Effect of Non-Condensable Gases on geothermal power plant performance. Case study: Kizildere Geothermal Power Plant-Turkey

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Abstract: Non-Condensable Gases (NCGs) are natural components of geothermal fluids, and they are a source of considerable capital and operating costs for power plants. The NCG content of geothermal steam varies over the world from almost zero to as much as 25% (wt). In this work, the influence of NCGs on the thermodynamic performance of geothermal power plants is analysed for various NCG content and turbine inlet temperatures. The results obtained can be useful on the feasibility study of single flash geothermal power plants. Depending on the NCG content of the field, the performance of the power plant can be determined roughly.

Keywords: NCGs; non-condensable gases; geothermal power plants; exergy; Kizildere Geothermal Power Plant; Turkey.

Reference to this paper should be made as follows: Gokcen, G. and Yildirim, N. (2008) 'Effect of Non-Condensable Gases on geothermal power plant performance. Case study: Kizildere Geothermal Power Plant-Turkey', *Int. J. Exergy*, Vol. 5, Nos. 5/6, pp.684–695.

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1 Introduction

Geothermal steam, which flows through the entire cycle of conventional geothermal power plants, contains a certain amount of Non-Condensable Gases (NCGs) (CO_2, H_2S, NH_3, N_2, CH_4, etc.). The presence of corrosive NCGs, require a more corrosion resistant turbine and condenser design.

The NCGs in geothermal steam interfere with heat transfer in the condenser by forming a 'gas-blanketing' effect, which raises the condenser temperature and back-pressure on the turbine, reducing its output. In practice, the gases' effect can only be overcome by evacuating them, along with a portion of steam. Gas removal system is costly in geothermal systems because of elevated gas levels (Vorum and Fritzler, 2000). The power needed to extract the NCGs from the condensers and exhaust them to the atmosphere or an abatement system is supplied from the generated electricity; this seriously impairs the power generation performance (Duthie and Nawaz, 1989).

NCGs also decrease the exergy of the fluid reducing the available work in the plant. Thus, evaluation of the net work of the turbine should consider the NCG content (Montero, 1990).

The practical problems associated with elevated levels of NCGs in geothermal power plants are:

- the gases reduce the heat transfer efficiency of the condensers increasing the condenser operating pressure, which reduces turbine power output
- NCGs contain lower recoverable specific energy than does steam
- higher capital and operating cost for gas removal in the cost of electricity than fossil-fuelled power plants
- acid gases such as carbon dioxide and hydrogen sulphide are highly water-soluble and contribute to corrosion problems in piping and equipment that contact steam and condensate (Vorum and Fritzler, 2000).

Energy and exergy analysis of geothermal power plants has been conducted by many researchers. The studies mostly are focused on determination of exergetic efficiency of the plants and sensitivity analysis of dead state properties. The authors considered that NCG content is zero through the cycle or NCGs are taken into consideration only at the gas extraction system not the entire cycle (DiPippo and Marcille, 1984; DiPippo, 1992, 1994, 2004; Cadenas, 1999; Cerci, 2003; Siregar, 2004; Kwambai, 2005; Aqui et al., 2005; Dagdas et al., 2005; Ozturk et al., 2006; Kanoglu et al., 2007).

The influence of NCGs on the performance of geothermal power plants was first studied by Khalifa and Michaelides (1978). The authors reported that the presence of 10% NCG in the geothermal steam, results in as much as a 25% decrease in the net work output compared to a clean steam system. Michaelides (1980), proposed a flash system at the wellhead to separate the NCGs before they enter the turbine and determined the flash temperature depending on the NCG content. It is emphasised that NCG content in the steam is an important factor for the estimation of the recoverable work. If NCG content is higher than 0.1%, separating the NCGs by flashing at the wellhead results higher amount of work recovery. It is recommended that if NCG content is high, NCG separation should be taken into account thermodynamically and economically for the construction of plants. NCG separation before the turbine using reboilers is studied by Gunerhan (2000) for Kizildere Geothermal Power Plant. To increase power generation performance for very high NCG content fields, upstream reboiler systems are investigated as an alternative to conventional gas extraction systems. The direct contact reboiler tests were carried out in the field with an increase in net capacity by 10.6% at the base case.

Yildirim and Gokcen (2004) considered the NCG content on each step of energy and exergy analysis of Kizildere Geothermal Power Plant. They emphasised the importance of NCGs on power plant performance and concluded that since geothermal power plants contain a considerable amount of NCGs, the NCG content should not be omitted throughout the process and dead state properties should reflect the specified state properties.

The present study aims to exhibit the effect of NCGs to the geothermal power plant performance since one of the most important differences between geothermal power plants and fossil-fuelled power plants is the working fluid which is not pure steam. Therefore for a confident energy and exergy analysis of a geothermal power plant, the NCG content should be considered while determining the properties through the cycle. A parametric study is conducted to exhibit the effect of NCGs (0–25%) for various turbine inlet temperatures (140–250°C) to cover various geothermal power plants at different resource temperatures and NCG content.

2 Kizildere geothermal field and power plant

Kizildere geothermal field is located near the city of Denizli in Western Anatolia, Turkey (Figure 1) (Vogel, 1997). The first studies began in 1968, and Kizildere geothermal power plant was installed in 1984 with an installed capacity of 20.4 MW_e (Simsek, 1985).

Kizildere geothermal field is a liquid dominated system with a reservoir temperature of 200–242°C and a steam fraction of 10–20%. The most significant characteristic of the field is high amount of NCGs, which is 2.5% in the reservoir, 10–21% at the wellhead and average 15% by weight of steam at the turbine inlet. The major component of NCGs is carbon dioxide (CO_2), which is extracted from condenser and sent to a CO_2 plant to produce liquid CO_2 and dry ice with a capacity of 80,000 tons/a.

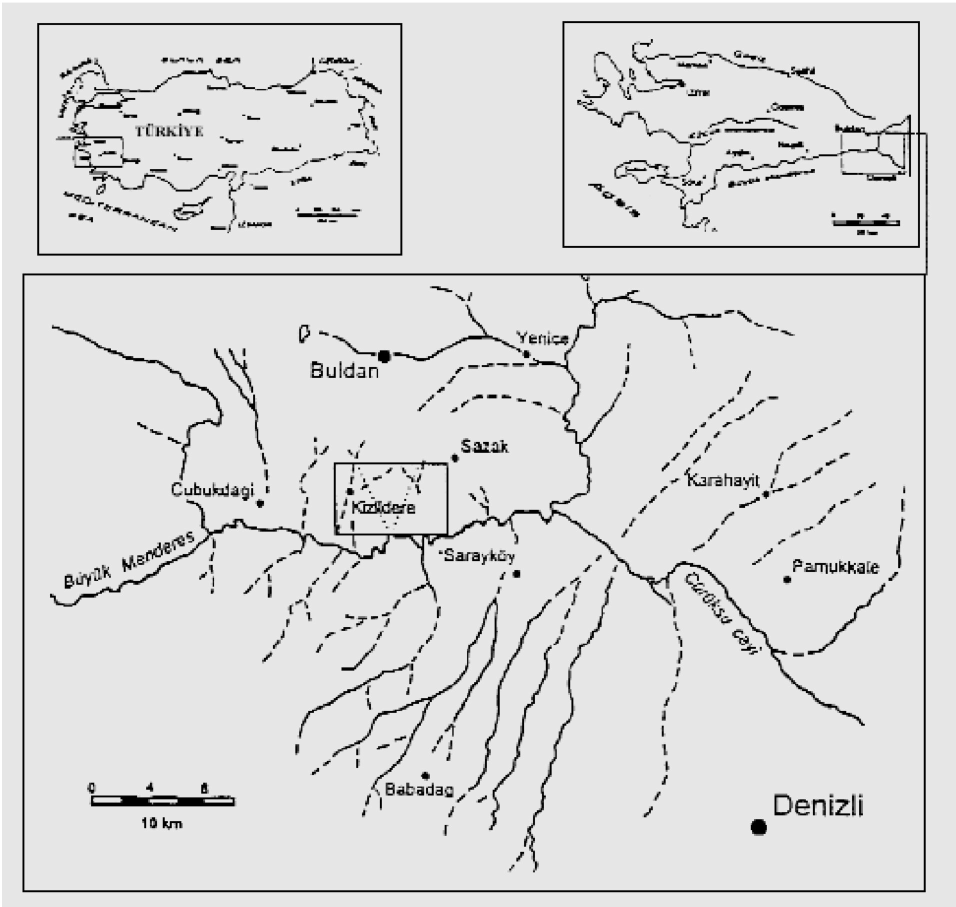
A flow diagram of Kizildere Geothermal Power Plant is given in Figure 2. Kizildere Geothermal Power Plant is a single flash design with a direct contact condenser. 22 production wells have been drilled but only 9 of which (KD 6, KD 13, KD 14, KD 15, KD 16, KD 20, KD 21, KD 22, R 1) are being operated. The average steam flow rate to the turbine is 33.3 kg/s.

The extracted geothermal fluid is saturated vapor-liquid-CO_2 mixture. When the geothermal fluid reaches to the wellhead, it is directed to a separator where steam and liquid phases are separated. Then steam is sent to the turbine where the electrical power is maintained while 257.7 kg/s liquid, which is 88.5% of the total flow rate, is used for district heating system of a town nearby, rejected to the Buyuk Menderes River through a

1.8 km long channel and a small fraction of the liquid is injected back to the reservoir since 2002 by the Well R 2. Turbine exit is connected to a direct-contact condenser. The steam and NCGs enter the condenser with the pressure of 0.01 MPa, NCGs are extracted by a compressor unit with intercooling and sent to the CO_2 plant. The gas extraction system consumes about 2.38 MW_e (18.3% of the gross capacity) due to the high NCG content. A mechanical draft-cooling tower is used to maintain the cooling water for condenser (Yildirim and Gokcen, 2004).

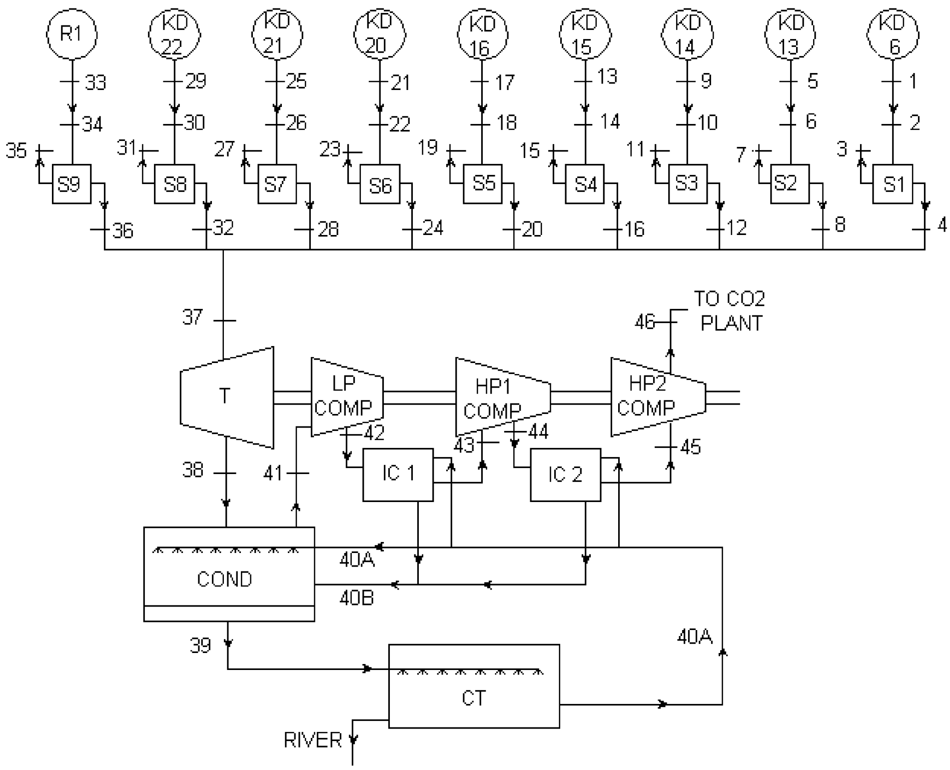
Kizildere geothermal field and power plant characteristics are given in Table 1. It can be seen that the amount of NCG is considerably high (average 15% by weight of steam) and consists mainly of CO_2 (Gunerhan, 2000).

Figure 1 Location of the Kizildere geothermal field, Turkey



Source: Vogel (1997)

Figure 2 Flow diagram of Kizildere geothermal power plant



COND: Condenser; COMP: Compressor; IC: Intercooler; CT: Cooling Tower;
T: Turbine; S: Separator; LP: Low Pressure; HP: High Pressure; CO_2: Carbon Dioxide.

Source: Yildirim and Gokcen (2004)

Table 1 Characteristics of the Kizildere geothermal field and power plant

Reservoir temperature (°C)	200–242
Operation pressure of wellhead (MPa)	1.2-3.0
Wellhead temperature (°C)	180–190
Total flowrate (*t/h*)	1155
Wellhead steam fraction (%)	10–20
Steam flowrate (*t/h*)	90–140
Total dissolved solids (TDS) for the wells (ppm)	2500–3200
NCG's % by weight of steam (%)	10–21 (average 15)
CO_2 content in NCG's (%)	96–99
H_2S content in NCG's (ppm)	100–200
Separator pressure (MPa)	0.48–0.55
Turbine inlet pressure (MPa)	0.47
Power plant capacity (MW_e)	20.4 (installed), 18 (gross)
Consumption of gas compressors (MW_e)	2.38 (18.3% of gross capacity)

Source: Gunerhan (2000)

3 Theoretical analysis

A geothermal power plant can be divided into two sections, namely.

- steam field
- power generation unit.

In this work, main components of a power generation unit such as turbine and gas extraction system are evaluated and a sensitivity analysis is conducted for varying NCG content and turbine inlet temperature.

3.1 Assumptions

- Only single flash systems are considered.
- All dissolved NCGs in the reservoir are assumed as flashed into steam phase.
- The mixture of NCGs is treated as only CO_2 since it constitutes the major fraction (>80%) of the NCGs (Michaelides, 1982). CO_2 behaves as an ideal gas in each step.
- System consists of an isentropic turbine, an isothermal condenser and an isentropic single-stage compressor.
- Condenser operation temperature and pressure is fixed to 43°C and 0.01 MPa.
- Pressure loss in the condenser is neglected.
- Turbine and compressor efficiencies are assumed as 75% and generator efficiency is assumed as 90%.
- Condensation rate in the condenser is assumed as 96%.
- The properties of dead state depends on the composition of turbine inlet at the ambient pressure (P_o), 0.101 MPa (~1 atm), and the ambient temperature (T_o), 18°C.

3.2 Exergy

Specific exergy is calculated as;

$$e = [(h - h_0) - T_0(s - s_0)] \tag{1}$$

The calculation of exergy requires the definition of a dead state which is given in Section 3.1. Exergetic efficiency of the turbine can be evaluated as follows

$$\varepsilon_t = \frac{w_t}{e_{t,\text{in}} - e_{t,\text{out}}} \tag{2}$$

The steam phase should be considered as steam and CO_2 mixture at given temperature and pressure. The specific enthalpy and entropy of the mixture is given by

$$\begin{aligned} h_{\text{mix}} &= fh_{\text{CO}_2,@(T)} + [1-f]h_{s,@(T)} \\ s_{\text{mix}} &= fh_{\text{CO}_2,@(T)} + [1-f]s_{s,@(T)} \end{aligned} \tag{3}$$

3.3 Turbine work

The mixture of saturated steam and CO_2 at the turbine inlet expands to a specified condenser temperature and pressure (43°C, 0.01 MPa).

Quality, which considers the NCG content at the turbine exit, is calculated as (Khalifa and Michaelides, 1978);

$$x(f) = f + x_{is} \times (1 - f) \quad (4)$$

Actual specific work output of the turbine calculated as;

$$w_{t,act} = x(f) \times w_{t,is} \quad (5)$$

3.4 Gas extraction system

Increasing NCG content increases mass flow rate of NCGs causing an increase in power requirement of the compressor. The net output of the plant is calculated as;

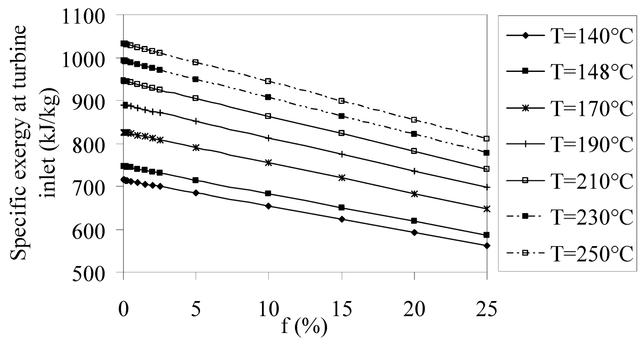
$$w_{net} = w_{t,act} - w_{c,act} \quad (6)$$

4 Results and discussion

In this parametric study, the effect of NCGs and turbine inlet temperature on the performance of geothermal power plants are analysed in a simple manner.

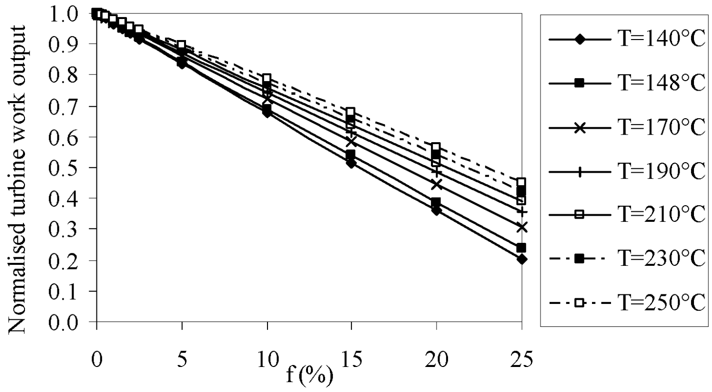
Figure 3 shows the variation of specific exergy at turbine inlet with NCG content (0–25%) at various turbine inlet temperatures (140–250°C). Exergy drops 0.86% by 1% increase in NCG. Figure also indicates that temperature effect on exergy change decreases with increasing turbine inlet temperature.

Figure 3 Specific exergy at turbine inlet vs. NCG content at various turbine inlet temperatures



The normalised specific actual work output of the turbine for various turbine inlet temperatures as a function of CO_2 mass fraction is shown in Figure 4. The actual work output is normalised by dividing the work output for a specific gas content to work output for gas content zero. Figure 4 indicates that increasing CO_2 fraction impairs the turbine power output drastically. For 140°C-turbine inlet temperature and, 5% and 25% NCG content, deterioration is 16% and 80% respectively. For 250°C-turbine inlet temperature, the same values are 11% and 55%.

Figure 4 The normalised specific turbine output vs. NCG content for various turbine inlet temperatures



The exergetic efficiency of the turbine for various turbine inlet temperatures as a function of CO_2 mass fraction is shown in Figure 5. Up to 7.5% NCG content, lower turbine inlet temperatures give higher exergetic efficiency. Above 7.5% NCG content, higher turbine inlet temperatures becomes more efficient.

The normalised exergetic efficiency of the turbine is also shown in Figure 6. Figure indicates that for any turbine inlet temperature, the exergetic efficiency decreases with increasing NCG content.

Figure 7(a) shows the specific net work output of the plant for various turbine inlet temperatures with varying NCG content. Increase in turbine inlet temperature causes an increase in net power output. For high NCG content, the improvement is as high as 40%. The loss in net power generation with NCG content exhibits the same behaviour as turbine output. Net work output decreases 3.7% by 1% increase in NCG. For 140°C and 25% NCG content, the net work output is only 25.86 kJ/kg while for 250°C and 25% NCG content, the net work output is 209.61 kJ/kg. A detailed view of 0–0.25% NCG content range is given at Figure 7(b). There is a sudden decrease in the net work output as high as 25.5% from zero to 0.1% NCG content.

Figure 5 Exergetic efficiency of the turbine vs. NCG content for various turbine inlet temperatures

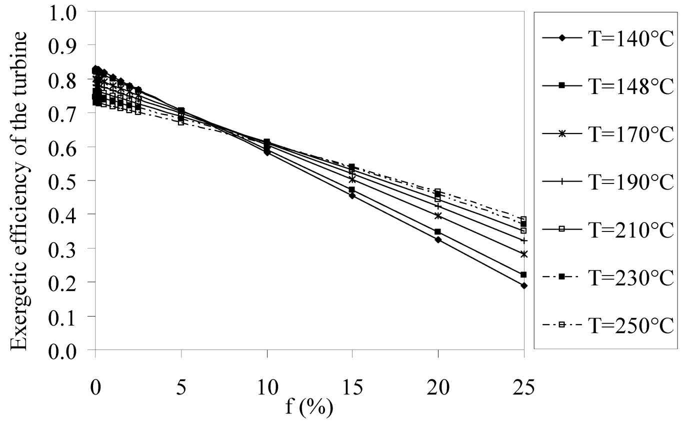


Figure 6 The normalised exergetic efficiency of the turbine vs. NCG content for various turbine inlet temperatures

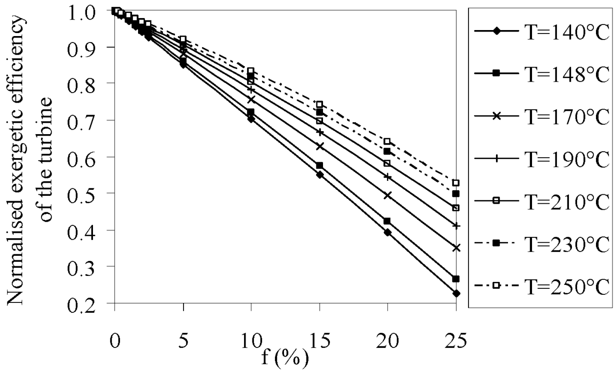
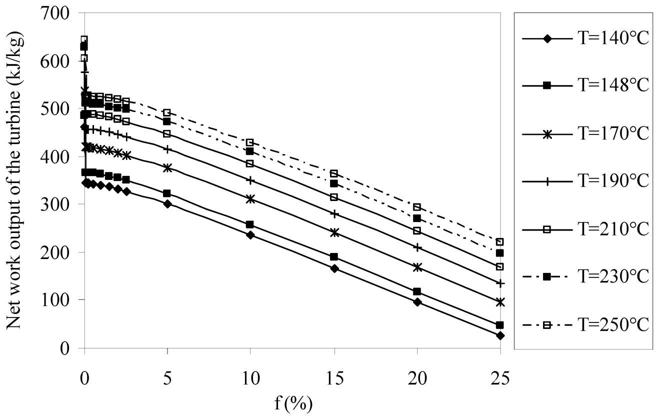
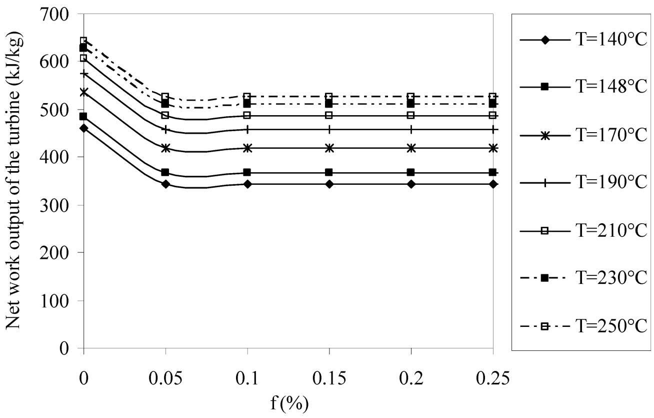


Figure 7 Net work output of the plant vs. NCG content for various turbine inlet temperatures: (a) non-condensable gas fraction ranging from 0% to 25% and (b) non-condensable gas fraction ranging from 0% to 0.25%



(a)



(b)

5 Conclusions

The influence of NCG content (0–25%) and turbine inlet temperature (140–250°C) on the turbine and the compressor of a geothermal power plant is analysed under the case of Kizildere Geothermal Power Plant. The main conclusions derived are given below:

- The presence of NCGs reduces the amount of work that can be extracted from the geothermal fluid in a single flash geothermal energy conversion system.
- Available work at the turbine inlet depends on NCG content more strongly than turbine inlet temperature. Maximum exergy drop encountered for 25% NCG content is about 22% comparing with zero NCG. For Kizildere case; at 148°C turbine inlet temperature and 15% NCG content, exergy loss at the turbine inlet is 96.4 kJ/kg, which corresponds to 13% decrease comparing with zero NCG content. Khalifa and Michaelides (1978) obtained a 25% decrease in the net work output at 10% NCG in the geothermal steam comparing with a clean steam system.
- Available work loss at the turbine inlet is 0.86% for each 1% NCG increase.
- Exergy loss and net work output is less sensitive to turbine inlet temperature than NCG content.
- Increasing NCG fraction and decreasing turbine inlet temperature impairs the turbine power output drastically. At low NCG contents, the influence of turbine inlet temperature is not significant but the higher the NCG content, the stronger the turbine inlet temperature effect.
- The magnitude of turbine inlet temperature effect increases with increasing NCG content.
- For design purposes, if the NCG content is below 7.5%, turbine inlet temperature can be decreased to increase the exergetic efficiency of the turbine. On the other hand, for NCG content higher than 7.5%, higher turbine inlet temperatures give higher turbine exergetic efficiencies. For Kizildere case; for 148°C turbine inlet temperature and 15% NCG gas content, the exergetic efficiency is 47.6%. A 10°C increase in turbine inlet temperature improves the exergetic efficiency by 3%. But additional temperature increases give less increase in efficiency each time.
- For low temperatures and high NCG content, the compressor work input would be equal to or higher than the turbine work output. In this case, to build a power plant is not economical. Thermodynamically, it is recommended to have a CO_2 plant to produce liquid CO_2 or dry ice instead.
- Knowing the NCG content of a resource, one can have a rough idea about the available work potential and work output of the turbine, net work output and exergetic efficiency of the turbine of a hypothetical power plant taken into account the assumptions given in Section 3.1.
- Increasing NCG content increases the turbine exit pressure thus decreases the turbine output further. But in this work, turbine exit pressure held constant. The increase should be considered in a future work.

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Nomenclature

e	Specific exergy (kJ/kg)
f	Non-condensable gas fraction (%)
h	Specific enthalpy (kJ/kg)
P	Pressure (MPa)
s	Specific entropy (kJ/kgK)
T	Temperature (°C)
w	Specific work (kJ/kg)
x	Quality (–)
Greek symbols	
ε	Exergetic efficiency (–)
Subscripts	
act	Actual
c	Compressor
CO_2	Carbon dioxide
in	Inlet
is	Isentropic
mix	Mixture
net	Net
o	Dead state
out	Outlet
t	Turbine
s	Steam