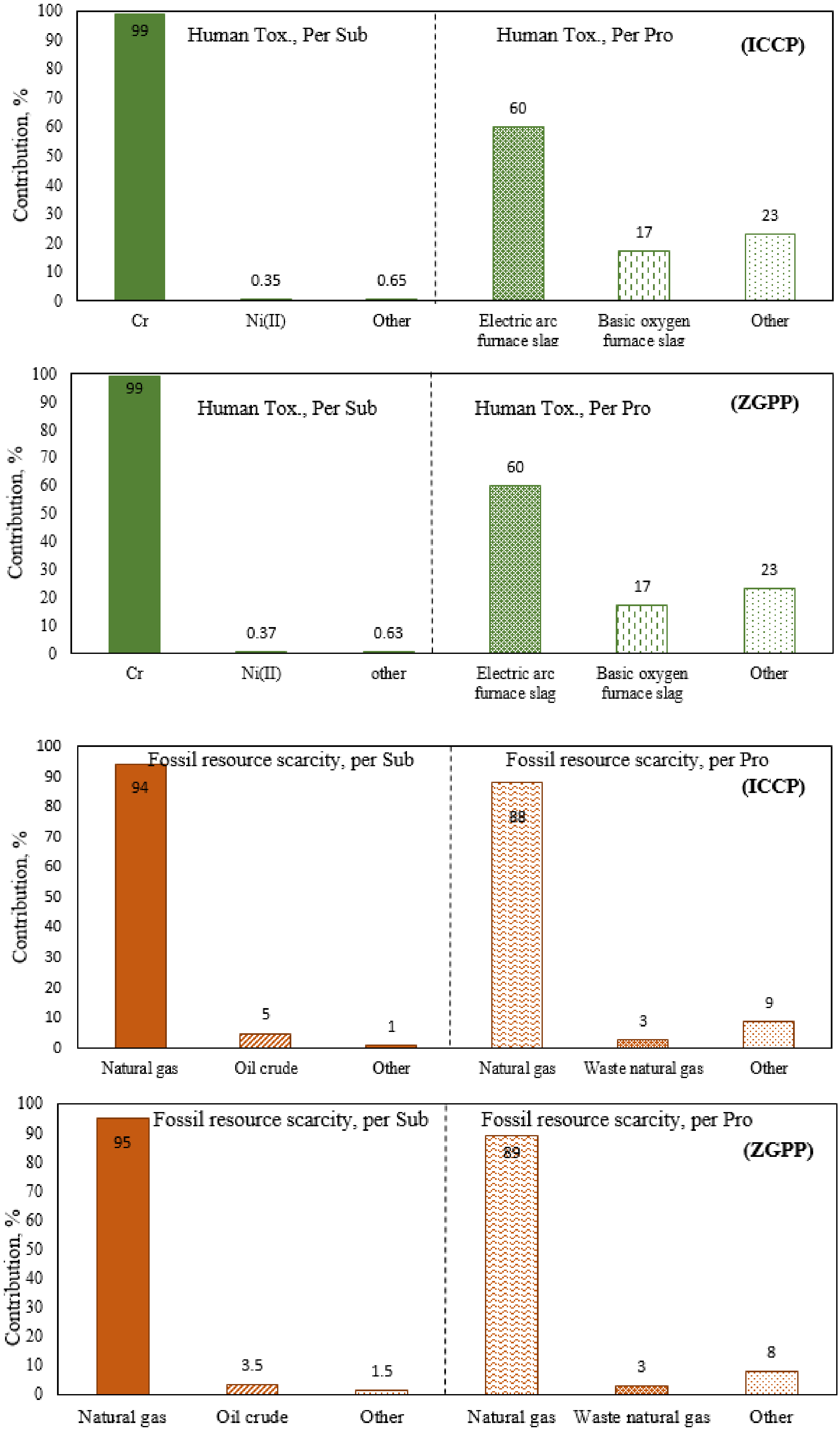
Table 4. Results of environmental impacts of 1 Kwh of electricity produced in ZGPP and sensitivity analysis

Impact category	Unit	Characterization	Normalization	Sensitivity analysis Natural gas
Global warming	kg CO2 eq	1.072322	0.000134	1.89%
Fossil resource scarcity	kg oil eq	0.399837	0.000408	9.66%
Terrestrial ecotoxicity	kg 1,4-DCB	0.202146	0.000013	632%
Human non-carcinogenic toxicity	kg 1,4-DCB	0.159251	5.1×10^{-6}	1.88%
Human carcinogenic toxicity	kg 1,4-DCB	0.017138	0.00166	9.13%
Terrestrial acidification	kg SO2 eq	0.004413	0.000138	1.56%
Marine ecotoxicity	kg 1,4-DCB	0.003969	0.000091	6.17%
Land use	m2a crop eq	0.003939	6.3×10^{-7}	8.69%
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.002898	0.000136	2.07%
Freshwater ecotoxicity	kg 1,4-DCB	0.002842	0.000113	5.38%
Ozone formation, Human health	kg NOx eq	0.002738	0.000133	1.63%
Ionizing radiation	kBq Co-60 eq	0.001843	0.0000038	5.75%
Mineral resource scarcity	kg Cu eq	0.000765	6.3×10^{-9}	9.18%
Fine particulate matter formation	kg PM2.5 eq	0.000513	0.000020	2.79%
Marine eutrophication	kg N eq	0.000204	0.0000444	0.05%
Freshwater eutrophication	kg P eq	1E-04	0.000154	1.25%
Stratospheric ozone depletion	kg CFC11 eq	1E-07	0.0000016	2.51%
Water consumption	m^3	0.0000001	0.0000019	0.09%

The most important consequences of the power generation system in the studied power plants based on the normalized test of the midpoint level index are presented in Figure 1.

Based on the results, the consequence of human carcinogenic toxicity ranks first in the category of environmental impacts in the midpoint level index in the present research.

As shown in Figure 2, one of the most important factors involved in human carcinogenic toxicity in the current study was Cr (VI) (97-99% in the studied power plants), followed by nickel with a negligible amount (0.35%-1%). Also, electric arc furnace slag processes (in the range of 57-60%) and oxygen furnace primary slag (15-17%) were among the effective processes in causing human carcinogenic toxicity impacts in the studied power plants. As shown in Figure 2, in two studied power plants, the greatest impact on the result of the fossil resource scarcity was related to natural gas and crude oil. So, in the case of the ICPP, natural gas (94%) and crude oil (5%) and the most important processes creating it were also natural gas (88%) and natural gas waste (3%). In the ZGPP, with the highest consumption of natural gas, (95%), and crude oil (3.5%), they were among the most important materials in the process of this impact. The most important processes were natural gas use with 89% and natural gas waste with 3%. Also, the third most important environmental consequence was the ozone formation in the terrestrial ecosystem. The most important materials of this process include nitrogen oxides (NO_x) and non-methane hydrocarbons (NOVOC). So, the amounts of NO_x were 85% and 77%, and NOVOC levels, were 9% and 14% in ICPP and ZGPP, respectively.


Human Tox., Per Sub
Human Tox., Per Pro
(ICCP)
Contribution, %
99
0.35
0.65
60
17
23
Cr
Ni(II)
Other
Electric arc furnace slag
Basic oxygen furnace slag
Other
Human Tox., Per Sub
Human Tox., Per Pro
(ZGPP)
Contribution, %
99
0.37
0.63
60
17
23
Cr
Ni(II)
other
Electric arc furnace slag
Basic oxygen furnace slag
Other
Fossil resource scarcity, per Sub
Fossil resource scarcity, per Pro
(ICCP)
Contribution, %
94
5
1
88
3
9
Natural gas
Oil crude
Other
Natural gas
Waste natural gas
Other
Fossil resource scarcity, per Sub
Fossil resource scarcity, per Pro
(ZGPP)
Contribution, %
95
3.5
1.5
89
3
8
Natural gas
Oil crude
Other
Natural gas
Waste natural gas
Other

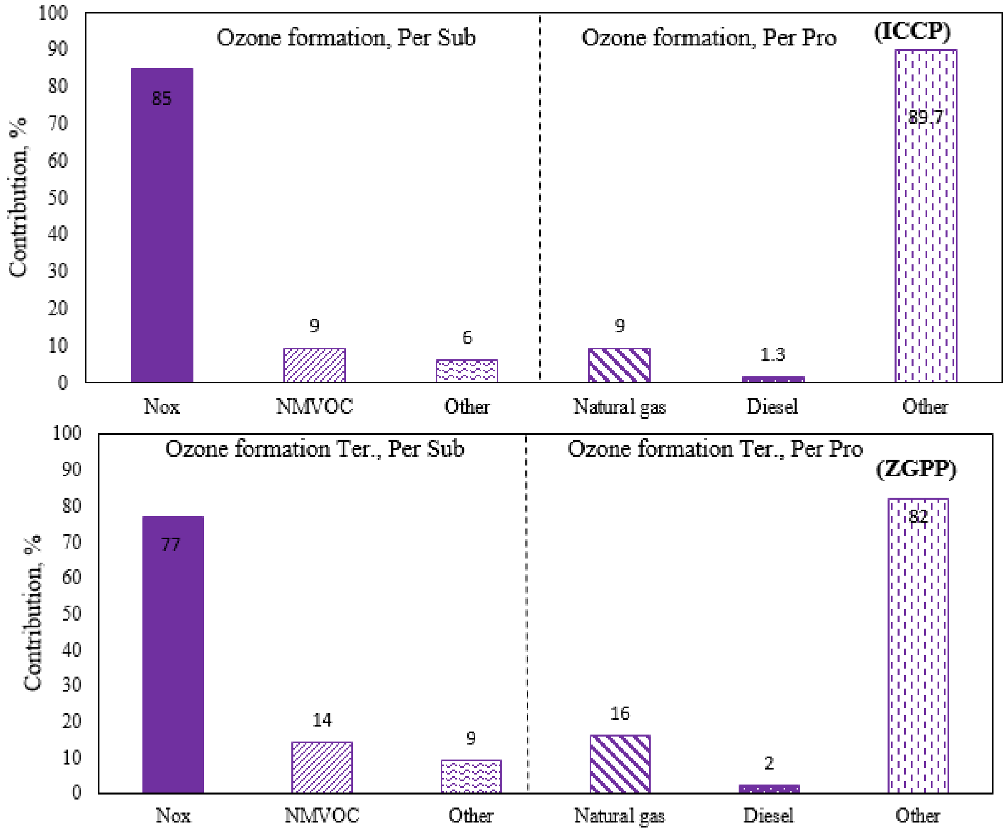


Figure 2. ReCiPe midpoint impact for the human carcinogen toxicity, fossil resource scarcity and ozone formation in the terrestrial ecosystem categories per substance (per sub.) and per process (per proc.), for the studied power plants (ICPP and ZGPP)

Endpoint level index results

According to Figure 3, the results of the endpoint level method show environmental effects in three categories, damage to human health (86% for two power plants), damage to ecosystem health (ICPP: 8% and ZGPP: 9%), and damage to resources (ICPP 6% and ZGPP: 5%). As shown in Fig. 4, CO_2 (53%) and NO_x (21%) were important substances in ICCP, and the processes affecting this impact included natural gas (11%) and natural gas waste (3%). Also, In the ZGPP, CO_2 (67%) and NO_x (14%) were found as important substances, and the processes affecting this impact include natural gas (12%) and natural gas waste (3%).

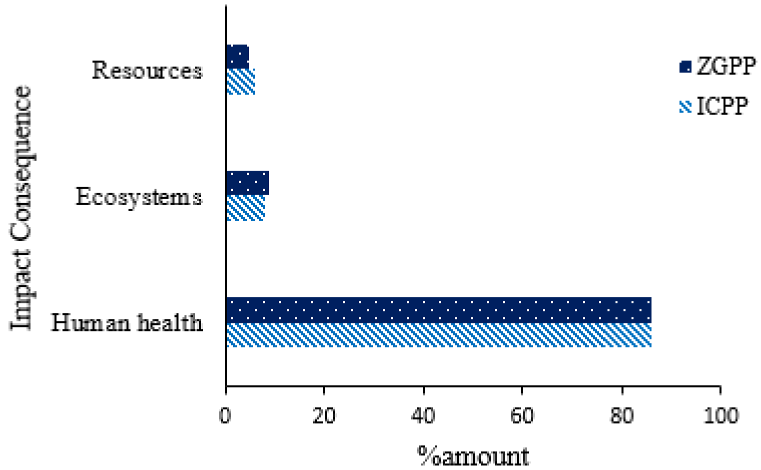
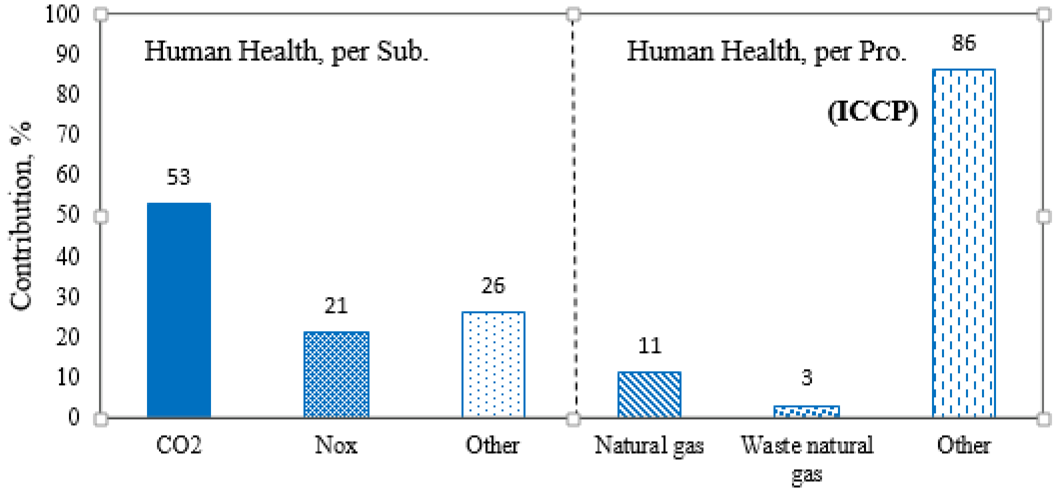


Figure 3. Percentage distribution of impacts in the endpoint level index



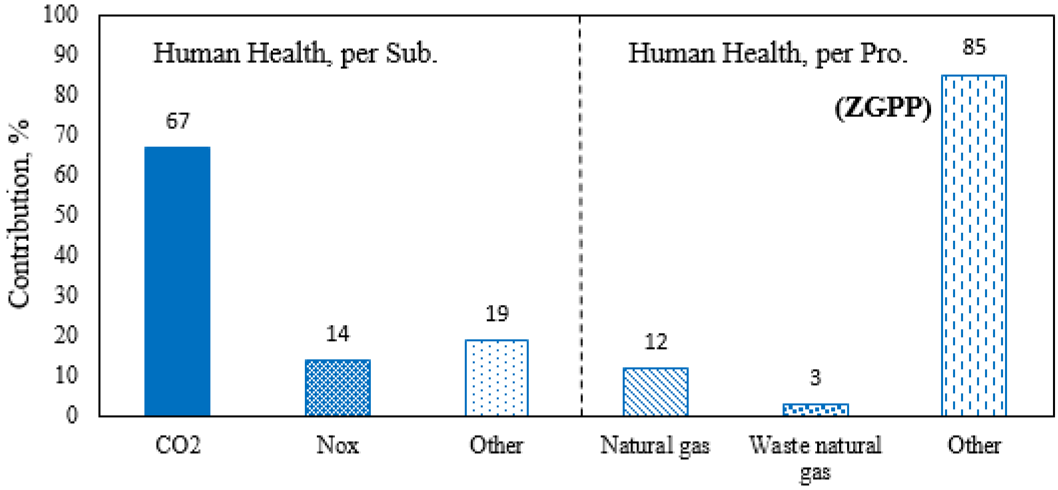


Figure 4. Contributed substances and process for the human health, categories at the endpoint level analysis for the ICPP and ZGPP

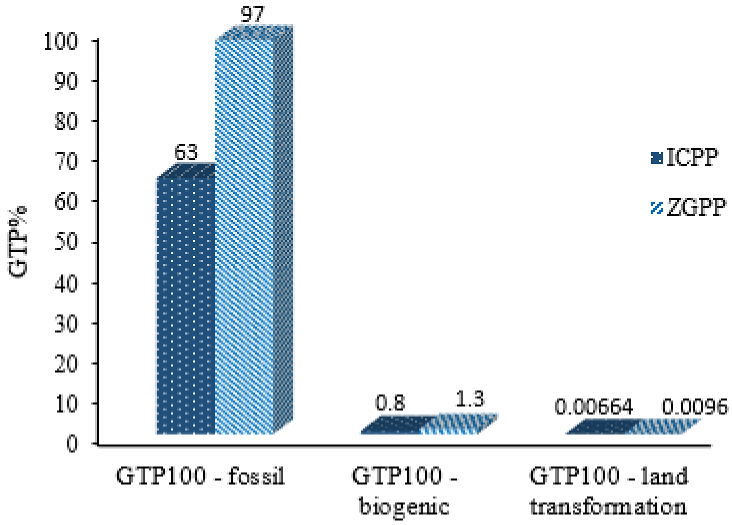


Figure 5. The IPCC results in the studied power plants

The results of the IPCC method

The results of the IPCC analysis to check the global warming potential (GWP) in kg CO_2-eq to determine the global warming potential in the studied power plants are shown in Figure 5. In order to perform this analysis, the amount of carbon dioxide emitted during 100 years was considered. In this research, the highest share in global temperature potential (GTP) was obtained in ZGPP (97%) and combined cycle power plant (63%), respectively.

Discussion

The results showed that in both power plants studied, the most important environmental impact in the midpoint level index was the human carcinogenic toxicity, with 58% and 52% for ZGPP and ICPP, respectively. The second most important consequence was the fossil resource scarcity amounting to 14% and 13%, for the ZGPP and ICPP, respectively. As for the consequence of ozone formation, terrestrial ecosystem was in the third category of the most important environmental impacts in the ICPP and ZGPP with 8% and 6%, respectively. At times, especially in the winter season, with the priority of city gas supply, the consumption of liquid fuels increased in power plants, and as a result, the amount of pollution in power plants increased. As mentioned in the research results of Malode et al. (2023), power plants have destructive impacts on the health of the environment and humans. The research of Agrawal et al. (2014) regarding the life cycle assessment of the thermal power plant of the combined cycle type identified the impacts on human health including carcinogenesis, which is similar to the findings of the present research. Naserirad et al. (2024) that evaluated the health impacts of the thermal power plant, acknowledged that the greatest impact on human health are caused by air pollutants, including breathing problems, and then the pollutants in the soil caused by the entry of the treated effluent of the power plant. On the other hand, the results of the Yazd combined cycle power plant evaluation using the LCA method showed that this power plant has wide environmental consequences, and the highest categories of environmental impacts of electricity production in this power plant were related to the toxicity of ground water and fossil resource scarcity. Acidification and global warming were also at the next level of importance (Rezaeerad et al., 2018). In their study, like the current research, the fossil resource scarcity was in the second category of environmental consequences. However, in their life cycle assessment of a combined cycle power plant in southwestern Iran, Motahari et al. (2023) found that global warming potential had the greatest impact at the midpoint level, accounting for 99% of the total consequence. This was followed by land use, fossil resource scarcity, and several other impact categories, including climate change, freshwater and terrestrial ecotoxicity, human toxicity, ozone formation (human health), terrestrial acidification, and freshwater eutrophication.

Comparing the results at the midpoint level index in both power plants were similar in terms of categories, but in terms of values, the combined cycle power plant was lower than the gas power plant. This can be due to the difference in the type of systems in their electricity generation process. In the combined cycle power plant, there is less environmental pollution due to higher thermal efficiency and higher efficiency compared to the gas power plant. Although in ICPP, the consumption of gas fuel per kilowatt hour of electricity production is less compared to ZGPP, when liquid fuels are used, their environmental pollution will be more.

After identifying the most important impacts categorized as a result of power plant systems in this study, SimaPro software based on the available data, performs two internal analyses called Per Substance and Per Process to identify the materials and processes that affect those types of impacts.

In current study, one of the most important factors involved in human carcinogenic toxicity was Cr (VI). Also, electric arc furnace slag processes and oxygen furnace primary slag were among the effective processes in causing human carcinogenic toxicity impacts. The greatest impact on the fossil resource scarcity impact was related to natural gas and crude oil. In fact, the combustion of fossil fuels is an important factor for generating the energy needed to rotate the turbine, and the chimney of power plants is also the most important source of carbon dioxide and other greenhouse gases into the air (Karmaker et al., 2020). The main emission of greenhouse gases in power plants with gas fuel is from gas processing, venting wells, operation of pipelines (mainly compressors) and leakage of transportation systems. Due to the fact that these factors are different in different countries, the amount of greenhouse gas emission will also be variable. Similarly, the direct emission of greenhouse gases from fossil fuel power plants depends on thermal efficiency, utilization method, type of technology and carbon content of the fuel (Weisser, 2007). The third most important environmental consequence is the ozone formation in the terrestrial ecosystem. The most important processes causing this result in both power plants were natural gas and diesel, which in the ICPP were 85% and 9% respectively, and in the ZGPP were 16% and 2%. Panbechi et al. (2024) stated that non-methane hydrocarbons can play an important role in the formation of ozone in the air. Studies have shown that the type of fuel can affect the amount of harmful NOx emissions in thermal power plants. Especially when there is no high temperature and proper oxygen supply, NO_x emissions increase at high engine loads.

The endpoint approach evaluates the impacts of processes and materials at three levels: resource consumption, human health, and ecosystems. Transforming the factors and describing the indicators in three limited levels facilitates the interpretation of the results. The endpoint level method and the midpoint level method use completely different methods to determine the environmental impacts. So that, the endpoint level method describes the impact assessment in different parts of protection and it is a damage-oriented approach, but the midpoint level method examines the cause and impacts of released substances (Abyar et al., 2020). The analysis of the endpoint impacts showed that the human health consequence is the most important endpoint outcome in this research. But in life-cycle assessment of a combined-cycle power plant for electricity generation that studied by Motahari et al. (2023), the highest impact was obtained in the endpoint level index regarding damage to resources (53%), followed by human health (43%) and ecosystem health (4%). Some studies have shown that fluctuations in the type of fuel can be effective in the type of gas emissions of thermal power plants (Issakhov and Mashenkova, 2019). Due to the reasons that were also mentioned about the impacts at the midpoint level, the same values of the consequences of the effects on human health of the two power plants may be due to the simultaneous use of more liquid fossil fuels in the combined cycle power plant.

According to the results of the IPCC analysis, the highest share in global temperature potential (GTP) was obtained in ZGPP (97%) and combined cycle power plant (63%), respectively. The results of Mousavi Reineh et al. (2019) are similar to our findings that, among the traditional methods of generating electricity, the combined cycle power plant has a lower cost to the environment. As shown in Fig. 6, the highest amount of CO_2 released per kWh of electricity was 0.971 kg for ZGPP and 0.636 kg for ICPP, respectively. These values are from the average emission factor of gas emissions from fossil fuel power plants in the country (taking into account the production share of hydroelectric power plants and wind turbines) for CO_2 gas at the rate of 0.640 kg/kWh (Nazari et al., 2010), for the power plant studied ZGPP and ISPP were higher than it and for the ICPP was low. Also, Motahari et al. (2023) also emphasized that more than 99% of the consequences of global warming and climate change are caused by CO_2 emissions, less than 0.5% are caused by N_2O emissions, and less than 0.5% are the result of CH_4 emissions from combustion fossil fuels. It is the same in terms of ranking as in the present study. In their study, the amount of carbon emission was estimated at 0.558 kg/kWh. This may be due to the lower efficiency of the studied power plant compared to previous studies. Similarly, in the study of Moosavian et al. (2022), the carbon footprint of the Tabas coal-fired power plant was estimated to be 968 g/kWh, which was higher than the ICPP and ISPP studied in this research and less than the ZGPP. They stated that the average carbon footprint in the combined cycle and steam power plant of South Khorasan province is 0.579 kg/kWh. Song et al. (2018) reported the average amount of greenhouse gas emissions of the entire local power grid in Maccao as 0.69 kg CO_2 per kWh and acknowledged that this amount is significantly lower than many neighboring countries and regions such as mainland in China, Taiwan and Japan.

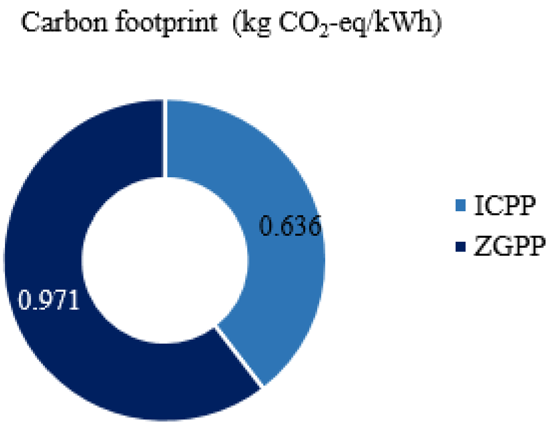


Figure 6. The comparison of CO_2 emission for 1kWh of electricity produced in the studied power plants

The amount of carbon dioxide production and its concentration increase in the atmosphere, as one of the main greenhouse gases and the most important component of the carbon cycle, has been a special concern in recent years. Carbon dioxide gas is mostly caused by the consumption of fossil fuels in various applications. Compared to fossil fuel-based power plants, renewable energy sources are effective in reducing greenhouse gas emissions.

Conclusion

According to the results of this research, although the combined cycle power plant had lower environmental consequences than the gas power plant, its consumption of liquid fossil fuels like fuel oil was high. Therefore, it is suggested that the use of this fuel be reduced to mitigate environmental impacts. Furthermore, it is highly recommended to prioritize renewable energy sources over fossil fuels and to increase the number of new renewable energy power plants. With about 70% of its land classified as arid or semi-arid, Iran has significant potential for renewable energy, particularly solar power. However, solar energy currently accounts for less than 1% of its energy use (Khaki et al., 2023). Iran's geographical location provides an average of over 300 sunny days per year, creating a favourable potential for solar electricity production (Shorabeh et al., 2022). Additionally, Iran is situated on a wind belt, yet its installed wind capacity is only about 300 MW—a very small share compared to the global capacity of 651 GW in 2021 (Mirnezami and Mohseni Cheraghlou, 2022). Some regions, especially in the east and southeast, have a wind energy potential ranging from 900 to 1500 W/m², representing suitable sites for development with low initial costs and minimal greenhouse gas emissions. Beyond reducing reliance on fossil fuels and lowering the carbon footprint, adopting renewable energy will also facilitate sustainable economic and social development. The analysis also emphasizes the significant effects of toxicity potential on human health, highlighting the need for further research into potential toxic exposures. A comprehensive review and understanding of these toxicity risks can enable the development of effective strategies to protect human health and preserve the environment.

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The work was unfunded.

Conflict of interest
The authors declare that they have no conflict of interest.

Author Contribution
All authors contributed to the study conception and design. Analysis; methodology: **MN**; Analysis; investigation; methodology; software; supervision; writing original draft: **NO**; Investigation; methodology; software: **FE**. All authors read and approved the final manuscript.

Availability of data and materials
The datasets used during the current study are available from the corresponding author on reasonable request.

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