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Original Article

Life-Cycle Assessment of a Combined-Cycle Power Plant for Electricity Generation

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Abstract

Background: Life-cycle assessment (LCA) is a comprehensive method used to evaluate the environmental effects throughout the entire lifespan (from creation to disposal) of a product or process. In this study, we conducted an analysis of the environmental impact associated with generating 1 kilowatt-hour of electricity in a combined-cycle power plant located in the southwest region of Iran.

Methods: An LCA following ISO 14044 standards was conducted via the ReCiPe method evaluating 10 impact categories at the midpoint level, and covering the entire life cycle. This method was selected for its comprehensive modeling of potential impacts from numerous chemicals and its practicality at both midpoint and endpoint levels.

Results: The study found that resource availability (RA) has the highest impact at 53% in endpoint categories, mainly due to natural land transformation (NLT) and fuel depletion (FD). Human health (HH) contributes 43%, while ecosystem diversity (ED) has a minor 4% role. In midpoint categories, over 99% of global warming potential (GWP) and climate change (CC) are from CO_2 emissions due to fossil fuel combustion.

Conclusion: Midpoint analysis identified NLT, FD, CC, freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication, and water depletion as the most impacted categories by the power plant. However, at the endpoint level, RA, HH, and ED were the primary concerns. Fossil fuel use significantly shaped the environmental impact throughout the power plant's life cycle.

Keywords: Life cycle assessment, Combined cycle power plant, Energy generation, Environmental impacts categories, ReCipe method

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Introduction

Electricity holds a significant role due to its provision of energy to various economic sectors and its impact on the social welfare index.[1] Presently, electricity generation heavily relies on fossil fuels, a practice that carries environmental consequences, notably contributing to climate change (CC) through the emission of greenhouse gases.[2] Notably, the Annual Greenhouse Gas Index (AGGI), employed by the National Oceanic and Atmospheric Administration (NOAA) to monitor global warming caused by gas emissions, witnessed a substantial 40% increase during the period from 1990 to 2016. This increase is predominantly associated with CO_2 emissions,[3] with electricity production activities being responsible for approximately 40% of global carbon emissions.[4] In Iran, the majority of the electricity demand, approximately 85%, is fulfilled by thermal power plants. Analyzing the five-year electricity generation trend in Iran using data from the Ministry of Energy for the period of 2014-2018 revealed an increase in production from combined cycle power plants and a decrease in production from steam power plants.[5] Power plants can have substantial environmental implications, which vary depending on their geographical location. Emissions resulting from the combustion of fossil fuels in these plants, such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrocarbons (HC), carbon dioxide (CO_2), and carbon monoxide (CO), can be significant. Previous research on the environmental impact of power plants in the country has indicated that these facilities have contributed to on-site environmental challenges by releasing gaseous pollutants, particulate matter, and effluents.

The rising demand for energy, mounting pressures stemming from energy and CC agreements, and the relatively low energy production efficiency have prompted actions to enhance energy efficiency. To align with the growing environmental consciousness, numerous industries are discovering the utility of environmental management systems as a means to bolster environmental performance. Among these systems, life-cycle assessment (LCA) stands out as a valuable tool for mitigating the environmental impact of processes or products. LCA can be employed in various stages, including planning, implementation, and evaluation of activities, to identify weaknesses and environmental consequences within energy production systems.[6] In accordance with the ISO 14040 standard, LCA is described as a systematic collection of methods for gathering and assessing data regarding the inputs, outputs, and possible environmental repercussions of a product system over its entire life cycle. This comprehensive assessment typically encompasses a broad spectrum of environmental impacts, including but not limited to CC, resource depletion, human toxicity (HT), terrestrial and freshwater ecotoxicity, terrestrial acidification, freshwater eutrophication, and various others.[7] LCA serves as an extensive evaluation method for examining the environmental impact of a product, process, or service. It primarily centers on quantifying the overall emissions released into the environment and resource utilization. LCA offers a valuable framework to prevent the shifting of environmental burdens from one stage to another within a system.[8] Consequently, it aids decision-makers in selecting products or processes that have the minimal environmental footprint.[9] LCA findings can be instrumental in decision-making across various sectors, including industry, government, and non-governmental organizations (NGOs). They can inform decisions based on financial considerations, political factors, or strategic planning.[10] LCA serves as a valuable tool for evaluating energy production technologies over their entire life cycle, utilizing a wide array of environmental indicators. Miguel and Cerrato investigated the sustainability of energy production systems in Spain since 1990 using LCA. Their findings indicated that between 1990 and 2008, the environmental impact of electricity production increased alongside economic development. However, during the economic recession and with the introduction of renewable energies, the environmental performance improved. They emphasized that in future scenarios, renewable energies exhibit the best environmental performance, while fossil fuels perform the worst.[11] Also, Šerešová et al conducted LCA studies aimed at reducing the environmental impact of electricity production, with a focus on both renewable and non-renewable sources. They found that black coal and lignite power plants have significant implications for global warming, resource utilization, and the release of inorganic substances. Additionally, photovoltaic power plants were noted for their substantial impact on water depletion, resource utilization, and mineral and metal consumption.[12] Moreover, Lelek et al conducted LCA studies on energy generation in Poland, employing the Impact 2002+ method across 18 impact categories. They identified fossil energy carriers, especially coal, as a primary concern in energy production.[6] Annisa et al explored the LCA of a combined cycle power plant from gate-to-gate. Their analysis highlighted acidification potential as the most significant effect, followed by photochemical oxidation potential, with global warming also ranking as an important environmental impact.[13] Ferat Toscano et al emphasized water depletion as the most affected impact category in their LCA assessment of a combined cycle power plant in Mexico, with a specific focus on the chemicals used in water treatment processes.[14] Agrawal et al conducted LCA studies of a combined cycle power plant in India, utilizing the CML 2001 and Eco-Indicator 99 approaches from cradle to grave. They found that, at the midpoint level, the most substantial impacts were attributed to upstream processes, except for global warming potential (GWP).[1]

Hence, the primary objective of this study was to conduct a comprehensive LCA of energy generation in a specific combined cycle power plant located in the southwestern region of Iran. This assessment aimed to evaluate the environmental impacts at both midpoint and endpoint levels throughout the entire life cycle of the power plant, with a particular focus on their repercussions on human health (HH), ecosystems, and resource consumption.

Materials and Methods

Description of the Study Site

The current study focused on a specific combined cycle power facility situated in the southwestern region of Iran. This plant featured four gas turbine units, each with an individual capacity of 123.4 MW, summing up to a total of 493.6 MW. Additionally, there were two steam turbine units with a capacity of 160 MW each, amounting to a combined total of 320 MW, serving as supplementary sources in the power generation cycle. The primary fuel source for the plant was natural gas, although gasoline could be utilized in the event of gas shortages or under emergency circumstances. The maximum power generation capacity of the plant, encompassing both the gas and steam units, reached 820 MW. To facilitate cooling, the power plant employed an air cooled condenser (ACC) tower, with a dedicated ACC tower allocated for each steam unit. For a visual representation of the combined cycle power plant, refer to Figure 1 for a schematic diagram.

Methodology

In this study, the initial phase involved conducting on-site visits to the power plant site and its various units. This entailed an evaluation of the existing conditions and processes. Subsequently, there was an effort to gain a comprehensive understanding of the processes through face-to-face interviews with experts from the power plant. The aim was to verify the inputs and outputs of the processes and to assess the release of pollutants. To gather the necessary data for creating an inventory, information was obtained through interviews and an examination of reports related to environmental emissions available in the health, safety, and environment (HSE) department of the power plant. Furthermore, the environmental impact assessment of the power generation process was carried out utilizing the LCA method, following the ISO 14040 and 14044 standards. ISO 14040 sets out the foundational principles and the overall framework for conducting an LCA. Conversely, ISO 14044 offers guidance on performing the LCA. As per these standards, the LCA comprises four distinct phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.[10] The framework for conducting a life cycle assessment is illustrated in Figure 2.

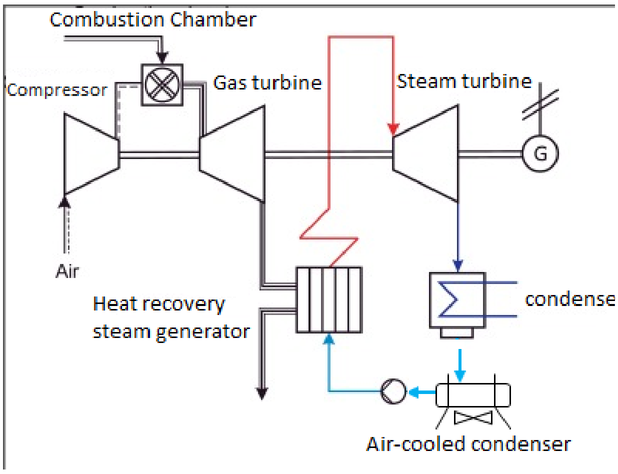

Figure 1. Schematic Diagram for the Combined-Cycle Power Plant

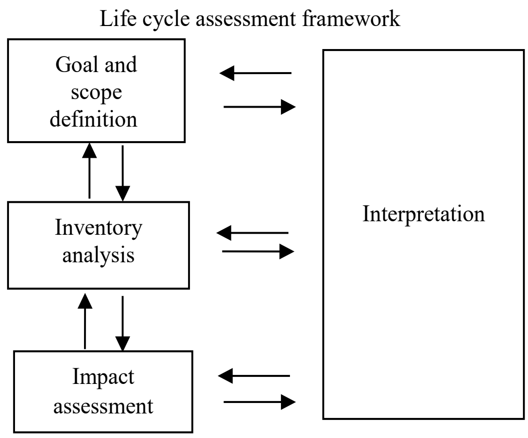

Figure 2. LCA Framework[15]

1. Goal and Scope Definition

In this stage of the study, we focus on establishing the goal and scope, defining the functional unit, delineating the system boundary, and specifying impact categories.[16] The primary aim of this study is to assess the potential environmental impacts associated with the combined cycle power plant throughout its entire life cycle, with a particular emphasis on analyzing its operational phase. It is important to note that LCA is a comparative approach based on a concept known as the “functional unit.” In this study, the functional unit was defined as one kilowatt-hour of electricity generated in a year (kWh/y). This functional unit serves as the basis for measuring and evaluating environmental impacts. Determining the system boundary is another crucial step in conducting an LCA. When defining the purpose and scope of the LCA study, it is essential to establish the system boundary. The system design should be structured to encompass all the inputs and outputs within this defined boundary as fundamental flows. Factors influencing the determination of the system boundary include considerations such as time limitations, financial constraints, and, notably, the availability of information.[1] Due to data accessibility challenges in this study, the life cycle system boundary was confined to the “gate-to-gate” perspective. This means that it encompasses the power plant’s operations but does not extend to include upstream processes such as gas extraction and refining, chemical transportation, or production. Similarly, downstream processes like waste disposal were not within the defined boundary. In this study, we assessed impact categories at two distinct levels: endpoint and midpoint. The midpoint impact categories encompassed CC, natural land transformation (NLT), water depletion, human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication, and fossil fuel depletion (FD). Additionally, there were three endpoint impact categories, which included damage to HH, impacts on ecosystem diversity (ED), and resource availability (RA).[17] Figure 3 illustrates the system boundary of the LCA conducted on the studied combined cycle power plant.

2. Life Cycle Inventory

This stage involves collecting the essential data required to meet the study’s objectives. LCI is the process of quantifying the energy and raw materials consumed, as well as atmospheric emissions, emissions into water, solid waste generation, and other materials released throughout the entire life cycle of a product, process, or activity. In the current study, all inputs and outputs associated with the power plant, within the gate-to-gate scope, were gathered and calculated based on the annual average per functional unit (kWh/y). In this context, inputs included water and energy consumption, while the outputs encompassed releases into water, soil, and the atmosphere during the operation of the power plant. All these inputs and outputs were assessed on an annual average basis per functional unit (kWh/y).

The LCI data were sourced through a variety of methods in this study. These methods included direct measurements of system inputs, such as water and energy (including gas

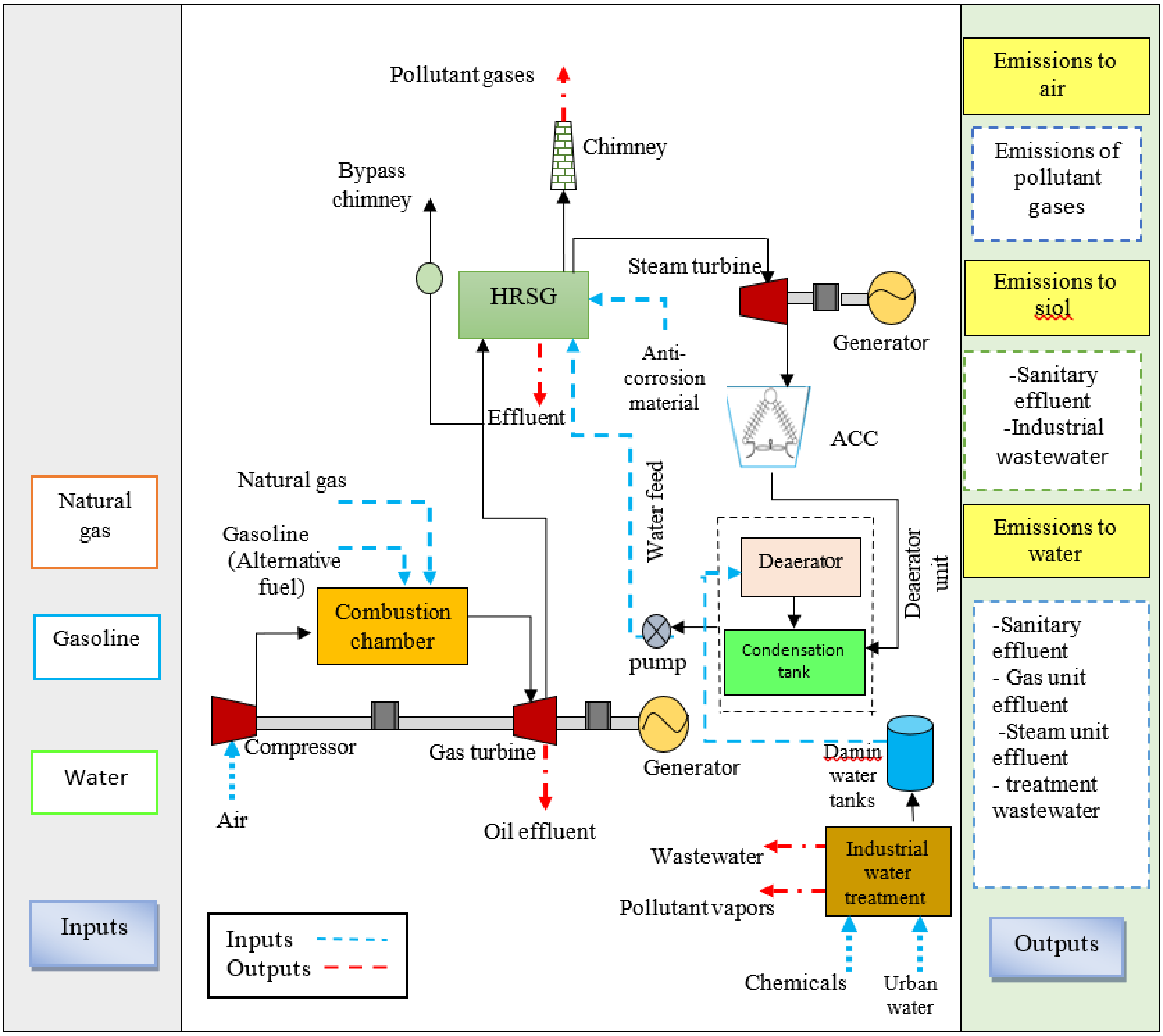

Figure 3. System Boundary Used During Electricity Generation of the Combined Cycle Power Plant

and gasoline), on a monthly basis. Additionally, self-reports from the power plant and certain environmental emissions data (specifically CH_4, N_2O, and CO_2) were obtained using emission factors provided by the Renewable Energy and Energy Efficiency Organization (SATBA). Annual average emissions were considered, utilizing data from the 2017 Energy Balance Sheet. However, a significant portion of the data related to environmental releases was collected through monthly monitoring of the power plant environment. This data pertained to the period from October 2017 to September 2018, and it primarily covered the most substantial emissions and resource and energy consumption quantities relevant to this study. In terms of geographical coverage, it's important to note that, according to ISO 14044, data must be collected from units (processes) within the study area to fulfill the study's objectives. Therefore, the calculated data in this study exclusively encompasses the processes and activities that fall within the defined scope of the study (gate to gate). Lastly, all the inventory data associated with various units underwent validation by experts from each respective unit to ensure accuracy and reliability.

Input Data

The consumptions of water (service and industrial), natural gas, and gasoline were used as the input data, as shown in Table 1.

Output Data

The primary emissions to both air and water from all discharge points within the power plant, considering the gate-to-gate scope, have been summarized in Table 1. It's worth noting that according to data from the Renewable Energy and Energy Efficiency Organization (SATBA), the emission factors for methane, carbon dioxide, and nitrous oxide resulting from natural gas utilization in thermal power plants are as follows: 0.0385 g/m3, 2178.2 g/m^3, and 0.0038 g/m^3, respectively.

Because the power plant was built on land that was once part of a wetland in the southwestern region of Iran, the area experiences both dry and wet periods throughout the year, particularly in summer and winter. Consequently, Contaminants originating from water sources can easily infiltrate the soil. Since precise data on the quantity of pollutants directly released from the power plant into the soil was unavailable, we used the emission rate of pollutants into the water as an approximation for their influence on the soil.

3. LCI Assessment

In this phase, the importance of potential environmental consequences is was examined by using the results of the inventory analysis, and the inventory data are were linked to specific environmental impact categories and impact category indicators. The LCIA includes determining the impact categories, classification, characterization and the two optional elements of normalization and weighting. The present study utilized the ReCiPe approach to assess LCI. The main advantage of this technique includes the provision of characterization factors at midpoint and endpoint levels for characterizing the LCI results in terms of impact category indicators. In addition, providing normalization and weighting factors, multiple midpoint impact categories and having all factors on a global scale are other benefits of this method. Linking the inventory data to one or a number of midpoints is the primary stage of this method. Then, each midpoint is linked to one endpoint for almost all impact categories. Equations 1 and 2 were, respectively, used for characterization at the midpoint and endpoint levels. It is worth noting that characterization at the endpoint level starts from the intermediate midpoints.

$$I_m = \sum_i Q_{mi} m_i \qquad (1)$$

$$I_e = \sum_m Q_{em} I_m \qquad (2)$$

where, m_i illustrates the magnitude of intervention i (e.g., the mass of the CO_2 emitted to air), and I_e and I_m reveal the indicator result for endpoint impact category e and midpoint impact category m, respectively. Furthermore, Q_{mi} and Q_{em} represent the characterization factor connecting intervention i with midpoint impact category m and midpoint impact category m with endpoint impact category e, respectively. All of the characterization factors were taken from the SimaPro database presented by the PRé Sustainability Company. Those relating the midpoint impact category m to the endpoint impact category e (Q_{em} factor) were provided by Goedkoop et al.[17]

4. Interpretation

The interpretation phase includes evaluating analysis results, and relevant choices and hypotheses in terms of accuracy and robustness, and offering the general results.

Results and Discussion

Classification Results

After obtaining the data, the LCI stage was completed at gate-to-gate, and the unification of the determined inventory unit was performed based on the functional unit. Each inventory must first be assigned to a certain midpoint impact category according to the method specified for LCIA. Table 2 outlines the classification results. Inventory of each of the emissions can be placed in several midpoint impact categories. For example, as can be seen in Table 2, CO_2 emission is assigned to both CC and photochemical oxidant formation potential (POF) impact categories, or the inventory related to PO_4^{-3} emission only belongs to the FE impact category.

Characterization Results

The characterization factors of each material in each impact category were utilized to determine its indicator results at two midpoint and endpoint levels. Concerning the WD impact category, the ReCiPe technique only accounted for characterization factors at the midpoint level. The indicator results for midpoint and endpoint impact categories have been demonstrated in Table 3.

Table 1. Input and Output Data Inventory

Material/Fuel	Consumption Level Per 1 kWh		Unit
Water	1.44E-04		kg
Natural gas	2.56E-01		m^3
Gas oil	3.13E-02		MJ
Emissions to Air			
Emissions	**Per 1 kWh/yr(Kg)**	**Emissions**	**Per 1 kWh/yr (kg)**
CO_2	58.5E-01	SO_2	0
NO_2	3.53E-06	CO	7.74E-07
NO	4.74E-05	H_2S	4.07E-08
NO_x	5.40E-05	CH_4	9.87E-06
N_2O	9.74E-07		
Emissions to Water			
Emissions	**Per 1 kWh/yr(Kg)**	**Emissions**	**Per 1 kWh/yr (kg)**
Phenol	5.83E-09	Ni	4.08E-11
TPH	3.42E-07	V	3.19E-10
PO4	1.35E-08	Cr^{3+}	4.34E-10
CL^-	5.91E-06	Zn	4.38E-10
Pb	3.79E-10		

Table 2. Classification Results

Midpoint Impact Category	LCI Results
CC	CO_2, CH_4, N_2O
HT	Phenol, CL^-, TPH
FET	Phenol, CL^-, TPH, Ni, V, ZN, CR^{+3}, Pb
TET	Phenol, CL^-, TPH, Ni, V, ZN, CR^{+3}, Pb
POF	CO, CH_4, NO_2, NO_x
TA	NO_2, NO_x
FE	PO_4^{-3}
FD	Natural gas, fossil fuels (diesel)
NLT	Occupied land area of the power plant
WD	Water consumption

Figures 4 and 5 show the results of the impact categories indicator at the midpoint and endpoint levels for the characterization, respectively. As can be seen, the NLT midpoint and RA endpoint impact categories were the most affected impact categories by a large difference.

Normalization and Weighting Results

Normalization and weighting are two optional stages in the LCIA. Normalization has a purpose to know the highest impact or the hotspot of LCA study.[18] In the ReCiPe approach, weighting factors are only provided at the endpoint level. Table 4 provides the results of normalization and weighting in this context.

In Figures 6 and 7, the results of normalization of the midpoint impact categories as well as the endpoint have been given, respectively. Also, the results of endpoint impact categories weighting have been shown in Figure 8.

According to the normalized results in endpoint impact categories, electricity generation in the plan studied involved 70% damage to available resources, 28% damage to HH and 2% damage to ED. Based on the ISO standards, normalization prepares the conditions for characterize results by linking the results to reference information.[7]

For the weighted endpoint impact categories, damage to RA is 53% of the total impacts, damage to HH is 43%

Table 3. Indicator Results for Midpoint and Endpoint Impact Categories

Midpoint		Endpoint	
Impact Category	**Indicator Result**	**Impact Category**	**Indicator Result**
FD	2.12E-01		
WD	1.44E-04	RA	3.50E-02
NLT	3.00E+07		
CC	5.59E-01		
HT	2.0E-03	HH	7.84E-07
POF	5.77E-05		
TET	4.81E-05		
FET	1.14E-04	ED	4.44E-09
TA	3.22E-05		
FE	8.89E-09		

Table 4. Normalization and Weighting Results

Midpoint Impact Category	Normal Result of Midpoint Impact Category (Dimensionless)	Endpoint impact category	Result of Endpoint Impact Categories (Dimensionless)	
			Normal	**Weigh**
FD	2.70E-14			
WD	0.00E+00	RA	2.35E-14	4.69E-12
NLT	4.10E-04			
CC	1.33E-14			
HT	1.00E-15	HH	9.45E-15	3.78E-12
POF	1.67E-16			
TET	1.33E-15			
FET	4.36E-15	ED	7.96E-16	3.18E-13
TA	1.39E-16			
FE	5.05E-18			

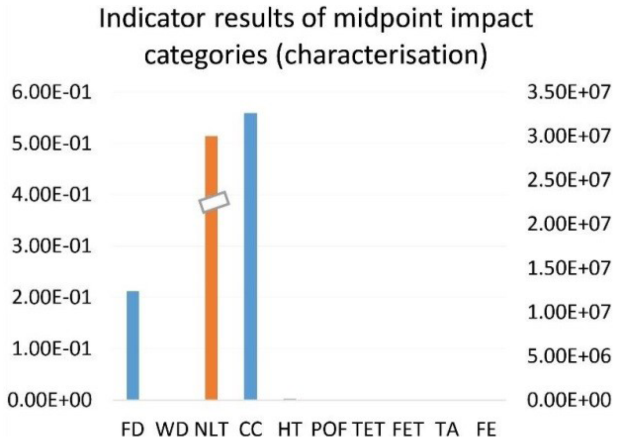

Figure 4. Indicator Results of Midpoint Impact Categories in the Characterization. Note: Rectangle shape shows gap in the graph with a large difference in values

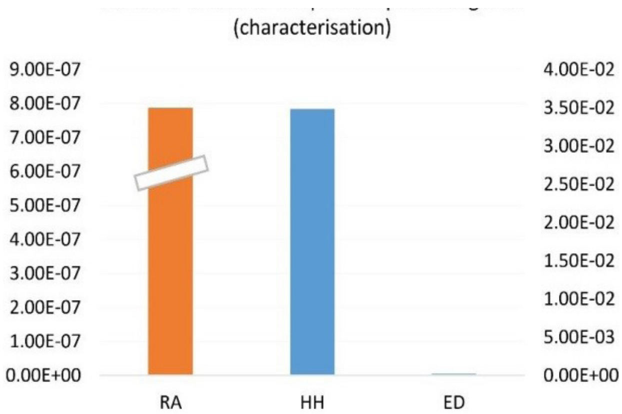

Figure 5. Indicator results of endpoint impact categories in the characterization

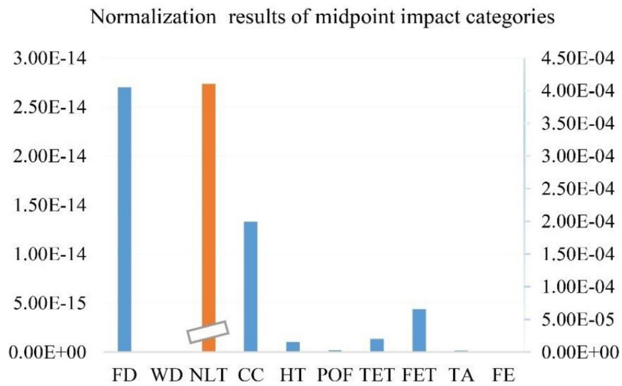

Figure 6. Normalization Results of Midpoint Impact Categories (Dimensionless)

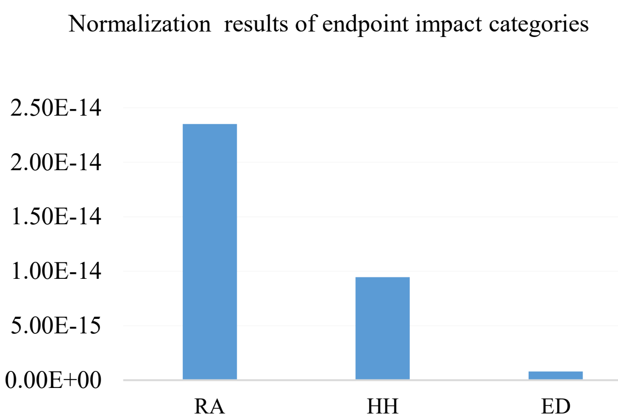

Figure 7. Normalization Results of Endpoint Impact Categories (Dimensionless)

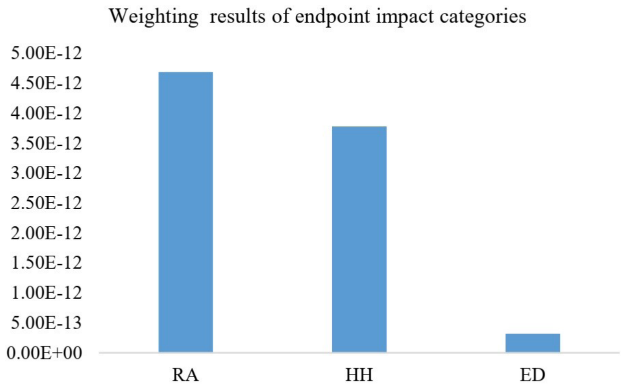

Figure 8. Weighting Results of Endpoint Impact Categories (Dimensionless)

and damage to ED is 4%. RA, which includes NLT and FD, is the most influential category. Weighting in LCA shows decision-maker values concerning the relative importance of each impact category and provides the ranking of options.[18]

In the midpoint impact categories, more than 99% of GWP and CC is caused by CO_2 emissions, less than 0.5% is due to N_2O emissions, and less than 0.5% is also the result of CH_4 emissions from fossil fuels combustion. In the present study, carbon emissions were estimated 5.58E-01Kg/Kwh, while in a study conducted by Phumpradab et al on a combined cycle power plant in Thailand, the estimated amount of carbon emissions was 4.58E-01 kg/kWh.[19] In the study by Santoyo-Castelazo et al in Mexico, CO_2 emissions in gate to gate of combined cycle power plants were estimated 4.12E-01 kg/kWh,[20] which are lower than estimated those in this study. This may be due to the lower efficiency of the studied power plant in comparison to previous studies.

The terrestrial acidification potential (TAP) was assessed based on NO_2 and NO_X emissions, measured in terms of kg SO_2 eq. The findings revealed that approximately 93% of TAP is attributed to NOx at a rate of 3.02E-05 kg SO_2 eq per 1 kWh/y of electricity generated. In this study, the indicator result for TAP was calculated as 3.22E-05 kg SO_2 eq/kWh, which is lower than the value reported in Ferat Toscano and colleagues' study on a combined cycle power plant in Mexico (8.31E-04 kg SO_2 eq/kWh).[14] It is also lower than the value estimated by Phumpradab et al (7.61E-01 kg SO_2 eq/kWh).[19]

The human toxicity potential (HTP) is quantified in terms of kg 1,4-dichlorobenzene (1,4-DB) equivalents per kWh of electricity generated, as determined using the ReCiPe method. HTP arises from the release of various organic toxic chemicals like toluene, xylene, benzene, ethylbenzene, phenol, aliphatic hydrocarbons, and chlorine into water or air. More than 50% of HTP is attributed to the release of chlorine into water. In this current study, the indicator result for the human toxicity impact category was 1.99E-03 kg1,4-DB-eq/kWh, which is lower than the estimation in Agrawal and colleagues' study, where they estimated HTP to be 5.67E-03 kg1,4-DB-eq/kWh.[1] Singh et al estimated HTP as 1.83E-03 kg1,4-DB-eq/kWh, which is fairly consistent with the findings of the present study.[21] The freshwater and terrestrial ecotoxicity potential is expressed in terms of kg 1,4-dichlorobenzene (1,4-DB) equivalents per kWh of electricity generated. The primary pollutants responsible for freshwater and terrestrial ecotoxicity include Nickel, vanadium, zinc, phenol, chlorine, toluene, xylene, benzene, ethylbenzene, and aliphatic hydrocarbons. Chlorine is the predominant pollutant released into water and soil. In this study, the indicator result for the freshwater ecotoxicity impact category was estimated at 1.14E-04 kg 1,4-DB-eq/kWh. In contrast, Agrawal et al reported a value of 1.70E-06 kg 1,4-DB-eq/kWh,[1] and Singh et al reported 2.60E-06 kg 1,4-DB-eq/kWh,[21] which are significantly lower than the findings of this study. In the present study, the indicator result for the terrestrial ecotoxicity impact category was determined to be 4.80E-05 kg 1,4-DB-eq/kWh, while Ferat Toscano et al estimated a much lower value of 1.37E-06 kg 1,4-DB-eq/kWh.[14]

The POF was assessed based on CO, CH_4, NO_2, and NOx emissions, expressed in terms of kg NMVOC (non-methane volatile organic compounds) equivalents. NO_X and NO_2 emissions contributed to approximately 93.5% and 6% of the photochemical oxidant formation potential, respectively. In this study, the indicator result for the POF impact category was 5.80E-05 kg NMVOC/kWh. This value is lower than the estimate provided by Ferat Toscano et al, which was 7.56E-04 kg NMVOC/kWh.[14] It is important to note that most of the NOx emissions are associated with the combustion process. The indicator result for the freshwater eutrophication impact category was determined based on the release of phosphate as 8.89E-09 kg P eq/kWh. This value significantly differs from the estimates in the study of Phumpradab et al (1.45E+00 kg P eq/kWh)[19] and Ferat Toscano et al (2.25E-06 kg P eq/kWh).[14] Based on analyzing the inputs and outputs of the power plant system for generating 1 kwh/y of electricity in the gate-to-gate scope, water consumption was 1.44E-01 m^3, which is higher than that of similar research. In this scope, Ferat Toscano et al estimated water consumption value as 7.09E-05.[14] Moreover, Phumpradab et al found that 8.00E-09 m^3 water is consumed for producing 1 kWh/yr of electricity (0.008 L per 1 MWh/y of electricity).[19] In addition, 2.56E-01 m^3 of gas is required to generate 1 kWh/y of electricity, which is not significantly different from that reported by Ferat Toscano et al (2.18E-01 m^3)[14] and Phumpradab et al (2.53E-01 m^3).[19] Based on the results, it has been observed that the efficiency of the power plant under study, particularly concerning carbon emissions and water consumption, is lower compared to earlier research findings.

Conclusion

The present study examined the environmental impacts of electricity generation in one of the combined cycle power plants of Iran through employing the LCA approach. Specifically, the ReCiPe method, which encompasses both problem-oriented (midpoint) and damage-oriented (endpoint) facets, was applied. Given environmental features, emission type, and resource consumption for generating 1 kWh/y electricity, 10 midpoint impact categories were selected and evaluated for environmental impacts. Normalizing the indicator results for each midpoint impact category revealed that midpoints NLT, FD, CC, FET, TET, HT, POF, TA, FE, and WD had the maximum environmental impacts of the life cycle of producing 1 kWh electricity, respectively. It is worth noting that the less priority of WD can be ascribed to the lack of midpoint normalization factor for this impact category in the ReCiPe method. Regarding the endpoint level, the most affected categories were RA, HH, and ED, respectively. It was also found that after NLT, reduction of fossil fuels is the most important environmental impact. As a result, we propose several significant operational recommendations to mitigate adverse environmental effects:

- Implementing carbon capture and utilization systems to mitigate CC.
- Substitution of fossil fuels with biogas to conserve fossil resources and combat global warming.
- Augmenting the proportion of renewable power plants in Iran's energy mix.
- Advancement of novel water treatment technologies and the recycling of effluents from industrial water treatment plants within the steam cycle to curtail water resource consumption.

Considering the power plant's subpar efficiency and the proliferation of detrimental environmental impacts, it is imperative to devote concerted efforts to enhance the overall efficiency of the power plant.

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Authors' Contribution
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References
1. Agrawal KK, Jain S, Jain AK, Dahiya S. A life cycle environmental impact assessment of natural gas combined cycle thermal power plant in Andhra Pradesh, India. Environ Dev. 2014;11:162-74. doi: 10.1016/j.envdev.2014.04.002.
2. Laurent A, Espinosa N. Environmental impacts of electricity generation at global, regional and national scales in 1980-2011: what can we learn for future energy planning? Energy Environ Sci. 2015;8(3):689-701. doi: 10.1039/c4ee03832k.
3. Perera F. Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: solutions exist. Int J Environ Res Public Health. 2017;15(1):16. doi: 10.3390/ijerph15010016.
4. Abdallah L, El-Shennawy T. Reducing Carbon Dioxide Emissions from Electricity Sector Using Smart Electric Grid Applications. Journal of Engineering. 2013. doi: 10.1155/2013/845051
5. Ministry of Energy. Energy Balance Sheet for 2014-2018,35. Office of Planning and Macroeconomics of Electricity and Energy. 2014-2018. Available from: https://isn.moe.gov.ir.
6. Lelek L, Kulczycka J, Lewandowska A, Zarebska J. Life cycle assessment of energy generation in Poland. Int J Life Cycle Assess. 2016;21(1):1-14. doi: 10.1007/s11367-015-0979-3.
7. International Organization for Standardization (ISO). Environmental Management: Life Cycle Assessment; Requirements and Guidelines. Vol 14044. Geneva, Switzerland: ISO; 2006.
8. Grieger KD, Laurent A, Miseljic M, Christensen F, Baun A, Olsen SI. Analysis of current research addressing complementary use of life-cycle assessment and risk assessment for engineered nanomaterials: have lessons been learned from previous experience with chemicals? J Nanopart Res. 2012;14(7):958. doi: 10.1007/s11051-012-0958-6.
9. Barberio G, Scalbi S, Buttol P, Masoni P, Righi S. Combining life cycle assessment and qualitative risk assessment: the case study of alumina nanofluid production. Sci Total Environ. 2014;496:122-31. doi: 10.1016/j.scitotenv.2014.06.135.
10. Guinée JB. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Netherlands: Kluwer Academic Publishers; 2002. https://onlinelibrary.wiley.com/doi/abs/10.1162/1088198041269373.
11. San Miguel G, Cerrato M. Life cycle sustainability assessment of the Spanish electricity: past, present and future projections. Energies. 2020;13(8):1896. doi: 10.3390/en13081896.
12. Šerešová M, Štefanica J, Vitvarová M, Zakuciová K, Wolf P, Kočí V. Life cycle performance of various energy sources used in the Czech Republic. Energies. 2020;13(21):5833. doi: 10.3390/en13215833.
13. Annisa R, Jiwandono K, Marteda G, Sinisuka NI, Surya Dinata I, Reski Hasibuan O, et al. Life cycle assessment of natural gas combined cycle steam power generation systems in Indonesia: case study on Gresik power plant. IOP Conf Ser Earth Environ Sci. 2021;753(1):012039. doi: 10.1088/1755-1315/753/1/012039.
14. Ferat Toscano C, Martin-del-Campo C, Moeller-Chavez G, Leon de los Santos G, François JL, Revollo Fernandez D. Life cycle assessment of a combined-cycle gas turbine with a focus on the chemicals used in water conditioning. Sustainability. 2019;11(10):2912. doi: 10.3390/su11102912.
15. European Commission, Joint Research Centre, Institute for Environment and Sustainability. International Reference Life

Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment–Detailed Guidance. EUR 24708 EN. 1st ed. Luxembourg: Publications Office of the European Union; 2010. doi: 10.2788/38479.

16. Evangelista PPA, Kiperstok A, Torres EA, Gonçalves JP. Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA). Constr Build Mater. 2018;169:748-61. doi: 10.1016/j.conbuildmat.2018.02.045.
17. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. 1st ed. The Hague: Ministry of Housing, Spatial Planning and the Environment (VROM); 2009.
18. Prado V, Wender BA, Seager TP. Interpretation of comparative LCAs: external normalization and a method of mutual differences. Int J Life Cycle Assess. 2017;22(12):2018-29. doi: 10.1007/s11367-017-1281-3.
19. Phumpradab K, Gheewala SH, Sagisaka M. Life cycle assessment of natural gas power plants in Thailand. Int J Life Cycle Assess. 2009;14(4):354-63. doi: 10.1007/s11367-009-0082-8.
20. Santoyo-Castelazo E, Gujba H, Azapagic A. Life cycle assessment of electricity generation in Mexico. Energy. 2011;36(3):1488-99. doi: 10.1016/j.energy.2011.01.018.
21. Singh B, Strømman AH, Hertwich EG. Comparative life cycle environmental assessment of CCS technologies. Int J Greenh Gas Control. 2011;5(4):911-21. doi: 10.1016/j.ijggc.2011.03.012.