Assessment of Yuntdağı Hydrothermal System in Dikili-İzmir Region, Western Turkey

Aysegul Turan, Emre Artun, Salih Saner

Middle East Technical University-Northern Cyprus Campus

Keywords

Hydrothermal, Western Turkey, Monte Carlo Simulation, resource assessment, sustainability, Dikili-İzmir

ABSTRACT

For Turkey, one sustainable way to increase the clean energy share in the power generation can be the utilization of geothermal resources. This study aims to investigate the potential of hydrothermal system in Dikili-İzmir to generate power. Accessible resource base and recoverable heat energy are calculated by employing a probabilistic approach-Monte Carlo simulation. A sensitivity analysis is performed for the input parameters related to the heat potential of the reservoir. Based on the existing accessible resource base and recoverable heat in place calculations, with 90% probability, the net electrical power can be produced from Yuntdağ reservoir is 30 MW_e. Sensitivity analysis showed that reservoir area, rock-fluid temperature and recovery factor have the greatest impact on net power output. Sustainability attributes of the discussed cases are evaluated in terms of saved CO₂ amount and saved money by employing a domestic energy source rather than an imported one.

1. Introduction

Turkey, strategically positioned at the crossroads of Asia, Europe and the Middle East, is heavily dependent on expensive imported energy sources such as natural gas and crude oil that place a big burden on Turkish economy. On the other hand, air pollution has become a great environmental concern since these sources provide energy through combustion. With the increasing energy demand mainly caused by Turkey’s economic growth rate that peaked as 9.2% in 2010 in the last ten years (as of the third quarter of 2015, it is 4%) (Republic of Turkey Ministry of Economy, 2016), sustainable supply became a problem that cannot be ignored. As a solution, a major renewable energy and energy efficiency program has been embarked in the country. The target is set to increase clean energy share at least to 30% of Turkey’s power supply by 2023-the 100th anniversary of Turkish Republic. Another goal stated in the strategy paper of security supply is to decrease natural gas share in power supply to 30% (Republic of Turkey Ministry of Development, 2009). As of 2014, it was 47.9% (Republic of Turkey Energy Market Regulatory, 2015).
When location-based motivation is considered, according to the 2013 statistics, 90.48% of the total net electrical power was supplied by natural gas in İzmir. Wind, the only renewable energy source utilized in İzmir for electricity generation, with its intermittent nature, contributed to the total production with a 6.99% share. Fuel oil provided 2.45% and waste gas provided 0.08% of production (Güldar, 2014). Thus, the share of renewable energy sources in the power generation, should be increased in the region. When it comes to the consumption, as of 2013, the electricity consumption is 17,657,930 MWh in İzmir. It corresponds to the 7.2% of Turkey’s total consumption. However, in İzmir, electricity consumption per person is 4,348 kWh which is 35.8% more than Turkey’s average (Güldar, 2014). The reason behind this fact may be the heavy use of cooling due to hot weather conditions. As a further recommendation, ground-sourced-geothermal heat pumps can be utilized to decrease the share of cooling via electricity in consumption. About 60% of geothermal energy utilized in İzmir is used for district heating. Greenhouse heating corresponds to around 35%. Thermal tourism has a 5% share (Güldar, 2014). It means that all of the utilized geothermal energy sources in İzmir are directly-utilized. In other words, none of them are used for electricity generation. This study suggests the untapped potential of hydrothermal systems in Dikili-İzmir to increase the share of geothermal in power production. Since geothermal energy can support the baseload (i.e., it can run 24 hours a day) without requiring a storage system, it is preferred over the other intermittent renewable energy resources such as wind and solar.

2. Dikili Geothermal Field

The latitude is 38°91′N and longitude is 26°55′E for Dikili county town center. However, the study area involves not only Dikili but also a larger area surrounded by Bergama in the south, Dikili and Ayvalık in the west coast, Madra Mountain in the north. Madra Mountain is located 100 km to the North of İzmir and hosts archaeological Bergama site in the Southern slope of the mountain. The study area involves about 20 hot springs, shown as blue circles in colored copies, in Figure 1. On the left hand side of the figure, Dikili area is seen as a red rectangular positioned to the north of main geological sites, marked as yellow, in Western Anatolia. On the right hand side, study area is seen in detail as a double chin surrounded by hot springs, colored as blue circles.

![Figure 1: Location map of Dikili-Izmir.](image-url)
In Dikili, the climate is semiarid with an annual precipitation of 652 mm and the annual average temperature is 16.5 °C (Climate-data.org, n.d). Mean monthly temperature values are shown in Figure 2. Based on that information, heating is needed for six months in Dikili considering the months with a temperature below 18 °C.

![Figure 2: Mean monthly temperature values in Dikili, modified from Climate-data.org.](image)

Identified geothermal systems in Dikili-Bergama area are all hydrothermal systems surrounding the Madra Mountain as seen in Figure 1. This study is concerned with the indirect utilization of hydrothermal (considering Yuntdağ Volcanites as the reservoir rock) systems in the region.

### 2.1. Geological Outlook

Previous studies (Hou et al. 2015, Parlaktuna et al. 2015, Özen et al. 2005) defined eight formations in the study area: Çamoba, Kınık, Kozak Granodiorite, Ballica, Soma, Yuntdağ Volcanites, Rahmanlar Agglomerate and Dededağ Basalt from oldest to youngest. All formations are overlain by Quaternary alluvium at the top. Geological map of the area is given in Figure 3. Elevation contours are drawn for each 100 m. They get close to each other in Madra Mountain representing higher elevation of the mountain compared to its vicinity.

Permian aged Çamoba formation, which is the oldest unit in the study area, is composed of sandstone, siltstone and limestone. Its expected average thickness is around 250 m. Mesozoic Kınık formation is composed of conglomerate, sandstone, siltstone, mudstone, clayey limestone and limestone. Its average thickness is 400 m (Parlaktuna et al. 2015). Altunkaynak and Yılmaz, 1999 state that ‘during the long history of ascent of Kozak pluton, a variety of emplacement mechanisms occurred at different depths since Kozak pluton exhibits different effects on the host rocks along different contact’. The Kozak pluton is mainly composed of granodiorite (Altunkaynak et al. 2009). Although its thickness is not known (it may go deeper under Çamoba and Kınık formations), an average thickness is given as 800 m (Parlaktuna et al. 2015). Özen et al. (2005) states that Yuntdağ volcanites unconformably overlie Kınık formation and are classified into three groups: Yuntdağ volcanites-I, which is the oldest part of the Yuntdağ
Yuntdağ volcanites-II consists of dark compact basalt, pyroxene andesite and hornblende andesite.

Figure 3: Geological map of the study area with elevation contours (Kayan et al. 2007).

The youngest part of Yuntdağ formation is Yuntdağ volcanites-III (Özen et al. 2005). It consists of rhyolite, hornblende, biotite andesite and dacite (Hou et al. 2015). The thickness of Yuntdağ formation is 400 m (Parlaktuna et al. 2015). Upper Miocene Soma formation consists of alternation of siltstone, marl, conglomerate, sandstone and clayey limestone. Its thickness is 1000 m. Pliocene Rahmanlar formation is mainly composed of agglomerate. Its thickness is 400 m. Pliocene Dedebağ formation overlies Rahmanlar formation. Dedebağ formation mainly consists of basalts. Formation thickness is 100 m. All the units are overlain by Quaternary alluvium at the top. Its thickness is 100-150 m. Figure 4 illustrates these formation characteristics with a generalized stratigraphic columnar succession.

Among aforementioned eight formations, Yuntdağ Volcanites behave like a reservoir rock with its highly fractured structure due to tectonism and hydrothermal alterations. Generally, a cap rock is not seen in the study area. However, at some locations, Soma formation and the thick tuff and marl layers within the Yuntdağ formation behave like cap rock. The heat source in the region has been a subject of debate. Source of the heat stored within the Earth crust could be heat coming from core, subsurface magma intrusions or plutonic rocks formed from: magma at 10-20 kilometers of depth, young volcanic rocks such as hot lava or pyroclastic rocks reaching to surface, radioactive decay of U, Th and K radioactive isotopes that are abundantly occurring in some igneous rocks, excess amount of friction along faults and fractures in tectonic belts and...
local exothermal reactions in permeable formations. Hou et al. (2015) suggested that radioactive decay in Kozak Granodiorite is the heat source in the region, whereas Özen et al. (2008) claimed that shallow magma is the heat source since Kozak pluton is too old to be (Özen et al. 2008). In the final report of Japan International Cooperation Agency on ‘The Dikili-Bergama Geothermal Development Project’, the heat source is stated as deriving from both tectonism and volcanism due to the fact that the volcanic activity and tectonic movements are very intense in the study area (MTA-JICA, 1987).

![Figure 4: Generalized columnar section of study area, modified from (Parlaktuna et al. 2015).](image_url)

Figure 5 shows crustal structure and magmatic intrusions in an extensional tectonic environment. Plutonic intrusions in the subsurface could be the source of local anomalies shown in heat flow maps as thin continental crust and plutonic intrusions jointly are responsible for high geothermal heat.

### 2.2. Tectonic Setting

Western Anatolia is accepted as one of the world’s most rapidly-extending, crustal thinning zones with an extension rate of 14 ± 5 mm/year (Bilim et al. 2016). Dikili district is a
tectonically active area, where this N-S extensional regime, causing E-W extending grabens, exist.

Figure 5: Schematic model of thin Earth Crust and plutonic intrusions developed to explain high heat flow and associated thermal resources in the study area (Turan et al. 2016).

Kozak Granite forming Madra Mountain is surrounded by Yuntdağvolcanites at its foothills and all geothermal springs are associated with Yuntdağvolcanites around the Madra Mountain. The distribution of these hot springs is controlled by fracture patterns. Dominant fractures in Kozak Pluton (from image lineaments) are marked in red and active graben faults are shown in black lines in Figure 6.

Figure 6: Dominant fractures in Kozak Pluton from image lineaments (marked in red) and active graben faults (shown in black lines) affecting the occurrences of hot springs (marked as blue circles in colored copies) (Turan et al. 2016).
Based on the available information related to study area and our observations, it is concluded that water seeping into deep seated dominantly northeast-southwest trending fractures in Kozak granite is heated at depth. These fractures are intersected by active normal graben faults which form a pathway for heated water to flow out towards surface. Water table elevation in Kozak fractures is higher than the elevations of graben fault traces on the surface. This builds a hydrostatic pressure for water to form hot springs on the surface.

2.3. Hydrogeological Outlook

Dikili geothermal field has been the focus of direct utilization such as district heating, greenhouse heating and thermal tourism since early 2000’s. Although the geothermal investigations had started in the region after the big earthquake in 1939 (Kalınçı et al. 2008). Nowadays there are more than 30 wells in the field with well temperatures ranging from 41.5 to 131.4 °C. Some of them are listed in Table 1. As of 2015, 1160 residences (one residence is assumed to have 100 m² floor area) and 1,000,000 m² greenhouses are being geothermally heated in the region (Mertoglu et al. 2015).

Dikili has number of hot springs with changing temperature from 30 to 100 °C (Tabar et al. 2013). The hydrogeological studies indicate a minimum age of 50 years in subsurface based on radioactive isotope chemistry. Stable isotope analysis show that thermal waters are of meteoric origins, which recharged in Kozak region, heated at depth and moved up to the surface along the faults (Özen et al. 2005).

The types of thermal waters are Na-HCO₃-SO₄ in Dikili, Na-SO₄-HCO₃ in Kaynarca and NaCa-SO₄ in Kocaoba (Özen et al. 2005). Dissolved salts, SO₄⁻ and HCO₃⁻ content of thermal waters are related to their depths. SO₄⁻ is dominant for thermal waters coming from depths of 500-700 m whereas HCO₃⁻ is dominant for thermal waters coming from 700 m depth. Thus it is concluded that the reservoirs of the thermal waters in the study area are not very deep because of the low SO₄⁻ and HCO₃⁻ values. High values of Cl⁻ ion in Bademli spring are due to the sea water mixing. Based on this information, Tabar et al. (2013) stated that the temperature of the thermal waters in Dikili geothermal area is not high. Thermal waters in the study area are slightly acidic which may be due to the contact with carbonate rocks (Roba et al. 2012). According to the mineral equilibrium modelling, calcite, aragonite and dolomite scaling problems are expected in production wells (Özen et al. 2005).

2.4. Drilling and Production History

Dikili geothermal field has been the focus of direct utilization such as district heating, greenhouse heating and thermal tourism since early 2000’s. Although the geothermal investigations had started in the region after the big earthquake in 1939 (Kalınçı et al. 2008). Nowadays there are more than 30 wells in the field with well temperatures ranging from 41.5 to 131.4 °C. Some of them are listed in Table 1. As of 2015, 1160 residences (one residence is assumed to have 100 m² floor area) and 1,000,000 m² greenhouses are being geothermally heated in the region (Mertoglu et al. 2015).

3. Methodology

This study is composed of three main parts that are geothermal resource assessment, impact analysis and critical analysis. Since earth sciences deal with subsurface that yields uncertainty in
related parameters, geothermal resource assessment is performed by employing probabilistic methods rather than deterministic ones. Among the other resource assessment methods, the volumetric method is selected to calculate the stored heat energy since it is well suited to being adapted to a probabilistic approach. To apply this method, Monte Carlo Simulation technique is employed to allow the variables to vary over a defined range, by minimum, maximum, and/or most likely values, with a defined probability distribution. While using this technique, a random number is first generated and then it is used to determine the values of the variables within the defined probability distribution. The stored heat is then calculated using the generated values. This process is repeated until a well-defined probability distribution is observed as the expectation curve (i.e., a plot that shows the distribution of possible outcomes under uncertainty) for heat output (MWt or MWe) is obtained. In the second part, an impact analysis that reveals the heavy hitters among all the input parameters is performed by constructing a tornado chart. In the third part, a critical analysis is performed to highlight the sustainability attributes of the discussed systems. The summary of the workflow is illustrated in Figure 7.

Table 1: Wells in Dikili Geothermal Field

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Ownership</th>
<th>Well Depth (m)</th>
<th>Well T (°C)</th>
<th>T Measurement Place</th>
<th>Flow Rate (l/sec)</th>
<th>Flow Rate Measurement Way</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-1</td>
<td>MTA</td>
<td>1500</td>
<td>130</td>
<td>WB</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>Dikili Belediyesi</td>
<td>33.5</td>
<td>119.3</td>
<td>WI</td>
<td>48</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>B-2</td>
<td>Dikili Belediyesi</td>
<td>36</td>
<td>98</td>
<td>WH</td>
<td>30</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>B-3</td>
<td>Dikili Belediyesi</td>
<td>26.80</td>
<td>120</td>
<td>WB</td>
<td>34.8</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>T-1</td>
<td>İzmir İl Özel İdaresi</td>
<td>355</td>
<td>130.7</td>
<td>WB</td>
<td>42</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>T-2</td>
<td>İzmir İl Özel İdaresi</td>
<td>356</td>
<td>131.4</td>
<td>WB</td>
<td>47</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>T-3</td>
<td>İzmir İl Özel İdaresi</td>
<td>547</td>
<td>97</td>
<td>WH</td>
<td>45</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>A-0</td>
<td>Agrobay Seracılık</td>
<td>256</td>
<td>98</td>
<td>WH</td>
<td>40</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>A-1</td>
<td>Agrobay Seracılık</td>
<td>208</td>
<td>93</td>
<td>WH</td>
<td>30</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>A-2</td>
<td>Agrobay Seracılık</td>
<td>254</td>
<td>97.7</td>
<td>WH</td>
<td>15</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>A-3</td>
<td>Agrobay Seracılık</td>
<td>392</td>
<td>110</td>
<td>WI</td>
<td>50</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>A-4</td>
<td>Agrobay Seracılık</td>
<td>420</td>
<td>110</td>
<td>WI</td>
<td>50</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Z-1</td>
<td>Zeytindalı Termal</td>
<td>254</td>
<td>45</td>
<td>WH</td>
<td>5</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Ç-1</td>
<td>Vegevital-Çakır Eğitim</td>
<td>210</td>
<td>110</td>
<td>WI</td>
<td>30</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Ce-1</td>
<td>Ali Celep</td>
<td>253</td>
<td>105</td>
<td>WI</td>
<td>40</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDB-1</td>
<td>MTA</td>
<td>1400</td>
<td>50</td>
<td>-</td>
<td>1</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDB-2</td>
<td>MTA</td>
<td>1500</td>
<td>69</td>
<td>-</td>
<td>55</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDH-2010/11</td>
<td>MTA</td>
<td>1250</td>
<td>145</td>
<td>WB</td>
<td>4</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>İDH-2010/11</td>
<td>MTA</td>
<td>1250</td>
<td>71.5</td>
<td>WH</td>
<td>38</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDK-2010/13</td>
<td>MTA</td>
<td>270.6</td>
<td>47.5</td>
<td>-</td>
<td>35</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDD-2010/17</td>
<td>MTA</td>
<td>572</td>
<td>51.5</td>
<td>-</td>
<td>50</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>İDN-2011/1</td>
<td>MTA</td>
<td>583</td>
<td>74.9</td>
<td>-</td>
<td>65</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>DKO-I(2007)</td>
<td>MTA</td>
<td>729.5</td>
<td>41.5</td>
<td>-</td>
<td>9</td>
<td></td>
<td>P</td>
</tr>
</tbody>
</table>

WB: WELL BOTTOM  A: Artesian
WH: WELL HEAD    P: with Pump
WI: INSIDE THE WELL C: with Compressor

(Karahan. n.d.) İzmir ili yenilenebilir enerji sektör analizi (Nisan 2012)
3.1. Geothermal Resource Assessment

Muffler and Cataldi (1978) define geothermal resource base as ‘all the thermal energy in the earth’s crust under a given area, measured from mean annual temperature’. There are four main methods used in geothermal resource assessment: volume method, surface thermal flux method, planar fracture method and magmatic heat budget method. Muffler and Cataldi (1978) suggested that among these four methods, the volume method is the most useful one for accessible resource base calculations. In this method, heat energy stored in the reservoir is equal to the sum of heat stored in certain volume of rock (solid part) and water (fluid part) considering the fluid in the hydrothermal reservoir is only water, not with steam.

All the equations employed in this method are as follows:

\[ Q_t = Q_s + Q_w \tag{3.1} \]

where;

- \( Q_t \): total heat content, kJ
- \( Q_s \): heat content in solid, kJ
- \( Q_w \): heat content in water, kJ

\[ Q_t = (1 - \phi)c \rho (Ah)T_u + \phi c \rho (Ah)T_u \tag{3.2} \]

where;

- \( Q_t \): Heat energy, kJ
- \( \phi \): Porosity, fraction
- \( c \): Specific heat capacity, kJ/kg°C
\(\rho\): Density, kg/m\(^3\)
\(A\): Area of the reservoir, m\(^2\)
\(H\): Reservoir thickness, m
\(T_u\): Utilization temperature, °C

and subscripts \(t\), \(s\) and \(w\) stand for total, solid rock and water, respectively.

\[
RHE = \frac{(RF)(Q_e)}{(LF)(t)}(3.3)
\]

where;

\(RHE\): recoverable heat energy, kJ
\(RF\): recovery factor, fraction
\(t\): project life, seconds
\(LF\): load factor, fraction

Load factor is the ratio of total time in which the system is active in a year.

\[
NEP = (RHE)(CF)(3.4)
\]

where;

\(NEP\): net electrical power, MW\(_e\)
\(CF\): conversion factor, fraction

Conversion factor represents the ratio that accounts for the efficiency in heat transfer and electricity generation (i.e., transduction). It mainly depends on the efficiency in heat exchangers for direct utilization ways. For indirect utilization ways, it depends on the efficiency of all system components.

### 3.2. Probabilistic Assessment

Uncertainty can be represented in terms of a probability range of an event’s occurrences. The degree of uncertainty is introduced in the heat in place calculations by assigning a range of probabilities attached to an input parameter. A probability distribution function can be developed for an input parameter based on the frequency of occurrence of various values of that parameter. Further, cumulative distribution plots often an S-curve can be generated to show the probability of the outcome (Satter et al. 2008).

Probability distributions are classified mainly into two groups: Discrete and continuous. Continuous distributions are binomial, normal, triangular, log normal and uniform. In uniform distribution, minimum and maximum values are entered and all the values between them have
same frequency to occur. In triangular distribution, minimum, most likely and maximum values are entered to the model (Satter et al. 2008). In this study, MS Excel was used to perform Monte Carlo simulation. The required input parameters and the probability density functions that represent them in this study are given in Table 2. Sources of input data used and the assumptions that are taken into consideration are presented below.

Table 2: Input parameters and their probability density functions (PDFs) defined in the model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>Triangular</td>
</tr>
<tr>
<td>Area</td>
<td>Triangular</td>
</tr>
<tr>
<td>Thickness</td>
<td>Triangular</td>
</tr>
<tr>
<td>Rock &amp; Fluid Temperature</td>
<td>Triangular</td>
</tr>
<tr>
<td>Fluid Density</td>
<td>Triangular</td>
</tr>
<tr>
<td>Recovery Factor</td>
<td>Triangular</td>
</tr>
<tr>
<td>Rock Density</td>
<td>Uniform</td>
</tr>
<tr>
<td>Project Life</td>
<td>Constant</td>
</tr>
<tr>
<td>Load Factor</td>
<td>Constant</td>
</tr>
<tr>
<td>Conversion Factor</td>
<td>Constant</td>
</tr>
<tr>
<td>Specific Heat Capacity of Fluid</td>
<td>Constant</td>
</tr>
<tr>
<td>Specific Heat Capacity of Rock</td>
<td>Constant</td>
</tr>
<tr>
<td>Fluid Utilization Temperature</td>
<td>Constant</td>
</tr>
</tbody>
</table>

Porosity:

Based on the previous resource assessment studies (Sanyal et al. 2005, Atmaca (2010), Avşar (2011)); porosity is represented by triangular PDF in this study as seen in Figure 8. The porosity values of Yuntdağ volcanites, since they are mainly composed of andesite, are chosen as minimum 0.01 and maximum 0.03 (Schön, 2011). Hou et al. (2015) estimated the porosity of Yuntdağ Volcanites as 0.0129 based on field study and related literature. That is why these values are assigned as most likely values in the model.
Figure 8: Histograms (as PDF) and cumulative expectation curves (as CDF) for porosity with triangular distribution.

Area:

Area is represented by triangular PDF in this model as seen in Figure 9 based on the related previous studies (Sanyal et al. 2005, Atmaca (2010), Avşar (2011), Arkan et al. 2005). The reservoir area can be calculated exactly by the help of resistivity maps. Due to the unavailable data, for Yuntdağ Volcanites, reservoir area is taken as $1.5 \times 10^7 \text{ m}^2$, $3.0 \times 10^7 \text{ m}^2$, and $4.5 \times 10^7 \text{ m}^2$ as minimum, most likely and maximum values, respectively.

Figure 9: Histograms (as PDF) and cumulative expectation curves (as CDF) for area with triangular distribution.


**Thickness:**

Thickness is represented by triangular PDF in this model as seen in Figure 10 based on the related literature (Sanyal et al. 2005, Atmaca (2010), Avşar (2011), Arkan et al. 2005). To take the uncertainty into account, **minimum thickness** is defined as the total thickness of the cap rock and the reservoir rock. **Most likely** one is assigned as the total of minimum thickness and one more formation which underlies reservoir rock. **Maximum** values are defined as the total of minimum thickness and all formations, given in the generalized columnar section in Figure 4, that underlie the reservoir rock. Yumtdag-1 formation is the reservoir rock whereas Soma formation is the cap rock. A sample configuration is given in Figure 11.

Hou et al. (2015) presents the minimum thickness of the stratigraphic units encountered during borehole drilling in their study area as follows: Yumtdag Volcanites-1 as 300 m and Soma formation as 200 m. The thickness of Kozak pluton and Kınik formation are given as unknown by Hou et al. (2015) so these values are taken as 800 m and 400 m respectively based on the data published by Avşar and Parlaktuna, (2015). Reservoir thickness is taken as 500 m, 1300 m, and 1950 m as minimum, most likely and maximum values, respectively.

![Figure 10: Histograms (as PDF) and cumulative expectation curves (as CDF) for thickness with triangular distribution.](image)

![Figure 11: Illustration of formation sequences of Yumtdag hydrothermal system, explaining minimum, most likely and maximum cases for the input ‘thickness’ (not to scale).](image)
Recovery Factor:

The recovery factor represents the amount of heat that is convected by fluid from the rock to the surface. As suggested by Muffler and Cataldi (1977), recovery factor is represented by a triangular PDF and the minimum, most likely and maximum values are taken as 0.07, 0.18 and 0.24, respectively.

![PDF and CDF for Recovery Factor](image1)

**Figure 12:** Histograms (as PDF) and cumulative expectation curves (as CDF) for recovery factor with triangular distribution.

Rock-Fluid Temperature:

The rock-fluid temperature (RFT) is actually the reservoir temperature in geothermal resource assessment since rock and fluid are accepted as in equilibrium in terms of heat transfer. RFT is represented by triangular PDF in this model, as seen in Figure 13, based on the previous studies (Sanyal et al. 2005, Atmaca (2010), Avşar (2011), Arkan et al. 2005).

![PDF and CDF for Rock-Fluid Temperature](image2)

**Figure 13:** Histograms (as PDF) and cumulative expectation curves (as CDF) for rock-fluid temperature with triangular distribution.
RFT was assigned based on the available field data since all the wells presented in Table 2, are producing from hydrothermal reservoirs in Dikili. Cumulative distribution function of well bottom temperatures was plotted as can be seen in Figure 14. Then the well bottom temperature that corresponds to 50% probability was taken as most likely value (93 °C). The minimum and maximum values were taken as 64.16 °C and 145 °C respectively based on the available well bottom temperature data, presented in Table 2.

![Cumulative expectation curve of well bottom temperatures.](image)

**Figure 14:** Cumulative expectation curve of well bottom temperatures.

**Rock density:**

Rock density is the only parameter that is represented by uniform distribution in this model. Because there was not any available rock density data measured in the field to assign as most likely value. Further, since andesite is igneous rocks, the chance (i.e., frequency) to have any rock density value between the given range (minimum to maximum) is same. Figure 15 illustrates histograms (as PDF) and cumulative expectation curves (as CDF) for rock density with uniform distribution. Rock density is taken as 2500 kg/m³ and 2800 kg/m³ as minimum and maximum values, respectively, based on the data provided by literature (Schön, 2011).

![PDF and CDF for Rock Density](image)

**Figure 15:** Histograms (as PDF) and cumulative expectation curves (as CDF) for rock density with uniform distribution.
Fluid Density

Fluid density is represented by triangular PDF in this model, as seen in Figure 16, based on previous studies (Atmaca, 2010 and Avşar, 2011). There are three parameters that affect fluid density; pressure, temperature and salinity.

For hydrothermal systems in Dikili, Alacalı and Yılmazer (2005), state salinity (i.e. total dissolved solids) as 3000 ppm. Depth of the reservoir is taken as 1420 m, consistent with the thickness data presented earlier. Thus, hydrostatic pressure is obtained as 2017 psi according to a pressure gradient of 0.433 psi/ft. Then for Yumtdağ Volcanites, fluid density values are obtained from related charts (Figure 17) as 945kg/m³, 980kg/m³ and 995kg/m³ as minimum, most likely and maximum values, respectively.

In addition to the aforementioned parameters with PDFs, there are six input parameters that are constant. These are project life, load factor, conversion factor, specific heat capacity of rock, specific heat capacity of fluid and fluid utilization temperature (i.e. rejection temperature). Since these parameters are known exactly (like load factor) or do not change significantly (like specific heat capacity), they are taken as constants. Project life is generally assumed to be 30 years (Garg et al. 2015). For the unit conversion, it is taken as 9.46x10⁸ seconds in the calculations. For electricity generation, power plants are active except the maintenance time since geothermal can provide base load. Thus, load factor is taken as 0.95 for indirect utilization (Garg et al. 2015). For this study, conversion factor is taken as 0.12 for indirect utilization. Specific heat capacity of rock is taken for andesite for Yumtdağ reservoir as 0.965 kJ/kg-ºC (Schön, 2011). For Yumtdağ hydrothermal system, specific heat capacity of water is taken as 4.14 kJ/kg-ºC that corresponds to 93ºC which is the most likely reservoir temperature of this system. For electricity production, rejection temperature is taken as 60 ºC considering the possibility of scaling under this temperature. As a result, ranges of input parameters used for the probabilistic assessment of indirect utilization of Yumtdağ Volcanites are shown in Table 3.
Figure 17: Fluid density chart for different salinity, temperature and pressure values.

Table 3: Input parameters, their ranges and distributions used for the probabilistic assessment of indirect utilization of Yuntdağ Volcanites reservoir.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>PDF</th>
<th>Minimum</th>
<th>Most Likely</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td></td>
<td>Triangular</td>
<td>0.01</td>
<td>0.0129</td>
<td>0.03</td>
</tr>
<tr>
<td>Specific Heat Capacity of Rock-Volcanites</td>
<td>kJ/kg°C</td>
<td>Constant</td>
<td></td>
<td>0.965</td>
<td></td>
</tr>
<tr>
<td>Rock Density-Volcanites</td>
<td>kg/m³</td>
<td>Uniform</td>
<td>2,500</td>
<td>2,800</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>m²</td>
<td>Triangular</td>
<td>1.5E+07</td>
<td>3.0E+07</td>
<td>4.0E+07</td>
</tr>
<tr>
<td>Thickness</td>
<td>m</td>
<td>Triangular</td>
<td>500</td>
<td>1,300</td>
<td>1,950</td>
</tr>
<tr>
<td>Rock-Fluid Temperature</td>
<td>°C</td>
<td>Triangular</td>
<td>64.16</td>
<td>93</td>
<td>145</td>
</tr>
<tr>
<td>Fluid Utilization Temperature</td>
<td>°C</td>
<td>Constant</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity of Fluid</td>
<td>kJ/kg°C</td>
<td>Constant</td>
<td></td>
<td>4.14</td>
<td></td>
</tr>
<tr>
<td>Fluid Density</td>
<td>kg/m³</td>
<td>Triangular</td>
<td>945</td>
<td>980</td>
<td>995</td>
</tr>
<tr>
<td>Recovery Factor</td>
<td></td>
<td>Triangular</td>
<td>0.07</td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>Project Life</td>
<td>seconds</td>
<td>Constant</td>
<td></td>
<td>946,080,000</td>
<td></td>
</tr>
<tr>
<td>Load Factor</td>
<td></td>
<td>Constant</td>
<td></td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Conversion Factor</td>
<td></td>
<td>Constant</td>
<td></td>
<td>0.12</td>
<td></td>
</tr>
</tbody>
</table>
4. Analysis and Results

Cumulative expectation curve of the net electrical power output by indirect utilization of Yuntdağ hydrothermal reservoir is shown in Figure 18. This curve indicates the following net electrical power outputs with corresponding probabilities:

- 30 MW\textsubscript{e} with 90% probability,
- 75 MW\textsubscript{e} with 50% probability,
- 150 MW\textsubscript{e} with 10% probability.

![Figure 18: Cumulative expectation curve for indirect utilization of Yuntdağ hydrothermal reservoir.](image)

4.1 Sensitivity Analysis of Heat Production to Input Parameters

Figure 19 presents the tornado chart that reveals the sensitivity of net electric power to input parameters related to reservoir characteristics. As seen, area of the reservoir and rock-fluid temperature (RFT) are the input parameters that have greatest impact on the net electric power that can be output. Recovery factor has also great effect, third ranked, on the output among seven parameters. Neither porosity nor fluid density has a significant impact on the net electrical power output.

4.2 Critical Analysis of the System

The sustainability attributes of the discussed systems are examined as follows:

a) In terms of saved CO\textsubscript{2} amount (environmental point of view): by employing a renewable energy source such as geothermal rather than fossil fuels, such as natural gas.
b) In terms of saved amount of money (economical point of view): by employing a domestic resource i.e. geothermal resources rather than an imported energy source (i.e., natural gas).

4.2.1 Saved CO$_2$ Amount by Employing Proposed Geothermal Systems rather than Natural Gas

The annual amount of saved CO$_2$ is calculated as around 105,519 ton when 30 MW$_e$ is produced from Yuntdağ Volcanites instead of natural gas.

Natural gas, which is mainly CH$_4$(i.e., methane), combustion reaction with oxygen is as follows:

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$$

The molecular weight of methane is 12 + (4*1) = 16 g

The molecular weight of CO$_2$ is 12 + (2*16) = 44 g

It means that when 16 grams of natural gas is combusted, 44 grams of CO$_2$ is released to the atmosphere.

To convert 30 MW to kcal;

$$30 \times 10^6 \text{ joules/sec} \times 0.239 \text{ cal/joules} \times 10^{-3} \text{ kcal/cal} = 7170 \text{ kcal/sec}$$

To find the annual amount of saved CO$_2$;

$$7170 \text{ kcal/sec} \times 60 \times 24 \times 365 \text{ sec/year} = 226,113,120,000 \text{kcal in one year.}$$

To find the amount of natural gas which can supply that much of energy;

$$226,113,120,000 \text{kcal} / 8250 \text{ kcal/m}^3 = 27,407,650.91 \text{ m}^3 \text{ natural gas.}$$
To find the mass of natural gas, the volume is multiplied by the density of natural gas:

\[
27,407,650.91 \text{m}^3 \times 0.7 \text{ kg/m}^3 = 19,185,355.64 \text{kg CH}_4
\]

As shown previously, 16 g CH\(_4\) yields 44 g CO\(_2\)

\[
19,185,355.64 \text{kg CH}_4 \text{ yields } 19,185,355.64 \times \frac{44}{16} = 52,759,728.00 \text{kg CO}_2
\]

If the efficiency of a natural gas cycle power plant is taken as 50%, then saved amount of CO\(_2\) is doubled. By using hydrothermal system rather than natural gas to generate 30 MW\(_e\), the annual amount of CO\(_2\) saved is 105,519,456.00 kg. Results are summarized in Table 5.

<table>
<thead>
<tr>
<th>Calculation Steps</th>
<th>Results</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 MW</td>
<td>30,000,000</td>
<td>J/s</td>
</tr>
<tr>
<td>1 joule</td>
<td>0.239</td>
<td>cal</td>
</tr>
<tr>
<td>1 cal</td>
<td>0.001</td>
<td>kcal</td>
</tr>
<tr>
<td>Seconds in year</td>
<td>31,536,000</td>
<td>sec/year</td>
</tr>
<tr>
<td>1 m(^3) CH(_4) in combustion</td>
<td>8,250</td>
<td>kcal</td>
</tr>
<tr>
<td>Density of natural gas</td>
<td>0.7</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>CO(_2) factor</td>
<td>2.750</td>
<td>44/16</td>
</tr>
<tr>
<td>Efficiency of power plant</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Paid per 1 m(^3)</td>
<td>0.175</td>
<td>$</td>
</tr>
<tr>
<td>30 MW</td>
<td>7,170</td>
<td>kcal/sec</td>
</tr>
<tr>
<td>Yearly kcal</td>
<td>226,113,120,000</td>
<td>kcal</td>
</tr>
<tr>
<td>Natural gas amount</td>
<td>27,407,650.91</td>
<td>m(^3)</td>
</tr>
<tr>
<td>Mass of natural gas</td>
<td>19,185,355.64</td>
<td>kg</td>
</tr>
<tr>
<td>CO(_2) amount</td>
<td>52,759,728</td>
<td>kg</td>
</tr>
<tr>
<td>Saved CO(_2)</td>
<td>105,519,456</td>
<td>kg</td>
</tr>
</tbody>
</table>

### 4.2.2 Saved Amount of Money by Employing a Domestic Resource rather than an Imported Energy Source

To calculate the overburden, the assumptions are as follows:

As of 2016, based on European Union natural gas import prices, 1000 m\(^3\) of natural gas costs 175 dollars (European Union Natural Gas Import Price Chart, 2016). There is no CO\(_2\) incentive or
tax regulation taken into account as it is now in Turkey (Kıvılcım, 2014). The efficiency of the natural gas cycle power plant is 50%.

When it comes to the overburden on Turkish economy due to imported energy sources such as natural gas, generating 30 MWₖ from domestic geothermal resources rather than imported natural gas saves 9,592,677.82 dollars, respectively.

Since Yuntdağ Volcanites hydrothermal reservoir generates 30 MWₑ,

\[ 2 \times 27,407,650.91 \text{ m}^3/1000 \text{ m}^3 \times 175 \$ = 9,592,677.82 \$ \]

5. Summary and Conclusions

The present feasibility analysis consists of resource assessment, sensitivity analysis and critical analysis of the resource assessment’s results in terms of sustainability. Resource assessment was carried out for low enthalpy Yuntdağ Volcanites hydrothermal system by applying volumetric method. In the sensitivity analysis part, the impacts of input parameters on the outputs in the recoverable heat content calculation were ranked. In the critical analysis part, the findings of the present study were evaluated in terms of saved money and CO₂ amount by employing a domestic renewable energy source (geothermal) rather than an imported fossil fuel (natural gas). Net electrical power is 30 MWₑ for a hydrothermal system producing from Yuntdağ Volcanites, with 90% probability. This amount increases to 75 MWₑ, with 50% probability and to 150 MWₑ, with 10% probability. Sensitivity analysis showed that the thickness and the area of the reservoir formation are the inputs that have greatest impact on accessible resource base and the recoverable heat energy outputs. It also showed that calculations are not sensitive to rock density, porosity and fluid density.

REFERENCES


