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Life Cycle Assessment of Electricity Production from Natural Gas Combined Cycle

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Natural gas has the largest share of utility power generation in Turkey, accounting for approximately 61.3% of all utility-produced electricity. Therefore, understanding the environmental implications of producing electricity from natural gas combined cycle is an important component of any plan to reduce total emissions and resource consumption. In this aim, a Life Cycle Assessment (LCA) for production of electricity from natural gas was performed. A process consisting of only electricity generation was formed. CML 2 baseline 2000 method included in SimaPro 7.0 software was used for the assessment. 1 kWh electricity production was selected as the functional unit. Data regarding the average technology for similar production facilities were obtained from literature and website of a facility. The results were given from the perspectives of impact categories. According to results, NO_2 emissions were the main factor for human toxicity, acidification and eutrophication. On the other hand, CH_4 emissions due to 65% fuel use ratio were key contributors for global warming potential impact.

1. Introduction

Natural gas is an important fuel in Turkey. It accounts for 61.3 % of all the energy consumed in Turkey for electricity production (TEIAS, 2006). Although the share of coal has also high rate, natural gas systems has higher conversion efficiencies compared to coal-fired power plants.

Cogeneration is a special application of gas turbine or stationary engine technology. Cogeneration utilizes the heat from the exhaust of the gas turbine, engine, or boiler, to heat water or raise stream for either domestic or industrial processes (Australian Government Dep., 2005).

LCA methodology has been used for a long time in developed countries, but it is very new for Turkey. Despite the publication of LCA standards of ISO in Turkiye [TS EN ISO 14040 (1998), TS EN ISO 14041 (2003), TS EN ISO 14042 (2003), and TS EN ISO 14043 (2003)] they have been used by neither the government nor private sector (Banar and Cokaygil, 2008). From this point, a LCA was performed to quantify and analyze the environmental aspects of producing of electricity from a NGCC power generation system.

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2. Material and Methods

This LCA study was conducted according to the ISO 14040 standards that include the following phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation (Conclusion).

2.1 Goal and scope definition

In this study, life cycle assessment (LCA) for production of electricity from natural gas combined cycle was performed in order to examine the environmental aspects of the system. SimaPro7 software has been applied to analyze the system. All the data needed for the life cycle inventory was gathered from web sites of the producers, the database of the software, and the literature. A natural gas combined cycle facility that has 180 MW_{el} and 180 MW_{heat} production capacity was selected for a model.

Functional unit: The functional unit of the system is 1kWh electricity production. But, for the results of an LCA of a combined cycle systems, the way that the co-product is considered turns out to be important. As cogeneration systems produce heat and electricity simultaneously, and the comparison to other, non-cogeneration systems often takes place based on the functional unit "1 kWh electricity (kWh_{el})" or "1 kWh heat", both products need to be taken into account together. So, the functional unit would be environmental impact of the production of 1 kWh_{el} plus the equivalent amount of heat in a cogeneration device (Pehnt, 2008). For that reason, an allocation procedure should be applied.

Allocation procedure: For the case of a cogeneration system, one allocation key could be the energy generated. Take the example of an electric efficiency of 40 % and a thermal efficiency of 40 %. For each kWh electricity, 1 kWh heat is produced. The allocation key would thus be 0.5. That means that 50 % of the, for instance, CO_2 emissions are related to the production of electricity and 50 % to heat. However, this allocation key does not really characterize the value of the products. Instinctively, 1 kWh_{el} seems more valuable than 1 kWh low-temperature heat. Therefore, often the exergy is used as the allocation basis. Exergy describes the amount of useful energy that is contained within a product. The exergy content of electricity $\zeta_{electricity}$ is equivalent to its energy (i.e. $\zeta_{electricity} = 1$), whereas the exergy of heat, in contrast, is given by the Carnot factor ($1-T_u/T$) (Pehnt, 2008; Schaumann, 2007).

Where the T_u is ambient air (293 K) and T is the steam temperature that enters the steam turbine. Carnot factor of the heat for this system is 0.64. It means that 1kWh of heat contains only 0.64 kWh of useful energy.

The allocation factor $\gamma_{electricity}$ characterizes the share of the environmental impact of the production of 1 kWh_{el} plus the equivalent amount of heat in a cogeneration device.

$$\gamma_{electricity} = \frac{\zeta_{electricity} \cdot \eta_{el}}{\zeta_{electricity} \cdot \eta_{el} + \zeta_{thermal} \cdot \eta_{th}} \qquad \text{In this system } \gamma_{electricity} \text{ is 0.61} \qquad (2)$$

System boundaries: In this facility there are three 40 MW gas turbine coupled to separate generators, three Heat Recovery Steam Generators (HRSG) and a steam turbine coupled to a generator. Steam produced by the HRSG is fed into a 72 MW steam turbine coupled to generator (Figure 1).

3. Inventory Analysis

The data regarding to system was investigated in two parts: air emissions and wastewater. It was assumed that there was no solid waste generation directly related with the process.

Air emissions were calculated via stoichiometric combustion of natural gas with 5% excess air. Natural gas composition was obtained from BOTAS in Turkey - Petroleum Pipeline Corporation – Table 1 (BOTAS, 2009). Fuel use (natural gas) ratio of the system was 65%.

Table 1 Natural gas composition

Components	Mole fraction (%)	Components	Mole fraction (%)
Methane	**96.63**	I-Pentane	0.01
Ethane	**1.87**	N-Pentane	0.02
Propane	0.50	CO_2	0.06
I-Butane	0.08	Hexane	0.01
N-Butane	0.08	Nitrogen	0.75

Only methane and ethane values were used for combustion calculations (in bold).
The specific weight of the natural gas is 5753 kg/m^3 and the calorific value is 8250 kcal/m^3.

According to facility data, natural gas use rate is 65 %. It was thought that Zeldovich mechanism is the cause of this situation with the use of 35 % oxygen. In compliance with Zeldovich mechanism, air nitrogen reacts with air oxygen to form NO_x at temperatures of 800°C and higher (Muezzinoglu, 2000). A mass balance based on gaseous components of the system is given in the Fig. 1.

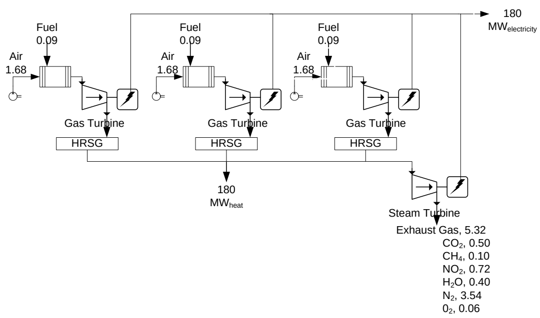

Figure 1: Mass balance for the gaseous components of the system (kg/kWh$_{el}$)

For the gas turbine and the HRSG, demineralised water is required for the following purposes:

to compensate for the blow down water from the drums for the HRSG. If steam or water injection is applied, the water loss also has to be compensated for by make-up water. The quality has to meet the requirements of the manufacturers and water treatment is, therefore, required. Demineralisation is usually sufficient to meet these requirements.

Demineralised water is usually used for washing the gas turbine compressor. Condensate from the water/steam cycle is sometimes used for online washing, but usually demineralised water is supplied to a separate water wash unit. For offline washing, a detergent is added to the demineralised water to improve the washing effect (European Commission, 2006).
In this study data related to wastewater discharge values of a NGCC facility cannot be obtained. So, discharge standards for cooling waters and demineralization waters in Turkish Water Pollution Control Regulation were used (Table2) (TWPCR, 2004). (Water requirement of combined cycle with wet cooling is 1.54 kWh/L and if it's assumed that 70% of used water discharges as wastewater 1.08 L wastewater is generated per kWh electricity (California Energy Commission, 2006). By using this data, wastewater parameters were calculated per production of kWh electricity (Table2).

Table 2 Wastewater discharge limits for cooling water and demineralization water in TWPRC and calculated wastewater parameters for kWh electricity production

Parameters	2 hours composite sample (mg/L)	Calculated wastewater parameters (mg/ kWh electricity production)
COD	200	216
Chloride (Cl^-)	2000	2160
Sulphate (SO_4^{-2})	3000	3240
Iron (Fe)	10	10.8

4. Impact Assessment

Inventory data was evaluated via CML 2 Baseline 2000 method by using SimaPro 7.0. Environmental impacts of the process were investigated from the point of global warming potential, human toxicity, acidification and eutrophication.
The total characterization values of impact categories are given in Table 3.

Table 3 Impact categories and values

Impact categories	Values
Global warming potential	2.8 kg CO_2 equivalent
Human toxicity	0.86 kg 1,4-DB eq
Acidification	0.36 kg SO_2 eq
Eutrophication	0.09 kg $PO4^{-2}$ eq

Normalization values are given in Figure 2.

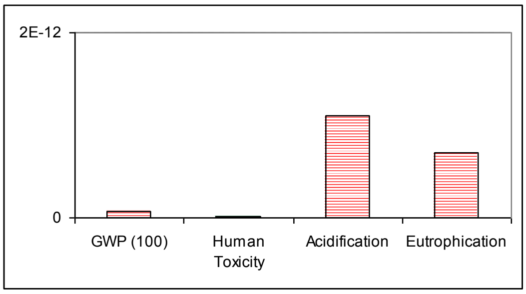

Figure 2 : Normalization results for impact categories

Global warming potential (GWP100) impact: GWP100 value of the process is 2.8 kg CO_2 equivalent. CO_2 and CH_4 causes to this impact with the ratios of 18 % and 82 %, respectively (Fig. 3).

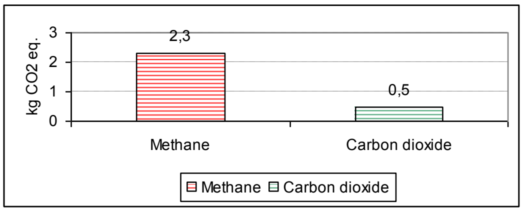

Figure 3 : Characterization results for global warming potential

Human toxicity impact: The value of this impact is 0.86 kg 1.4-DB eq. NO_2 is the cause of this impact totally.
Acidification impact: The acidification value of the 1 kWh_{el} production is 0.36 kg SO_2 eq. NO_2 is the cause of this impact totally.
Eutrophication impact: The value of this impact is 0.09 kg $PO4^{-2}$ eq. NO_2 is the cause of this impact totally.

5. Conclusion

This LCA study was conducted for 1 kWh electricity production. In combined cycle, heat is the co-product of the system. For that reason environmental impact of the system is shared between electricity and heat production with the ratio of 0.61 and 0.39, respectively.
According to impact assessment results, NO_2 emissions are the main factor for human toxicity, acidification and eutrophication, as also indicated by May and Brennan (2003), In this process, NO_x reduction technologies are not taken account. But, as seen from the results, in a natural gas combine cycle plant NO_x reduction process such as Dry Low NO_x and Selective Catalytic Reduction have to be used. For example, if this process has a Dry Low NO_x combustor, NO_x emission reduction rates would be between 60 and 80%. On the other hand, CH_4 emissions were key contributors for global warming potential impact but the calculated GWP (100) value of this LCA study (2.8 kg/kWh) is

higher than Meier and et al. (2005) indicated (0.38 kg/kWh) because of 65% fuel use ratio. For that reason, fuel use ratio should be increased with research and development studies. Increasing of the fuel use ratio will reduce CH_4 emission which have 20 times higher global warming potential than CO_2. CO_2 emissions made minimal contribution to this impact.

When the other LCA studies results investigated it is seen that CO_2, NO_x and SO_x emissions of natural gas combined cycles are much lower than a coal or fuel fired combined cycles but higher than hydroelectric, geothermal, nuclear and wind power processes (May and Brennan 2003; Meier and et al. 2005; Odeh and Cockerill, 2008). But, this LCA study's results are higher than a coal or fuel fired combined cycles results. This case shows the importance of fuel use ratio for the total emissions.

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