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Drilling and Well Completion Cost Analysis of Geothermal Wells in Turkey

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ABSTRACT

More than one thousand wells have been drilled in Turkey for geothermal energy development which ranked the country up to fourth in total geothermal energy production worldwide. Despite of the high number of the wells, there are very limited resources on the costs of these wells and whether it is more affordable to invest in geothermal energy in Turkey in comparison with other geothermal producing countries. The objective of this paper is to provide a numerical method and code to calculate the drilling, completion and testing costs of new wells which can be used as an estimation by operators who are interested in investing in this market and as a result provide a comparison of these costs with the well costs in other thermally active countries. Well drilling and completion data from more than twenty wells have been analyzed and merged together to form a software to calculate the estimated costs of drilling, completion and testing a well with a diesel rig in Turkey. This software uses the rig capacity, rig type, the drilling type (kelly or top drive), casing setting depths for each casing, existing drilling third party services (mud, directional drilling, performance drilling etc.) and estimated rate of penetration values from offset wells as the input. The code runs with already calculated casing running times, tripping speeds and connection times for each different size of casing and drill pipe together with the time estimation formulas and provides the service costs and time graphs with the option of changing each input easily. As a result of the study, it was observed that the associated costs in Turkey are the cheapest amongst the costs of wells in Australia, France, Germany, Iceland, Kenya, Netherlands and the United States. The major reasons of these low costs are mainly because of the following three main parameters. Firstly, daily operating costs of rigs and third-party services and labor costs in Turkey are more affordable compared to other countries. Secondly, the major equipment of the well which are the casings are chosen from the lowest cost option since wells are not overbalanced and there is no need for a high cost or high-grade casing to drill these wells. Thirdly, the drilling experience in Turkey resulted in a competitive market which resulted in more optimized wells with minimum drilling times. In literature, there is no published study for the estimation of drilling, well completion and well testing costs of geothermal wells in Turkey. This study and the associated code are very important for a geothermal operator to estimate the project times and related costs associated with their investment.

1. INTRODUCTION

Increasing demand for energy with lower CO_2 emissions in today's world has resulted in the necessity of alternative energy sources. In the last decade, there is more and more interest in renewable energy sources due to their low CO_2 emissions and sustainability. One of the most influenced energy source in Turkey today is geothermal energy. Turkey is ranked number 4 in the total capacity of geothermal energy in the world with its 1,053-MW installed capacity (Gul, 2017). Figure 2 illustrates the top 10 countries in installed capacity worldwide while Figure 3 illustrates the increase in the installed geothermal capacity of Turkey in last decade and under-development & planned capacity for the following years. With the completion of the planned capacity addition, Turkey is estimated to be the third largest geothermal operating country in the world with 1827 MW total capacity. Rig counts in Turkey for geothermal well drilling as of January 2017 was 26, being ranked first with the total amount of 60 geothermal rigs worldwide. In total 32 of 98 drilling activities in Europe is in Turkey (Hughes, 2017).

Turkey is situated on the Alps-Himalayas belt and, although, the geothermal energy potential of Turkey was historically estimated as 31500 MW, that value has recently been increased to 60000 MW (Mertoglu, Sismek, & Basarir, 2015). According to Geothermal Country Update Report of Turkey, there are five major grabens which are Buyuk Menderes, Gediz, Dikili-Bergama, Kucuk Menderes and Edremit grabens along the Northern Anatolian Fault zone and in the Central and Eastern Anatolia volcanic regions (Mertoglu, Sismek, & Basarir, 2015). The geothermal gradient in Turkey ranges between 8.33 °C/100m to 11.10 °C/100m in thermally active regions (Njolnbi, 2015).

On the other hand, the drilling costs are mostly affected by the daily rig rates from drilling contractors and with the developed experience in the field by contractors and service companies, the daily drilling rig rates have been decreased dramatically in the last 3 years (Kaya, 2017). As illustrated in Figure 1, in the mentioned period Turkey has an average of 45% of the geothermal drilling rigs throughout the world. Moreover, this ratio is approximately 30% compare with all the drilling rigs in Europe. Therefore, it can be concluded that Turkey is currently a market leader in geothermal drilling activities in Europe and that is the main aspect of the reduction in daily drilling costs.

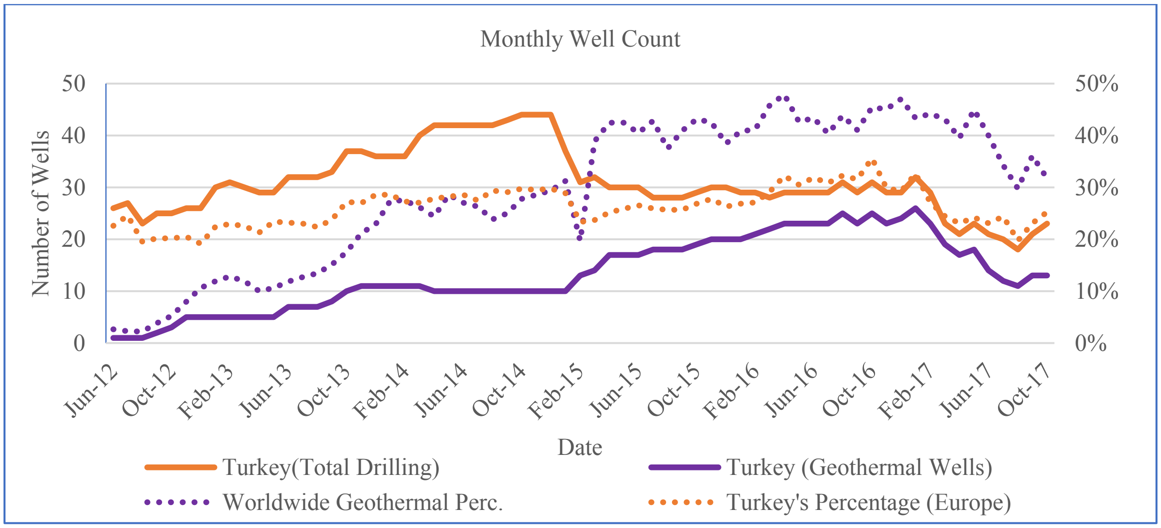

Figure 1. Monthly well count (June 2012-October 2017) (Hughes, 2017)

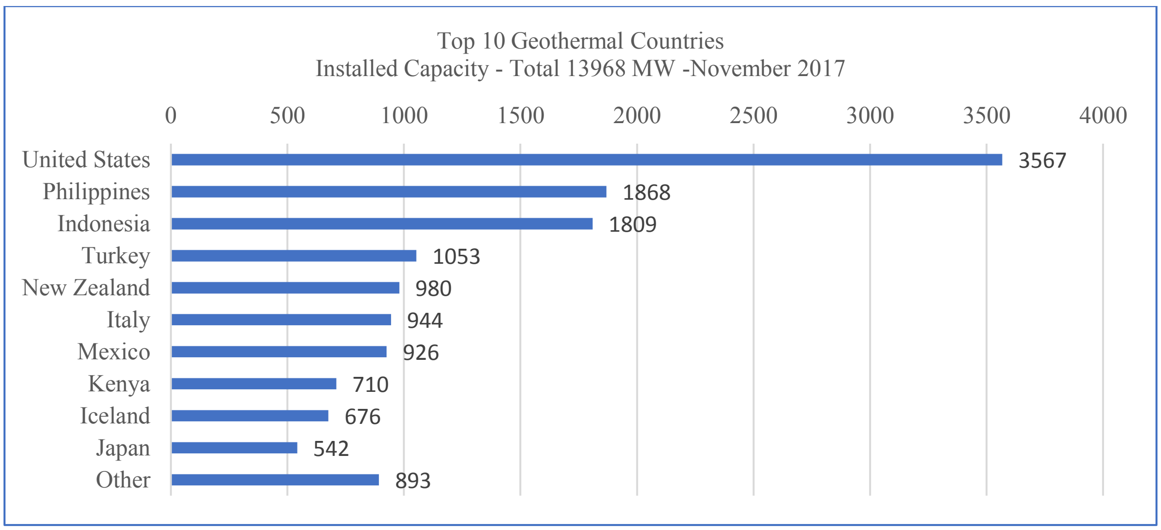

Figure 2.Geothermal power operation capacity by country (Gul, 2017)

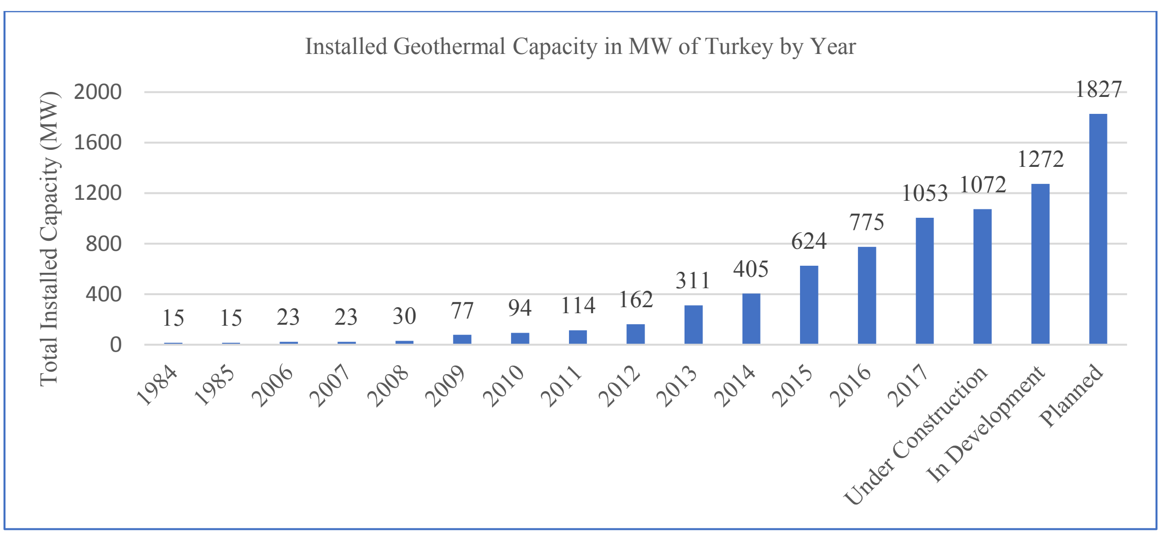

Figure 3.Installed geothermal capacity of Turkey by year (Richter, 2017)

2. THE COST OF DRILLING A GEOTHERMAL WELL

Geothermal drilling is very similar to oil and gas drilling with minor differences, which are explained in chapter 4 of this paper. The drilling phase includes all the activities starting from the well spud until the target depth is reached. The cost of drilling a geothermal well is estimated to be approximately 40% of the total investment cost for a new high temperature geothermal plant. This makes the geothermal plant more expensive to build than conventional fuel fired power plants and as a result the cost of the well becomes a key consideration when determining the economic viability of a geothermal field. Obtaining accurate costs for the geothermal well is therefore very important as it quantifies a substantial percentage of the cost of the geothermal project (Carolyn, 2013). Drilling a geothermal well is a complex process that uses expensive drill rigs, a wide range of drilling experts and a lot of financial muscle. It is also a labor-intensive operation with most of the jobs being performed 24 hours a day, seven days a week, in all weather conditions. Only extreme weather, mechanical failure or lack of supplies will warrant the shutting down of these operations (Carolyn, 2013). Several factors affect the cost of geothermal wells. These factors include well design, the total depth of the well, the type of drill rig and the methods used. Other parameters may include the efficiency of the drilling operation and the optimization of the drilling variables. The total well time constitutes both the drilling and the non-drilling time (Carolyn, 2013).The general design of a vertical geothermal well in Turkey is provided as in Figure 4. As can be seen in Figure 4, 26” hole are drilled to 200m and 20” casings are run at that depth to prevent the chemical mixing in ground water zones. The next section follows as 17 ½” section drilling and 13 3/8” casing running at an average depth of 700m and 12 ½” section drilling with 9 5/8” casing running at around 2000 meters depending on the formation changing depths. The last section is always drilled with bit diameter of 8 ½” and 7” slotted casings are used to allow producing through the casings and eliminate the perforation costs

Hole Diameter	Casing Outer Diameter	Well Profile	Depth (m)
26 "	20 "		200
17 1/2 "	13 3/8 "		700
12 1/4 "	9 5/8 "		2000
8 1/2 "	7 "		3250-4500 (depends from field to field)

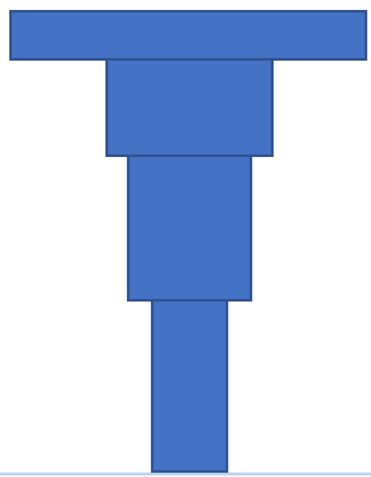

Figure 4:General design of a vertical geothermal well in Turkey

The estimated total cost of a geothermal well is studied in 11 different parts such as drilling location preparation, tubular equipment, liner hangers, wellhead, drilling contract, mud service, drilling bits,directional drilling or performance drilling services, cementing, logging, company labor and supervision. Out of these 11 steps of the drilling cost, only the costs of 4 of them (drilling contract,mud service, drilling bits and directional drilling service) are a function of the total drilling time while the other 7 are not related to the rate of penetrations in the drilling. Therefore, even though the main aim in drilling is to reduce the total active drilling times and obtain lower costs, there will also be a constant amount of cost due to location preparation, tubular equipment, liner hangers, wellhead, cementing, logging and company labor which will not be reducing as the total drilling times are decreased. This situation is illustrated in the sensitivity analysis (appendix B) of the software.

As an example, for the case with 7” casing setting depth of 3000 meters and effective average rate of penetration in 8.5” section of 5.2 m/hr (other inputs as provided in Figure 5), the maximum share of the cost (approximately 42%) belongs to the drilling contract which includes daily drilling rate, top drive rate, mobilization and demobilization rate, diesel costs and water costs. Tubular equipment is ranked two with approximately 18% of share from the total cost of well which includes the 30” conductor casing, 20” surface casing, 13 3/8” and 9 5/8” intermediate casings and 7” production casing. Mud service, which is mud material, chemicals, personnel and mud laboratory equipment, follow as ranked 3 with approximately 12% and drilling location preparation, which is site survey, location and road construction and location rehabilitation follows up with 11.5%. All other associated costs, suchs as liner hangers, wellheads, drilling bits, directional services, cementing, logging and company labor have a sum of 17% share in the total costs.

The costs associated with drilling a geothermal well can be outlined as follows:

1. Drilling location preparation
    a. Site survey
    b. Location and road construction
    c. Location rehabilitation
2. Tubular equipment
    a. 30" conductor casing
    b. 20" casing
    c. 13 3/8" casing
    d. 9 5/8" casing
    e. 7" casing
3. Liner hangers
    a. 7" liner hanger
4. Wellhead
    a. 21 1/4" x 2m casing head housing
    b. 13 5/8" x 3m casing head housing
    c. 11" master valve
5. Drilling contract
    a. Daily drilling rate
    b. Top drive rate
    c. Mobilization rate
    d. Demobilization rate
    e. Diesel cost
    f. Water cost
6. Mud service
    a. Mud material and chemicals
    b. Personnel
    c. Mud laboratory equipment
7. Drilling bits
    a. 26" tricone bit
    b. 17 1/2" tricone bit
    c. 12 1/4" tricone bit
    d. 8 1/2" tricone bit
    e. Nozzles
8. Directional services
    a. Personnel
    b. Equipment rental
    c. Surveys
9. Cementing
    a. 20" casing cementing operation
    b. 13 3/8" casing cementing operation
    c. 9 5/8" casing cementing operation
10. Logging
    a. Pt log
    b. Pts log
    c. Compressor service
11. Company labor and supervision
    a. Drilling manager
    b. Drilling engineer
    c. Geologist

As mentioned before, the costs associated with a geothermal well drilling and completion has been studied in 11 main items with a total of 38 subitems.

3. SOFTWARE MODEL AND ESTIMATIONS

An excel spreadsheet has been developed to estimate the total required time and costs associated with each item in the outline provided above. As the inputs, rig capacity (tons), rig type (single, double or triple stands), the rotary system (kelly or top drive), casing setting depths for each section and the existence of directional drilling services should be provided. In the geothermal fields of Turkey, the average rate of penetration (ROP) values are estimated as 4 m/hr. in 26" section, 8 m/hr. for 17.5" section, 5 m/hr. for 12 ¼" section and 4 m/hr. for 8.5" section. These values are input as default and can also be changed in the input page. Similarly, casing running times, tripping speeds for drill pipes and drill collars and connection times for drill pipe, drill collar and directional surveys are also default but can also be altered depending on the performance of rig crews. The visual of the "Input and constants" page is provided in figure 5.

The excel spreadsheet with open source code is accessible by contacting the researchers of this paper.

Rig Capacity (tons)	200	
Rig Type	Double	
Kelly or Top Drive?	Kelly	
20" Casing Setting Depth (m)	200	
13 3/8" Casing Setting Depth (m)	700	
9 5/8" Casing Setting Depth (m)	2000	
7" Casing Setting Depth (m)	3000	Hanged
Directional Drilling Services (Yes/No)	Yes	
Estimated Effective ROP for 26.0" Section Drilling (m/hr)	4	
Estimated Effective ROP for 17.5" Section Drilling (m/hr)	8	
Estimated Effective ROP for 12.25" Section Drilling (m/hr)	5	
Estimated Average ROP for 8.5" Section Drilling (m/hr)	5.2	
20" BTC Casing Running Time	3.00	min/meter
13 3/8" BTC Casing Running Time	1.00	min/meter
9 5/8" BTC Casing Running Time	0.60	min/meter
7" BTC Casing Running Time	0.60	min/meter
Tripping Speed - Drillpipe	3.00	min/stand
Tripping Speed - Drillcollar	6.50	min/stand
Connection Time - Drillpipe (for Drilling)	10.00	min/single
Connection Time - Drillcollar (for Drilling)	15.00	min/single
Connection Time Addition for Directional Surveys	10.00	min/single

Figure 2:Input and constants page of the spreadsheet

Casing running times, tripping speeds and connection times for drill pipes, drill collars as well as the additional time for directional surveys (the additional time for directional survey includes an if/else condition in the code in which if the directional drilling service is selected as no in the input page, there will be no additional time reflected in the connection times) have been calculated from average worker performances. These numbers are below the average compared to wells in Europe and the US but in the overall scenario for the costs, these times do not reflect too much on the overall costs of the wells. Therefore, in the example simulated well, 20", 13 3/8" and 9 5/8" BTC casing running times are approximated as 3, 1 and 0.6 min/meter respectively. Tripping speed for drillpipes and drillcollars are accepted as 3 and 6.5 min/stand and connection times for drillpipes and drill collars are accepted as 10 and 15 minutes/single respectively. The use of top drive increases connection and tripping times, but in the same time increases the daily rig costs as well as non-productive times due to maintenance problems, therefore not all operators prefer rigs with top drives for geothermal drilling in Turkey. The effect of directional drilling services mostly increases the rate of penetration since the reason of having a directional drilling service is rather drilling a vertical well and staying in the limits of the lease and making sure that the well is not deviating. Therefore, the use of mud motor increases the rate of penetration gradually especially in really high strength formations which in the end compensates the additional cost due to service and decreases the total well costs.

The second page of the code calculates the estimated times for each operation depending on the provided inputs and provides "Operation Time vs Depth" graph for the estimated well conditions as visualized in Table 1. The total time in hours or in days is calculated by summing up all the time values and multiplying them by 1.1 to compensate for non-productive or unestimated times due to well or field conditions.

In the simulated well and drilling conditions as provided in Table 1, drilling times were observed to be the lead participant in the total well operations times with 57%. On the other hand, it was observed that a lot of time is spent in connection times (9%) in the simulated example well since this well is drilled with kelly and therefore connection times taking longer than the top-drive case. Moreover, casing running is observed to be 7% and trips as 6%, while all other operations such as casing cementing, wait on cement, wellhead operations and well testing operations stand for the remaining 21% of the time spent in operations. This also matched with the general understanding of well costs as the time spent on drilling the well is the most important part of deep geothermal drilling process since the rate of penetration values are lower compared to oil and gas wells. More research should be performed on increasing the drilling speeds on geothermal wells with either different types of muds or new technology drilling bits.

Table 1: Time estimation table with estimated input parameters in Figure 5

Item	Time (hours)	Time (days)	Cumulative time with %10 allowance (days)	Depth (m)
Start of Operations	0.0	0.0	0.0	0
26" Section Drilling	50.0	2.1	2.3	200
26" Connection Time	5.0	0.2	2.5	200
26" Drillstring Trips	1.1	0.0	2.6	200
20" Casing Running	10.0	0.4	3.0	200
20" Casing Cementing	4.0	0.2	3.2	200
Wait on Cement	12.0	0.5	3.8	200
21 1/4" Wellhead	24.0	1.0	4.9	200
Run in Hole to Bottom	1.1	0.0	4.9	200
17 1/2" Section Drilling	62.5	2.6	7.8	700
17 1/2" Connection Time	8.3	0.3	8.2	700
17 1/2" Drillstrings Trips	7.0	0.3	8.5	700
13 3/8" Casing Running	11.7	0.5	9.0	700
13 3/8" Casing Cementing	6.0	0.3	9.3	700
Wait on Cement	12.0	0.5	9.8	700
13 5/8" Wellhead	24.0	1.0	10.9	700
Run in Hole to Bottom	2.3	0.1	11.0	700
12 1/4" Section Drilling	260.0	10.8	23.0	2000
12 1/4" Connection Time	43.3	1.8	24.9	2000
12 1/4" Drillstring Trips	15.0	0.6	25.6	2000
9 5/8" Casing Running	20.0	0.8	26.6	2000
9 5/8" Casing Cementing	8.0	0.3	26.9	2000
Wait on Cement	12.0	0.5	27.5	2000
9 5/8" Wellhead	12.0	0.5	28.0	2000
Run in Hole to Bottom	5.6	0.2	28.3	2000
8 1/2" Section Drilling	192.3	8.0	37.1	3000
8 1/2" Connection Time	33.3	1.4	38.6	3000
8 1/2" Drillstring Trips	22.5	0.9	39.6	3000
7" Casing Running	30.0	1.3	41.0	3000
Well Testing	48.0	2.0	43.2	3000
Others	48.0	2.0	45.4	3000
TOTAL	1090.16	45.42		

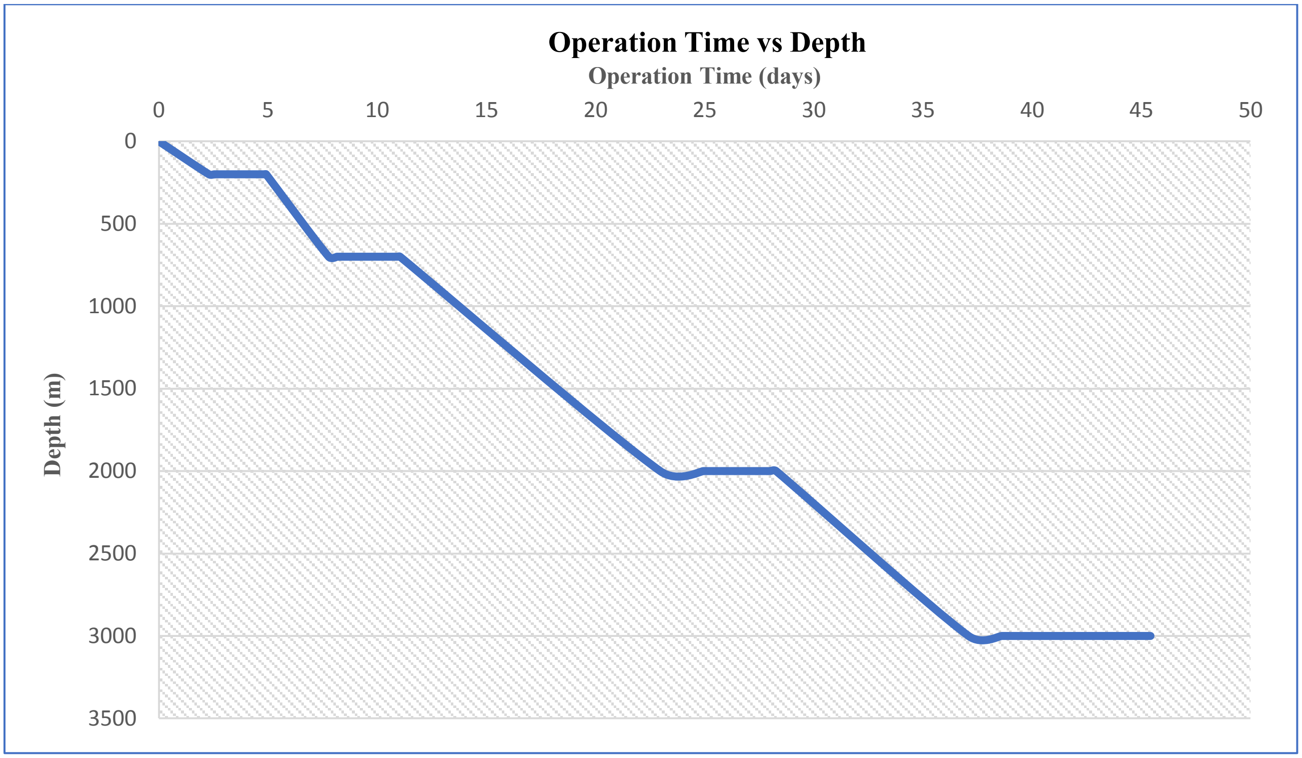

Figure 3: Operation time vs. depth graph for the simulated example well

The last part of the spreadsheet is provides the related costs with all the 11 items as outlined in the previous parts of this paper. The screenshot of the "cost" section is as in below figures.

It has been estimated in the code and calculations that no main equipment such as cementing units, drilling rigs or directional drilling equipment are owned by the operator and these are all obtained as third-party services. Bottom hole assembly (BHA) length in the calculations and time estimations are estimated as 200 meters for each section.

The effect of directional drilling (extra time due to survey times) is reflected only on 12.25" and 8.5" drilling sections. After each cementing operation, due to high temperatures, the common procedure is to wait on cement for 12 hours in Turkey.

Therefore, the same value is considered after each cementing job in each diameter of casings. Moreover, since all drilling operations are conducted with mobile or semi-mobile rigs, the space below the structure is generally very limited and almost no contractor uses wellhead installation mechanisms with their rigs. For the same reason, the wellhead operation time is considered as 24 hours for 21 1/4 "and 13 5/8" wellheads and 12 hours for 9 5/8" wellheads since the work conducted for 9 5/8" wellhead is mostly only the make-up of the master valve and some adapters to get ready for production from the well. For each tricone bit, the life of the bit is estimated as 100 hours, which is the general assumption of the operators and service companies. For the company labor and supervision, total costs are included in a way to include the travel costs of the personnel. In the time estimations, 10% allowance is added to total times to compensate for the unexpected time losses and non-productive times in the operations. The associated costs of all spare equipment such as casings, drilling bits, wellhead, etc. are illustrated in provided figures. As the daily rig rates, it has been estimated to be $9000 for rigs with capacity lower than 200 tons (small rigs) and $11000 for rigs with capacity higher than 200 tons (big rigs). Similarly, mobilization and demobilization costs are $50000 and $75000 for small and big rigs respectively. The model is not compensating for the increases in ROP due to performance drilling, therefore this value should be changed in the software if there is an expected increase in ROP. Lastly, the casing running times are calculated to include the casing running equipment preparations in the field. There is a 1.3 safety factor for casing lengths (to compensate for the damaged casing threads during casing running) and a 1.5 safety factor for drilling bits (suggested to be stored in the field in case of extra bit needs).

It should also be noted that the costs associated with every item in Figure 4 are mostly estimations and are subject to change by different operators/contractors and/or suppliers of equipment and therefore should not be taken as final costs of each operation or equipment but as an estimation on pricing of the whole project.

Drilling Location Preparation	Unit Cost ($)	Unit	Quantity	Total Cost ($)
Site Survey	10000	Ea	1	10,000.00
Location and Road Construction	50000	Ea	1	50,000.00
Location Rehabilitation	200000	Ea	1	200,000.00
Tubular Equipment	Unit Cost ($)	Unit	Quantity	Total Cost ($)
30" Conductor Casing	250	meters	20	5,000.00
20" Casing	150	meters	260	39,000.00
13 3/8" Casing	100	meters	910	91,000.00
9 5/8" Casing	75	meters	2600	195,000.00
7" Casing	60	meters	1300	78,000.00
Liner Hangers	Unit Cost ($)	Unit	Quantity	Total Cost ($)
7" Liner Hanger	20000	Ea.	1	20,000.00
Wellhead	Unit Cost ($)	Unit	Quantity	Total Cost ($)
21 1/4" x 2M Casing Head Housing	10000	Ea.	1	10,000.00
13 5/8" x 3M Casing Head Housing	6000	Ea.	1	6,000.00
11" Master Valve	20000	Ea.	1	20,000.00
Drilling Contract	Unit Cost ($)	Unit	Quantity	Total Cost ($)
Daily Drilling Rate	11000	day	45.42	499,658.25
Top Drive Rate	0	day	45.42	0.00
Mobilization Rate	50000	Ea.	1	50,000.00
Demobilization Rate	50000	Ea.	1	50,000.00
Diesel Cost	5000	liters/day	45.42	340,676.08
Water Cost	2000	liters/day	45.42	18,169.39
Mud Service	Unit Cost ($)	Unit	Quantity	Total Cost ($)
Mud Material and Chemicals				200,000.00
Personnel	1000	day	45.42	45,423.48
Mud Laboratory Equipment	200	day	45.42	9,084.70
Drilling Bits	Unit Cost ($)	Unit	Quantity	Total Cost ($)
26" Tricone Bit	20000	Ea.	1	20,000.00
17 1/2" Tricone Bit	12500	Ea.	1	12,500.00
12 1/4" Tricone Bit	9000	Ea.	4.5	40,500.00
8 1/2" Tricone Bit	5000	Ea.	3	15,000.00
Nozzles	100	Set	9.5	950.00
Directional Services	Unit Cost ($)	Unit	Quantity	Total Cost ($)
Personnel (2DD + 1MWD)	1500	day	45.42	68,135.22
Equipment Rental	3000	day	45.42	136,270.43
Cementing	Unit Cost ($)	Unit	Quantity	Total Cost ($)
20" Casing Cementing Operation	15000	Operation	1	15,000.00
13 3/8" Casing Cementing Operation	30000	Operation	1	30,000.00
9 5/8" Casing Cementing Operation	20000	Operation	1	20,000.00
Logging	Unit Cost ($)	Unit	Quantity	Total Cost ($)
PT Log	7500	Operation	1	7,500.00
PTS Log	7500	Operation	1	7,500.00
Compressor Service	7500	Operation	1	7,500.00
Company Labor and Supervision	Unit Cost ($)	Unit	Quantity	Total Cost ($)
Drilling Manager	10000	Ea.	1	10,000.00
Drilling Engineer	4000	Ea.	5	20,000.00
Geologist	4000	Ea.	3	12,000.00
Grand Total				2,359,867.55

Figure 4: Cost estimations page of the spreadsheet for the simulated example well

4. COMPARISON OF GEOTHERMAL AND OIL & GAS WELLS

In geothermal drilling, some specific problems are encountered more compared to oil and gas drilling [6]. These problems can be listed as below:

1. High-temperature instrumentation and seals.

Geothermal wells expose drilling fluid and downhole equipment to higher temperatures than in common oil and gas drilling. High-temperature problems are most frequently associated with the instruments used to measure and control drilling direction and logging equipment. Most of the tools have limitations of 150°C active bottom hole temperature during drilling.

2. Logging

Geothermal logging units require wirelines that can withstand much higher temperatures than those encountered in everyday oil and gas applications.

3. Thermal expansion of casing

Thermal expansion can cause buckling of casing and casing collapse, which can be costly. Cement operations take more precedence for geothermal drilling rather than oil & gas. For the same reason, there is no hanger slips used in the wellhead in geothermal drilling to let the casings expand and prevent possible collapses due to thermal expansion effect.

4. Drilling fluids and mud coolers

Mud coolers are mostly used when flow line temperature exceeds 75°C. High mud temperature causes danger for rig personnel and results in longer trip times as well as damages the mud pump components. Other than this, the increase in mud temperatures decreases the mud viscosity and yield point, which results in more usage of viscosifier to obtain the required rheological properties.

5. Drill bits

Formations bearing geothermal reservoirs tend to be harder and more fractured crystalline compared to sedimentary formations in oil and gas operations. Most of the resources are in formations that are igneous, influenced by volcanic activity or altered by high temperatures. These formations are generally more difficult to drill due to geophysical activities and confined stresses.

6. Lost circulation

Geothermal reservoirs are quite often under-pressured and prone to lost circulation due to faults associated in the zones, which results in very difficult casing and cementing operations. In total loss circulations, lower cuttings carrying capacity of the mud results in higher torque and drag, which may result in stuck pipe problems. Similarly, in casing operations, an empty well means higher pipe weights and in some situations, it is not possible to cement these casings even while mixing them with lost circulation materials.

5. DISCUSSIONS AND CONCLUSIONS

Geothermal drilling costs follow the general oil and gas industry trend, which exemplifies a total dependence to crude oil prices. This situation is likely to persist as long as the geothermal drilling sector does not build-up a strong market share of its own (Dumas, Antics, & Ungemach, 2013). As shown in figure 8, a graph with the current trend of oil prices vs yearly average daily drilling rates has been prepared. As can be seen in the figure, the trend of daily rig rates in Turkey are also following the trend of crude oil prices. That can best be explained by the decreasing interest in demand which results in a more competitive market. On the other hand, another graph comparing the total drilling costs from Australia, France, Germany, Iceland, Kenya, Nevada (US), Netherlands and US Oil & Gas with the simulation results from the developed code is shown as in figure 9. In this calculation, the same inputs shown in figure 5 have been used only with changes in production casing setting depth and ROP (decreasing average ROP 20% percent in each 500 meters increment). The estimated average ROP for 8.5" section vs depth has been provided in table 2.

Table 2: Depth vs ROP values for the comparison study

Depth (m)	8.5 section ROP (m/hr)	Total Estimated Cost ($)
2100	7.50	2,028,640
2500	6.20	2,158,660
3000	5.20	2,359,867
3500	4.30	2,619,311
4000	3.60	2,935,344
4500	3.00	3,339,145

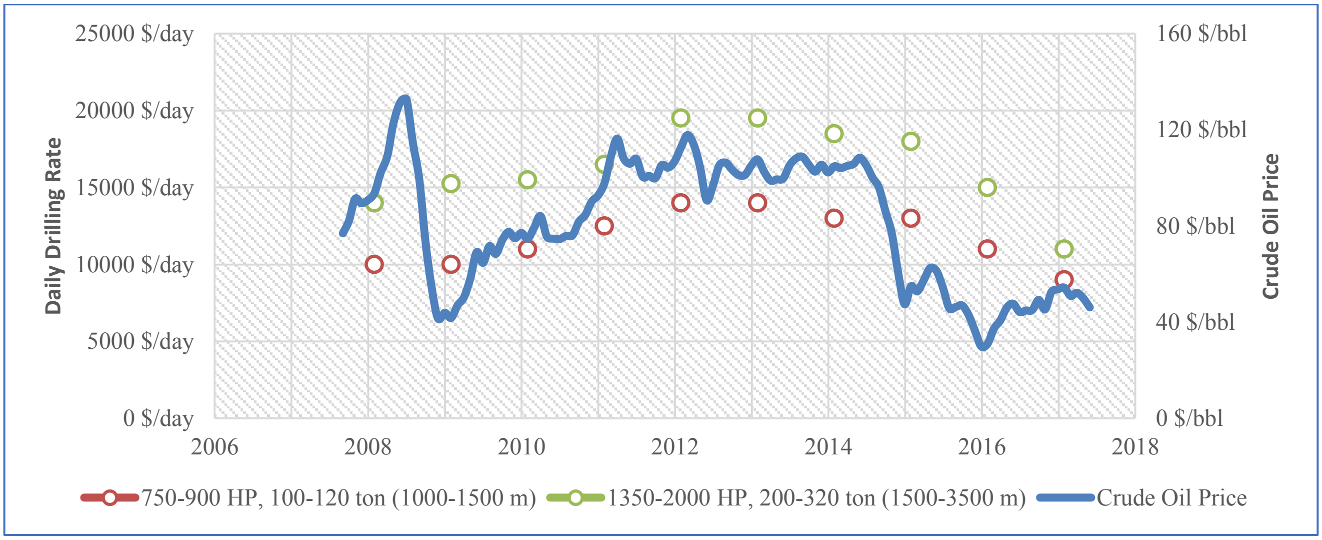

Figure 5: Crude oil prices vs daily rig rates in Turkey

As can be seen from figure 8, total well costs (drilling, well completion and well testing) have been compared with other geothermal producing countries, with blue dots showing the results from the model provided. As illustrated here, well costs in Turkey are gradually cheaper compared to other countries. The reasons of cheaper well construction can be explained in three manners. Firstly, daily operating costs of rigs, third-party services and labor costs in Turkey are more affordable compared to other countries. Secondly, the major equipment of the well, which are the casings, are chosen from the lowest cost option since wells are not overbalanced and there is no need for a high cost or high-grade casing to drill these wells. Thirdly, the drilling experience in Turkey resulted in a competitive market which resulted in more optimized wells with the minimum drilling times. There is also the need to note that the costs associated with value added taxes are not included in model estimation calculations.

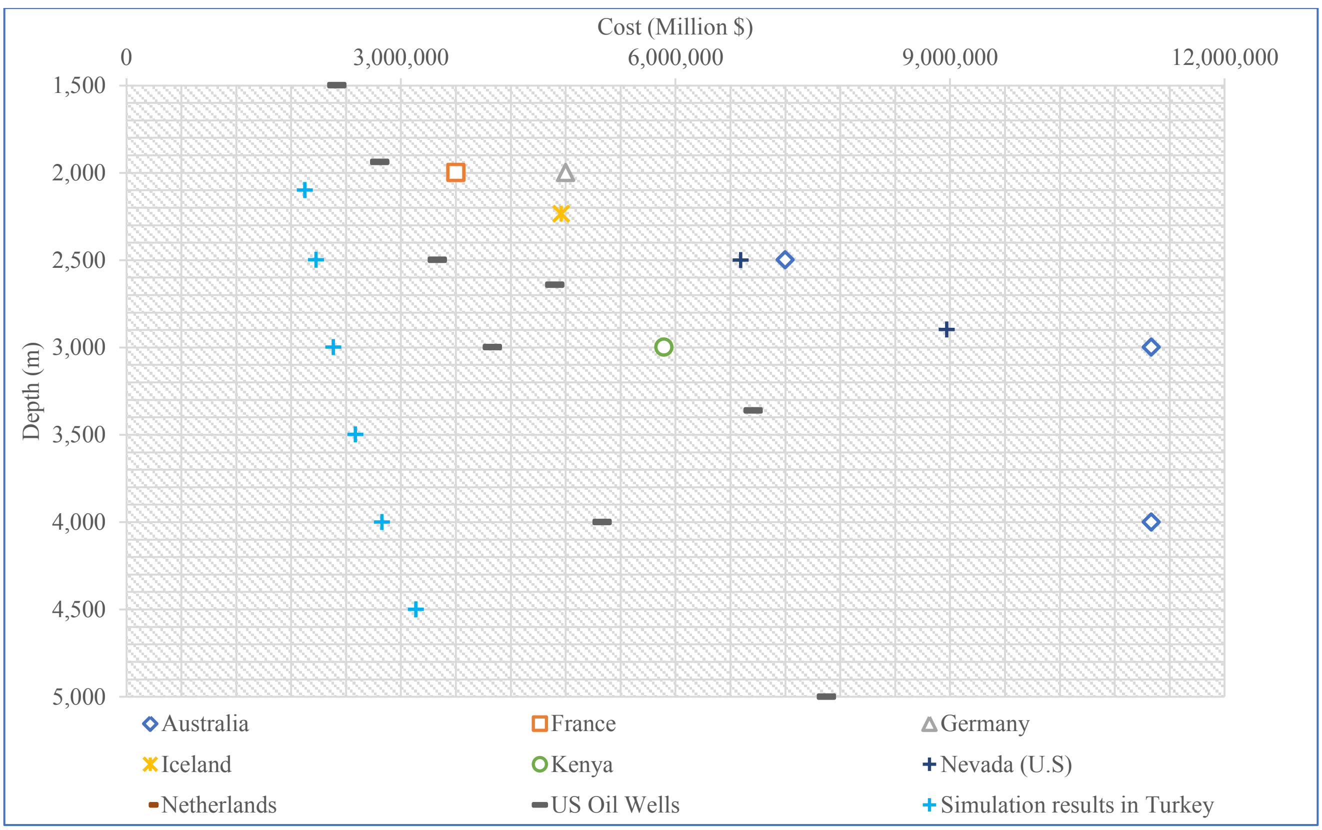

Figure 6: Comparison of published well costs of different countries vs model results in different depths in Turkey

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APPENDIX A. DATA

Table A1: Geothermal power operation capacity by country (Gul, 2017)

Top 10 Geothermal Countries		
Installed Capacity - MW (November 2017) - 13.968 Mw In Total		
Rank	Country	Capacity
1	United States	3567
2	Philippines	1868
3	Indonesia	1809
4	Turkey	1053
5	New Zealand	980
6	Italy	944
7	Mexico	926
8	Kenya	710
9	Iceland	676
10	Japan	542
-	Other	893
-	TOTAL	13968

Table A2: Installed geothermal capacity of Turkey by year (Richter, 2017)

Turkey Geothermal Development	
Installed Capacity (1984-2017)	
Year	Capacity (MW)
1984	15
1985	15
2006	23
2007	23
2008	30
2009	77
2010	94
2011	114
2012	162
2013	311
2014	405
2015	624
2016	775
2017	1053
Under Construction	1072
In Development	1272
Planned	1827

Table A3: Additional Installed Geothermal Plan Capacity During 2017

ADDITIONAL CAPACITY DURING 2017		
Rank	Country	Capacity (MW)
1	Turkey	325
2	Indonesia	165
3	Chile	48
4	Iceland	45
5	Mexico	25
6	United States	24
7	Japan	5
8	Portugal (Azores)	3
9	Hungary	3
-	TOTAL	643

Table A4: Crude oil prices WTI (2007-2017) from Nasdaq, Nymex (Crude Oil WTI)

Month	Year	Crude Oil Price	Month	Year	Crude Oil Price	Month	Year	Crude Oil Price	Month	Year	Crude Oil Price
October	2007	82.15 $/bbl	April	2010	84.14 $/bbl	October	2012	103.39 $/bbl	April	2015	57.42 $/bbl
November	2007	91.27 $/bbl	May	2010	75.54 $/bbl	November	2012	101.17 $/bbl	May	2015	62.50 $/bbl
December	2007	89.43 $/bbl	June	2010	74.73 $/bbl	December	2012	101.17 $/bbl	June	2015	61.30 $/bbl
January	2008	90.82 $/bbl	July	2010	74.52 $/bbl	January	2013	105.04 $/bbl	July	2015	54.43 $/bbl
February	2008	93.75 $/bbl	August	2010	75.88 $/bbl	February	2013	107.66 $/bbl	August	2015	45.72 $/bbl
March	2008	101.84 $/bbl	September	2010	76.11 $/bbl	March	2013	102.61 $/bbl	September	2015	46.29 $/bbl
April	2008	109.05 $/bbl	October	2010	81.72 $/bbl	April	2013	98.85 $/bbl	October	2015	46.96 $/bbl
May	2008	122.77 $/bbl	November	2010	84.53 $/bbl	Haz	2013	99.35 $/bbl	November	2015	43.13 $/bbl
June	2008	131.52 $/bbl	December	2010	90.07 $/bbl	June	2013	99.74 $/bbl	December	2015	36.56 $/bbl
July	2008	132.55 $/bbl	January	2011	92.66 $/bbl	July	2013	105.21 $/bbl	January	2016	29.92 $/bbl
August	2008	114.57 $/bbl	February	2011	97.73 $/bbl	August	2013	108.06 $/bbl	February	2016	31.05 $/bbl
September	2008	99.29 $/bbl	March	2011	108.65 $/bbl	September	2013	108.78 $/bbl	March	2016	37.34 $/bbl
October	2008	72.67 $/bbl	April	2011	116.32 $/bbl	October	2013	105.46 $/bbl	April	2016	40.75 $/bbl
November	2008	54.04 $/bbl	May	2011	108.18 $/bbl	November	2013	102.58 $/bbl	May	2016	45.98 $/bbl
December	2008	41.53 $/bbl	June	2011	105.85 $/bbl	December	2013	105.49 $/bbl	June	2016	47.69 $/bbl
January	2009	43.91 $/bbl	July	2011	107.88 $/bbl	January	2014	102.25 $/bbl	July	2016	44.22 $/bbl
February	2009	41.76 $/bbl	August	2011	100.45 $/bbl	February	2014	104.82 $/bbl	August	2016	44.84 $/bbl
March	2009	46.95 $/bbl	September	2011	100.83 $/bbl	March	2014	104.04 $/bbl	September	2016	45.06 $/bbl
April	2009	50.28 $/bbl	October	2011	99.92 $/bbl	April	2014	104.94 $/bbl	October	2016	49.29 $/bbl
May	2009	58.10 $/bbl	November	2011	105.36 $/bbl	May	2014	105.73 $/bbl	November	2016	45.28 $/bbl
June	2009	69.13 $/bbl	December	2011	104.26 $/bbl	June	2014	108.37 $/bbl	December	2016	52.61 $/bbl
July	2009	64.65 $/bbl	January	2012	106.89 $/bbl	July	2014	105.22 $/bbl	January	2017	53.63 $/bbl
August	2009	71.63 $/bbl	February	2012	112.70 $/bbl	August	2014	100.05 $/bbl	February	2017	54.36 $/bbl
September	2009	68.38 $/bbl	March	2012	117.79 $/bbl	September	2014	95.89 $/bbl	March	2017	50.91 $/bbl
October	2009	74.08 $/bbl	April	2012	113.75 $/bbl	October	2014	86.13 $/bbl	April	2017	52.23 $/bbl
November	2009	77.56 $/bbl	May	2012	104.16 $/bbl	November	2014	76.96 $/bbl	May	2017	49.91 $/bbl
December	2009	74.88 $/bbl	June	2012	90.73 $/bbl	December	2014	60.55 $/bbl	June	2017	46.13 $/bbl
January	2010	77.12 $/bbl	July	2012	96.75 $/bbl	January	2015	47.45 $/bbl	July	2017	54.78 $/bbl
February	2010	74.72 $/bbl	August	2012	105.28 $/bbl	February	2015	54.93 $/bbl	August	2017	51.87 $/bbl

Table A5: Yearly daily drilling rates in Turkey

Rig Type	Daily Rig Cost (Yearly Average)									
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
750-900 HP, 100-120 ton (1000-1500 m)	$10.000	$10.000	$11.000	$12.500	$14.000	$14.000	$13.000	$13.000	$11.000	$10.000
1350-2000 HP, 200-320 ton (1500-3500 m)	$14.000	$15.250	$15.500	$16.500	$19.500	$19.500	$18.500	$18.000	$15.000	$12.000
	(Kaya, "An Overview on Geothermal Drilling and Projects in Turkey, 2013", 2013)						Yearly Averaged Rig Rate			

Table A.6: Annual U.S Inflation (1985-2017) from Worldbank

Year	Inflation (%)	Year	Inflation (%)	Year	Inflation (%)	Year	Inflation (%)
1985	3.56	1993	2.95	2001	2.83	2009	-0.36
1986	1.86	1994	2.61	2002	1.59	2010	1.64
1987	3.74	1995	2.81	2003	2.27	2011	3.16
1988	4.01	1996	2.93	2004	2.68	2012	2.07
1989	4.83	1997	2.34	2005	3.39	2013	1.46
1990	5.40	1998	1.55	2006	3.23	2014	1.62
1991	4.23	1999	2.19	2007	2.85	2015	0.12
1992	3.03	2000	3.38	2008	3.84	2016	1.26

Table A.7: Geothermal drilling features in EU

Country	Depth (m)	Total Cost (USD)	Unit Cost (USD/m)	Well Description
France	2.000	3.600.000	1.800	Deviated geothermal district heating doublets
Germany	2.000	4.800.000	2.400	Deep, deviated wells.
Italy	3.000	9.000.000	3.000	Mainly 2000-3000 m deep high enthalpy, dry-wet stram wells
Netherlands	4.000	19.200.000	4.800	Wells drilled on a lump sum base

Table A.8: Drilling cost of a geothermal well in Australia based on the SAM model (Huddlestone-Holmes, 2015)

Country	Depth (m)	Total Cost (USD)	Unit Cost (USD/m)	Well Description	Diameter (in)
Australia	2.500	7.200.000	2.880	Completely within sedimentary basin	8
Australia	4.000	11.200.000	2.800	Completely within sedimentary basin	8
Australia	3.000	11.200.000	3.733	Sedimentary basin with crystalline basement	8
Australia	4.000	19.200.000	4.800	Sedimentary basin with crystalline basement	8
Australia	5.000	28.800.000	5.760	Sedimentary basin with crystalline basement	8
Australia	4.000	16.800.000	4.200	Sedimentary basin with crystalline basement	6

Table A.9: Average well cost for different regions of Nevada by using Klein Regression (Shevenell, 2012)

Country	Depth (m)	Total Cost Escalated to 2016 (USD)	Unit Cost (USD/m)	Region	Reservoir Depth (ft)	Year	Cost (USD)
Nevada (U.S)	2.502	6.715.112	2.684	Beowawe	8207	1985	2.907.000
Nevada (U.S)	504	2.030.158	4.026	Bradys	1654	1992	1.152.000
Nevada (U.S)	1.677	565.945	337	Desert Peak	5501	1985	245.000
Nevada (U.S)	2.899	8.964.434	3.092	Dixie Valley	9509	1988	4.417.000
Nevada (U.S)	516	987.901	1.913	San Emidio	1694	1987	468.000
Nevada (U.S)	335	8.578.698	25.580	Soda Lake	1100	1987	4.064.000
Nevada (U.S)	922	2.018.666	2.190	Steamboat	3023	1986	905.000
Nevada (U.S)	909	2.721.600	2.994	Stillwater	2982	1989	1.341.000

Table A.10: Summary for an average well in Kenya (Carolyn, 2013)

	Unit	Total
Pre-spud costs		
Drillsite preparation	Fixed	$70.000
Rig mobilisation and transport	On-off	$420.000
Sum		$490.000
Daily operating costs		
Rig rental with crew	Day rate	$1.893.000
Rig rental with crew-standby	Day rate	$350.000
Air compressors, balanced drilling	Day rate	$9.500
Cementing equipment	Day rate	$8.000
Maintenance Engineering	From table	$24.000
Drill stem inspection	Fixed	$300.000
Directional drilling equipment rentals	Day rate	$1.250
Lodging, catering (camp&food)	Day rate	$82.030
Sum		$2.667.780
Drilling consumables		
Rock bits	From table	$182.000
Drilling detergent	From table	$46.000
Diesel&lubricationg oil	From table	$736.424
Cement	From table	$39.674
Cement additives	From table	$3.967
Drilling mud	From table	$170.610
Sum		$1.178.675
Casing and wellhead		
Casing	From table	$556.718
Casing accessories & consumables	From table	$29.350
Wellhead equipment	From table	$79.550
Sum		$665.618
Services		
Drilling supervision	From table	$30.000
Civil engineering	From table	$6.000
Site geologist	From table	$12.000
Geological services	From table	$9.000
Reservoir engineering	From table	$6.000
Planning & logistics	From table	$12.000
Logging services	Fixed	$30.000
Sum		$105.000
TOTAL		$5.107.073
TOTAL +15% CONTINGENCY		$766.061
PROJECT TOTAL		$5.873.134

Table A.11: U.S onshore oil well depth vs. cost (Lukawski, et al., 2014)

Country	Depth (m)	Total Cost (USD)	Unit Cost (USD/m)
U.S Onshore Oil	555	548.107	988
U.S Onshore Oil	945	772.036	817
U.S Onshore Oil	1.339	1.173.000	876
U.S Onshore Oil	1.940	2.768.836	1.427
U.S Onshore Oil	2.643	4.682.709	1.772
U.S Onshore Oil	3.361	6.848.041	2.038
U.S Onshore Oil	4.146	12.936.478	3.120
U.S Onshore Oil	4.911	16.999.206	3.461

Table A.12: EGS well drilling-cost estimates from Wellcost Lite model (Tester, et al., 2016)

Country	Depth (m)	Total Cost (USD)	Unit Cost (USD/m)
U.S	1.500	2.300.000	1.533
U.S	2.500	3.400.000	1.360
U.S	3.000	4.000.000	1.333
U.S	4.000	5.200.000	1.300
U.S	5.000	7.650.000	1.530

Table A13: Turkey Market Comparison (2012-2017)

2012-2017 Europe Continent Rig Count					
	Oct-17	Lowest	Highest	Average	St.Deviation
Turkey	23	18	44	30,89	6,41
Europe	91	82	153	118,45	20,85
Share	25,27%	19,12%	35,63%	26,20%	3,66%
2012-2017 Worldwide Geothermal Rig Count					
	Oct-17	Lowest	Highest	Average	St.Deviation
Turkey	13	1	26	13,37	7,02
Worldwide	41	32	66	45,97	8,02
Share	31,71%	2,22%	47,92%	29,25%	13,92%

Table A.14: Drilling activities in Europe (June 2012-October 2017) (Hughes, 2017)

Date	Europe	Turkey	Norway	Sakhalin	Romania	U.K Offshore	Poland	Italy	Serbia & Montenegro	Germany	Netherlands	Percentage (Turkey)
Jan-13	134	30	22	7	8	22	5	3	4	8	8	22.39%
Feb-13	135	31	21	7	8	20	6	4	4	8	9	22.96%
Mar-13	133	30	20	7	8	21	5	3	4	6	8	22.56%
Apr-13	136	29	20	7	8	19	4	5	6	7	8	21.32%
May-13	124	29	18	9	8	14	3	5	4	5	7	23.39%
Jun-13	138	32	19	9	8	18	5	5	5	5	9	23.19%
Jul-13	139	32	16	11	8	16	8	5	5	6	8	23.02%
Aug-13	143	32	22	11	8	18	7	3	5	5	9	22.38%
Sep-13	139	33	25	11	8	10	6	4	5	4	9	23.74%
Oct-13	136	37	19	8	8	13	8	3	5	4	7	27.21%
Nov-13	137	37	20	8	9	15	9	3	5	6	5	27.01%
Dec-13	126	36	14	8	8	12	9	4	5	4	5	28.57%
Jan-14	126	36	14	5	8	14	6	5	5	4	6	28.57%
Feb-14	132	36	17	7	9	12	3	5	5	7	7	27.27%
Mar-14	148	40	21	7	9	16	3	7	5	5	10	27.03%
Apr-14	151	42	21	5	12	20	3	5	5	4	10	27.81%
May-14	149	42	18	7	13	19	3	5	5	3	10	28.19%
Jun-14	147	42	16	8	14	12	5	4	5	4	11	28.57%
Jul-14	153	42	17	12	12	14	7	5	5	4	12	27.45%
Aug-14	143	42	12	12	13	14	7	5	5	3	8	29.37%
Sep-14	148	43	15	12	15	13	7	5	5	2	8	29.05%
Oct-14	148	44	16	7	14	15	7	5	5	4	10	29.73%
Nov-14	149	44	17	7	15	17	7	4	5	5	10	29.53%
Dec-14	148	44	14	7	15	18	7	4	5	3	10	29.73%
Jan-15	128	37	13	6	11	15	7	4	5	3	6	28.91%
Feb-15	133	31	19	6	13	20	7	4	5	3	6	23.31%
Mar-15	135	32	18	6	13	19	7	3	5	4	8	23.70%
Apr-15	119	30	18	6	12	15	7	5	5	3	4	25.21%
May-15	116	30	18	6	10	16	7	5	5	3	5	25.86%
Jun-15	113	30	19	6	8	12	7	5	5	2	6	26.55%
Jul-15	108	28	20	8	8	12	7	3	5	0	5	25.93%
Aug-15	109	28	16	8	8	12	7	3	5	1	7	25.69%
Sep-15	109	28	17	8	8	14	6	4	5	1	5	25.69%
Oct-15	108	29	15	8	7	14	8	3	5	3	3	26.85%
Nov-15	108	30	14	8	6	12	12	3	5	3	3	27.78%
Dec-15	114	30	17	7	7	9	12	3	5	6	4	26.32%
Jan-16	108	29	18	5	7	8	10	3	5	7	4	26.85%
Feb-16	107	29	18	6	7	7	7	4	5	7	2	27.10%
Mar-16	96	28	19	6	6	9	4	5	3	5	4	29.17%
Apr-16	90	29	17	6	4	8	4	5	3	4	3	32.22%
May-16	95	29	17	10	4	9	4	5	3	3	2	30.53%
Jun-16	91	29	16	8	3	9	4	5	3	3	2	31.87%
Jul-16	94	29	20	8	3	10	4	4	3	2	2	30.85%
Aug-16	96	31	17	8	5	9	8	4	3	3	3	32.29%
Sep-16	92	29	16	8	6	8	8	3	3	1	3	31.52%
Oct-16	87	31	9	7	6	7	8	3	3	2	4	35.63%
Nov-16	97	29	15	7	6	10	8	4	3	4	3	29.90%
Dec-16	99	29	16	7	6	11	8	4	3	4	2	29.29%
Jan-17	98	32	12	7	6	8	8	5	3	3	3	32.65%
Feb-17	107	29	16	12	7	11	10	4	3	3	2	27.10%
Mar-17	94	23	15	12	7	8	10	4	3	4	0	24.47%
Apr-17	91	21	17	11	7	8	10	3	3	2		23.08%
May-17	95	23	18	11	5	10	10	4	3	3	1	24.21%
Jun-17	91	21	15	11	5	8	10	4	3	3	2	23.08%
Jul-17	82	20	13	11	5	10	10	2		2	2	24.39%
Aug-17	91	18	15	11	5	12	10	2	2	4	3	19.78%
Sep-17	91	21	11	10	7	10	7	3	2	4	3	23.08%
Oct-17	91	23	16	11	7	6	6	4	3	2	2	25.27%

Table A.5: Geothermal drilling worldwide (June 2012-October 2017) (Hughes, 2017)

Date	Worldwide	Turkey	Indonesia	Kenya	France	Italy	Algeria	Philippines	Germany	Iceland	Netherlands	Percentage (Turkey)
Feb-14	40	11	1	9		1		2	1		1	27.50%
Mar-14	42	11		9		2	0	1	1		1	26.19%
Apr-14	41	10		9		2	1		1		1	24.39%
May-14	35	10		9		1	1	0	0		1	28.57%
Jun-14	37	10		9		1	1	0			2	27.03%
Jul-14	38	10		10		2		2			2	26.32%
Aug-14	42	10		10		2		3			2	23.81%
Sep-14	40	10		10		2		3			1	25.00%
Oct-14	36	10	0	10		2	1	4			1	27.78%
Nov-14	35	10		10		2	1	4			1	28.57%
Dec-14	34	10		10		2	1	4			1	29.41%
Jan-15	32	10		10		1		3			1	31.25%
Feb-15	66	13	2	10		2		3		1	0	19.70%
Mar-15	36	14		10		2		2		1		38.89%
Apr-15	40	17		10		2	0	3				42.50%
May-15	40	17		10		2	1	3				42.50%
Jun-15	42	17	0	11		2	1	4		1		40.48%
Jul-15	42	18	3	11		1		3		0		42.86%
Aug-15	48	18	4	12		2		3		1	1	37.50%
Sep-15	44	18	3	12		1		1		0	1	40.91%
Oct-15	44	19	2	11		1	0	2	1	0		43.18%
Nov-15	47	20	1	10		2	1	3	1	1		42.55%
Dec-15	52	20	2	10		2	1	4	1	1		38.46%
Jan-16	49	20	2	10		2	1	3	1	0	1	40.82%
Feb-16	51	21	1	10		2		3	2	1	0	41.18%
Mar-16	48	22	4	10		2	1	3	1	0	1	45.83%
Apr-16	48	23	5	10		2	1	2	1			47.92%
May-16	54	23	5	10		2	1	2	2	1		42.59%
Jun-16	53	23	5	10		2	1	2	1	0		43.40%
Jul-16	57	23	6	10		2		2	1	1		40.35%
Aug-16	57	25	6	10		2		2	2	1		43.86%
Sep-16	56	23	7	10		2	0	2	0	2	1	41.07%
Oct-16	55	25	6	10		2	1	1		2	1	45.45%
Nov-16	51	23	5	10		2	1		1	2	1	45.10%
Dec-16	51	24	6	10	0	2	0	1	1	2		47.06%
Jan-17	60	26	12	10	1	2		1	1	2		43.33%
Feb-17	52	23	11	10		2		1	2	1		44.23%
Mar-17	44	19	9	10		2	0	1	1	0		43.18%
Apr-17	43	17	7	10		2	1	1		1		39.53%
May-17	40	18	5	8		2	1	1	1	1		45.00%
Jun-17	35	14	6	7		2	0	1	2	1		40.00%
Jul-17	35	12	8	7	1	2		1	2	0		34.29%
Aug-17	37	11	9	7	1	2	0	1	2	1		29.73%
Sep-17	36	13	7	7	1	2	1	1	2	1	0	36.11%
Oct-17	41	13	8	7	2	2	1	1	1	1	1	31.71%

APPENDIX B. SENSITIVITY ANALYSIS