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Resource Assessment of Kozak Granodiorite for an EGS Application in Dikili-İzmir Region, Western Turkey

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ABSTRACT

A sustainable energy future for Turkey depends on a balanced low-carbon energy mix with continued access to geothermal resources since they are abundant, domestic, renewable and able to supply base load and high energy security. Over 30 years of utilization of hydrothermal systems enabled Turkey to break into the 1 GW Geothermal Country Club as of August 2017. Today, with an installed capacity of 1615 MW_e 'low-hanging fruit' of geothermal energy have gone whereas enhanced geothermal systems (EGS) offer the chance to exploit more from the geological settings, previously taken as non-economic.

This study aims to investigate the untapped potential of Kozak granodiorite as an enhanced geothermal reservoir to generate thermal and electrical power. Kozak pluton in Dikili-İzmir geothermal field is selected to be assessed with four different production scenarios, based on artificial reservoir volume and production purpose. Accessible resource base and recoverable heat energy are calculated by employing a probabilistic approach- Monte Carlo simulation. A sensitivity analysis is performed for the effects of reservoir parameters on heat potential. Sustainability attributes of the discussed cases are evaluated in terms of saved CO_2 amount and saved money by employing a local energy source rather than an imported one.

Based on the existing accessible resource base and recoverable heat in place calculations, net electrical power is 8 MW_e for Kozak-EGS, with 90% probability. This amount increases to 17 MW_e, with 50% probability and to 32 MW_e, with 10% probability. On the other hand, net thermal power is 150 MW_t for Kozak-EGS, with 90% probability. This amount increases to 300 MW_t, with 50% probability and to 560 MW_t, 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 for real volume case. This is due to the large band of uncertainty regarding the bulk volume as a result of limited data. Since the reservoirs in EGS applications are man-made, a unit volume case is also considered for Kozak granodiorite reservoir. For a unit volume of 1 km^3, based on P90 estimates, Kozak-EGS generates 3.8 MW_e. This amount increases to 6.7 MW_e, with 50% probability and to 10 MWe, with 10% probability. On the other hand, net thermal power is 72 MW_t, with 90% probability. This amount increases to 118 MWt, with 50% probability and to 172 MW_t, with 10% probability. In this case, the temperature and the recovery factor are the inputs that have greatest impact on the accessible resource base and the recoverable heat energy outputs for the unit-volume case. To highlight the sustainability attributes of the present study; the unit-volume case of Kozak EGS is selected to be compared with natural gas, the dominant player in Turkey's energy supply. 3.8 MW_e generated from 1 km^3 of Kozak-EGS reservoir saves 13.4 million kg of CO_2 and $ 1.2 million annually without any regulation for CO_2-related tax. With a CO_2 tax regulation such as 13.6 euro per tons of CO_2, annual saved amount changes to $1.4 million from the operating companies' perspectives.

1. INTRODUCTION

The subject of this research roots from the common existence of young volcanic regions that are the geothermal environments with high heat flow, low permeability and no water. With today's technology, the enhanced geothermal system (EGS) is the best energy conversion system to exploit these resources, by circulating water through wells in artificially fractured hot rock, both from a technical and environmental point of view. In this study, four different scenarios were defined to see how feasible the utilization of Kozak granodiorite performs as an EGS reservoir in Dikili-İzmir region is. The conducted feasibility study is based on the results of the heat in place calculation and sensitivity analysis of input parameters. It also takes the comparison of carbon emissions of each discussed system into account. For geothermal resource assessment, volume method was applied to calculate thermal energy contained in a given volume of rock and fluid and to estimate how much of this energy is recoverable. A probabilistic study is carried out rather than a deterministic one since the nature of the uncertainty of input parameters is described with probability density functions. Thus, the heat in place calculation is carried out by utilizing Monte Carlo simulation. The impact of the sensitivity of input parameters such as porosity, formation volume, rock and fluid temperature, fluid density, and recovery factor on heat generation was also investigated.

2. DIKILI GEOTHERMAL FIELD

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, as can be seen in Figure 1. Till now, all the identified geothermal systems in Dikili-Bergama area are hydrothermal systems surrounding the Madra Mountain whereas northeast-southwest trending ellipsoidal granitic Kozak Pluton, forming 500 to 800-meter-high (highest point 1,341 m) mountains surrounded by Yuntdağ Volcanites at lower elevations, may be a hot dry rock system.

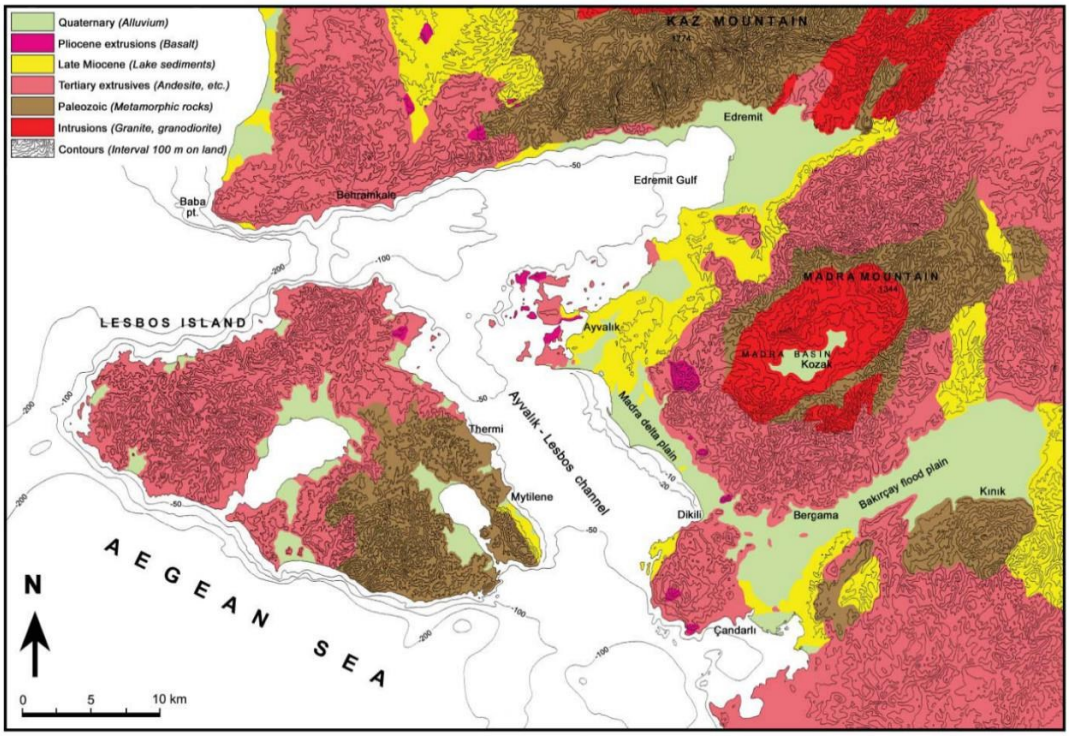

Figure 1: Geological map of the study area with elevation contours (Kayan et al. 2007)

Eight formations, namely; Çamoba, Kınık, Kozak Granodiorite, Ballıca, Soma, Yuntdağ Volcanites, Rahmanlar Agglomerate and Dededağ Basalt (from oldest to youngest) were defined by previous studies (Hou et al. 2015, Parlaktuna et al. 2015 and Özen et al. 2005) in the study area. Quaternary alluvium overlies all the formations at the top.

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 contacts.' The Kozak pluton is mainly composed of granodiorite. Although its exact thickness is not known (it may go deeper under Çamoba and Kınık formations), an average thickness is given as 800 m by Parlaktuna et al. 2015.

Dikili district is a tectonically active area, where existing N-S extensional regime causes E-W extending grabens. Dominant fractures in Kozak Pluton (from image lineaments) are marked in red and active graben faults are shown in black lines in Figure 2.



Figure 2: 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)

3. METHODOLOGY

The objective of the present study is to perform a feasibility study for an enhanced geothermal system application in Dikili-İzmir region. This feasibility 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 in uncertainty in related parameters, geothermal resource assessment is done 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 for heat output is obtained. Sensitivity of the output to the number of simulations is also tested. In the second part, an impact analysis that reveals the heavy hitters among all the input parameters is done by plotting tornado charts. In the third part, a critical analysis is done to highlight the sustainability attributes of the discussed systems.

3.1. Geothermal Resource Assessment

Volume method, suggested by Muffler and Cataldi 1978, is employed for accessible resource base calculations. 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

$$Q_t = (1-\varphi)\, c\, \rho\, (A*h)\, T_u + \varphi\, c\, \rho\, (A*h)\, T_u\,, \tag{3.2}$$

where;

Q_t= Heat energy, kJ

φ = Porosity, fraction

c= Specific heat capacity, kJ/kg-ºC

ρ= Density, kg/m^3

A= Area of the reservoir, m^2

h= Reservoir thickness, m

T_u= Utilization temperature, ºC

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

$$RHE= (Q_t*RF)/ (t*LF), \tag{3.3}$$

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.

$$NEP= RHE*CF, \tag{3.4}$$

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).

3.2. Probabilistic Assessment

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. Input parameters, their probability density functions and the assumptions defined in the model were discussed in detail by Turan 2016 and Turan et al. 2017.

Table 1: Input parameters for indirect utilization of Kozak Granodiorite EGS reservoir.

	Unit	PDF	min.(x_l)	(x_m)	max.(x_h)	x_r
Porosity		Triangular	0.01	0.0200	0.03	0.50
Specific Heat Capacity of Rock-Granodiorite	kJ/kg°C	Constant		1.090		
Rock Density-Granodiorite	kg/m^3	Uniform	2570.00		2800.00	-11.17
Area	m^2	Triangular	3.30E+05	8.80E+05	2.21E+06	0.29
Thickness	m	Triangular	2150.00	2400.00	2800.00	0.38
Rock-Fluid Temperature	°C	Triangular	96.00	165.00	237.00	0.49
Fluid Utilization Temperature	°C	Constant		60.00		
Specific Heat Capacity of Fluid	kJ/kg°C	Constant		4.26		
Fluid Density	kg/m^3	Triangular	830.00	905.00	965.00	0.56
Recovery Factor		Triangular	0.07	0.18	0.24	0.65
Project Life	seconds	Constant		946080000.00		
Load Factor		Constant		0.96		
Conversion Factor		Constant		0.12		

Table 2: Input parameters for direct utilization of Kozak Granodiorite EGS reservoir.

	Unit	PDF	min.(x_l)	(x_m)	max.(x_h)	x_r
Porosity		Triangular	0.01	0.0200	0.03	0.50
Specific Heat Capacity of Rock-Granodiorite	kJ/kg°C	Constant		1.090		
Rock Density-Granodiorite	kg/m^3	Uniform	2570.00		2800.00	-11.17
Area	m^2	Triangular	3.30E+05	8.80E+05	2.21E+06	0.29
Thickness	m	Triangular	2150.00	2400.00	2800.00	0.38
Rock-Fluid Temperature	°C	Triangular	96.00	165.00	237.00	0.49
Fluid Utilization Temperature	°C	Constant		41.50		
Specific Heat Capacity of Fluid	kJ/kg°C	Constant		4.26		
Fluid Density	kg/m^3	Triangular	830.00	905.00	965.00	0.56
Recovery Factor		Triangular	0.07	0.18	0.24	0.65
Project Life	seconds	Constant		946080000.00		
Load Factor		Constant		0.50		
Conversion Factor		Constant		0.95		

4. ANALYSIS AND RESULTS

Overall obtained results for real volume case are summarized in Table 3 and they are read from related plots presented in Figure 3 and Figure 4.

Table 3: Power output of each case in units of MW, with 10%, 50% and 90% probability, respectively (for real volume of reservoir).

	P10	P50	P90
EGS-electricity	32	17	8
EGS-heating	560	300	150

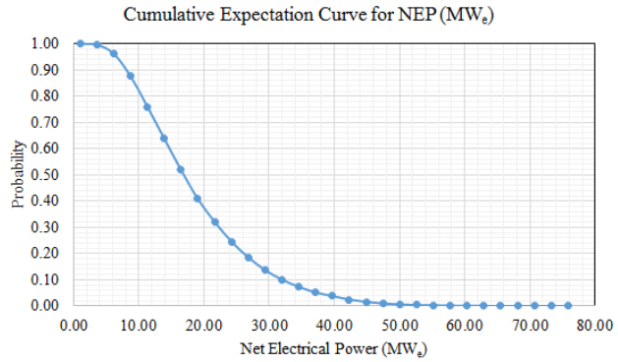

Figure 3: Cumulative expectation curve for indirect utilization of real volume EGS reservoir.

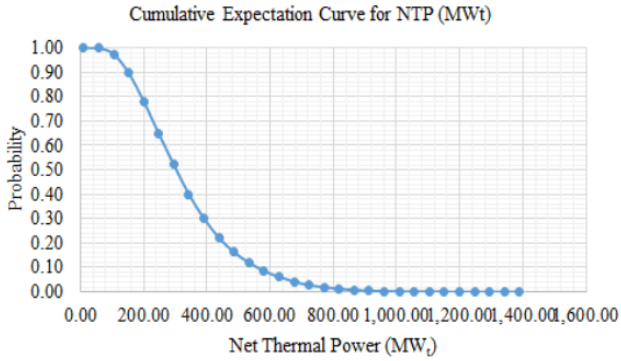

Figure 4: Cumulative expectation curve for direct utilization of real volume of EGS reservoir.

If the volume of EGS reservoir is considered as 1 m^3, then, with P90, EGS can produce $7.2*10^{-8}$ MW_t and $3.8*10^{-9}$ MW_e. Overall obtained results for unit volume case are summarized in Table 4 and they are read from related plots presented in Figure 5 and Figure 6.

Table 4: Power output of each case in units of MW, with 10%, 50% and 90% probability, respectively (for unit volume of reservoir).

	P10	P50	P90
EGS-electricity	1.01E-08	6.70E-09	3.80E-09
EGS-heating	1.72E-07	1.18E-07	7.20E-08

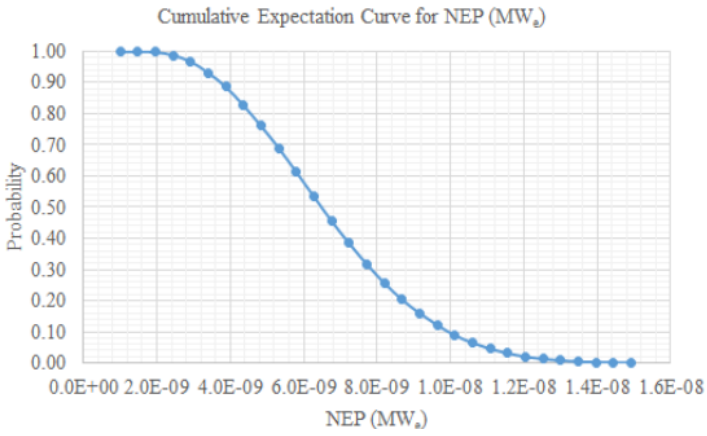

Figure 5: Cumulative expectation curve for indirect utilization of unit volume of EGS reservoir.

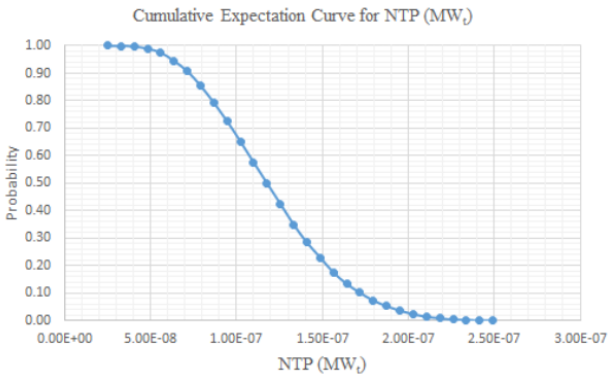

Figure 6: Cumulative expectation curve for direct utilization of unit volume of EGS reservoir.

4.1. Sensitivity Analysis

Figure 7 presents tornado charts that reveal the sensitivity of heat potential to input parameters for real volume case. As seen, area of the reservoir and rock-fluid temperature (RFT) are the input parameters that have greatest impact on accessible resource base and the recoverable heat energy outputs. 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. However, for the unit volume case, rock-fluid temperature (RFT) and recovery factor have greatest effects on the output as seen in Figure 8. Rock density is the third ranked parameter having great effect on the output. Similar to the real volume case, neither porosity nor fluid density has a significant effect on the output. In unit volume case, as expected, area and thickness do not affect the result significantly since they are taken as constant, as 1 m^2 and 1 m respectively, to represent 1 m^3 unit volume.

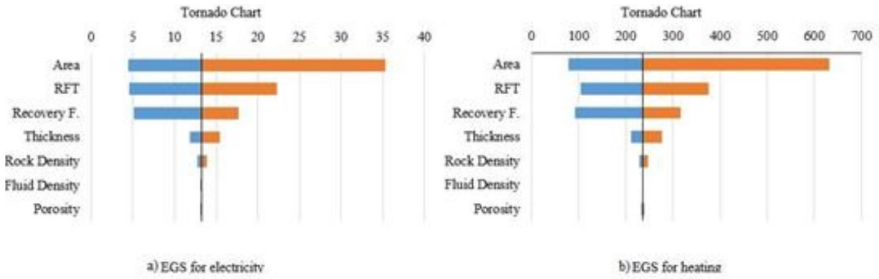

Figure 7: Sensitivity analysis for real volume case for indirect and direct utilization ways, respectively.

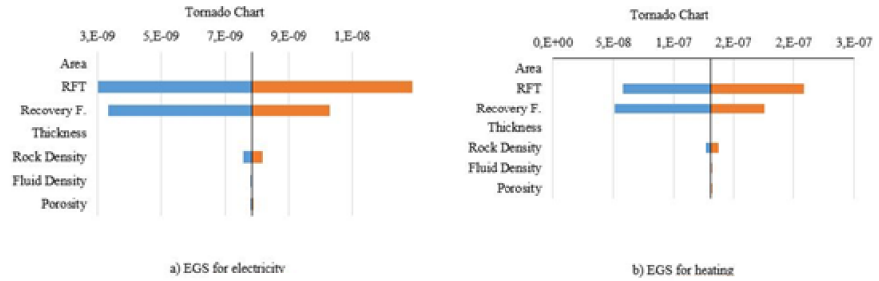

Figure 8: Sensitivity analysis for unit volume case for indirect and direct utilization ways, respectively.

4.2. Critical Analysis

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

- In terms of saved CO2 amount (environmental point of view): by employing a renewable energy source such as geothermal rather than fossil fuels, such as natural gas.
- 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

The annual amount of saved CO_2 is calculated as around 28,139 ton when 8 MW_e is produced from Kozak granodiorite instead of natural gas.

Natural gas, which is mainly CH4, i.e. methane, combustion reaction with oxygen is as follows:

$CH_4+2O_2 \rightarrow CO_2+2H_2O$

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 8 MW to kcal;

$8*10^6$ joules/sec *0.239 cal/joules $*10^{-3}$ kcal/cal = 1912 kcal/sec

To find the annual amount of saved CO_2;

1912 kcal/sec * 60*60*24*365 sec/year = 60,296,832,000 kcal in one year.

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

60,296,832,000 kcal / 8250 kcal/m^3= 7,308,706.909 m^3 natural gas.

To find the mass of natural gas, the volume is multiplied by the density of natural gas:

7,308,706.909 m^3 *0.7 kg/m^3 = 5,116,094.836 kg CH_4

As shown previously, 16 g CH_4 yields 44 g CO_2

5,116,094.836 kg CH_4 yields 5,116,094.836 * 44/16= 14,069,260.80 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. It means that by using EGS rather than natural gas to generate 8 MW electricity the annual amount of CO_2 saved is 28,138,521.60 kg. Results are given in Table 5.

Table 5: Basic steps and results of saved CO_2 amount calculation for electricity production from Kozak granodiorite EGS.

Calculation Steps	Results	Units
8 MW	8,000,000	J/s
1 joule	0.239	cal
1 cal	0.001	kcal
Seconds in year	31,536,000	sec/year
1 m^3 CH_4 in combustion	8,250	kcal
Density of natural gas	0.700	kg/m^3
CO_2 factor	2.750	44/16
Efficieny of power plant	0.500	
Paid per 1 m^3	0.175	$
8 MW	1,912	kcal/sec
Yearly kcal	60,296,832,000	kcal
Natural gas amount	7,308,706.91	m^3
Mass of natural gas	5,116,094.84	kg
CO_2 amount	14,069,260.80	kg
Saved CO_2	28,138,521.60	kg

4.2.2 Saved Money

When it comes to the overburden on Turkish economy due to imported energy sources such as natural gas, generating 8 MWe from domestic geothermal resources rather than imported natural gas saves 2,558,047.42 dollars.

For real volume case; Kozak Granodiorite HDR reservoir generates 8 MWe;

2* 7,308,706.91 m^3/1000 m^3*175 $ = 2,558,047.42 $

If unit volume case is also considered with an existing CO_2 tax regulation of 13.6 euro; annual amount of saved money changes as follows:

When the unit volume of reservoir is taken as 1 km^3, Kozak-EGS generates 3.8 MW. This saves 13,365,797.76 kg of CO_2 and 1,215,072.52 $ annually without any CO_2 tax case. With a CO_2 tax regulation like 13.6 euro per tons of CO_2 (Hotunluoğlu et al.2007), annual saved amount changes to 1,394,174.206 $ from the operating companies' perspectives.

5. SUMMARY AND CONCLUSIONS

The main conclusions drawn from this thesis study are summarized as follows:

1) For unit volume case (considered as 1 m^3 reservoir), net electrical power is 3.80E-09 MW_e for a HDR system producing from Kozak granodiorite, with 90% probability. This amount increases to 6.70E-09 MW_e, with 50% probability and to 1.01E-08 MW_e, with 10% probability. Net thermal power is 7.20E-08 MW_t for a 1 m^3 HDR reservoir producing from Kozak granodiorite, with 90% probability. This amount increases to 1.18E-07 MW_t, with 50% probability and to 1.72E-07 MW_t, with 10% probability.
2) For real volume case, net electrical power is 8 MW_e for a HDR system producing from Kozak granodiorite, with 90% probability. This amount increases to 17 MW_e, with 50% probability and to 32 MW_e, with 10% probability. Net thermal power is 150 MW_t for a HDR system producing from Kozak granodiorite, 90% probability. This amount increases to 300 MW_t, with 50% probability and to 560 MW_t, with 10% probability.
3) 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 for real volume case. Sensitivity analysis showed that the temperature and the recovery factor are the inputs that have greatest impact on accessible resource base and the recoverable heat energy outputs for unit volume case. Sensitivity analysis showed that calculations are not sensitive to rock density, porosity and fluid density for neither real nor unit volume cases.
4) When the unit volume of reservoir is taken as 1 km^3, Kozak-EGS generates 3.8 MW_e. This saves 13,365,797.76 kg of CO_2 and 1,215,072.52 $ annually without any CO_2 tax case. With a CO_2 tax regulation such as 13.6 euro per tons of CO_2, annual saved amount changes to 1,394,174.206 $ from the operating companies' perspectives.

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