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Cost Model for Geothermal Wells

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ABSTRACT

The cost of drilling geothermal wells is estimated to be about 40% of the total investment cost for a new high temperature geothermal plant (Thorhallsson and Sveinbjornsson, 2012). This makes geothermal plants more expensive to build than the conventional fuel fired power plants, and as a result the cost of the wells becomes a key consideration when determining the economic viability of a geothermal field. Accurate costing of geothermal wells is therefore very important as it quantifies a substantial percentage of the cost of the geothermal project. This will help in future planning and budgeting of geothermal projects within the region. Accurate well cost records also makes it possible to carry out analysis of drilling-cost-with-depth and evaluate the benefits of selecting different drilling technologies and materials for various geothermal fields and regions and further couple them with the energy-recovery-with-depth for the field. The purpose of this paper is to develop a cost model for costing high temperature geothermal wells that allow the estimation of well costs from a few key input variables such as well depth, number and size of casing intervals, and well trajectory. The model uses two input parameters, the criteria where the well design is established and the price book where all the costs are listed down. The cost model then calculates the drilling materials required to drill each section of the specified well to completion. The cost of these materials is then automatically calculated using the unit cost that is automatically picked from the price book. The summary sheet then gives the total cost of the well. The paper also describes the well cost structure, the factors that affect the cost of the well and items considered when costing a geothermal well. There is surprisingly little published data available on the breakdown of geothermal drilling costs due to the competitive nature of the drilling market and confidentiality clauses. As a result, the data used for the price book for this model are estimated values. The cost model divides the well cost into three major parts; pre-spud, drilling and completion costs. The pre-spud cost includes all the costs prior to spud-in, while the drilling costs are all the costs incurred while making hole. This includes the rig rental cost and the supervision cost. This is where the bulk of the cost is. Finally the completion costs are the costs incurred after achieving total depth to rig release.

1. INTRODUCTION

The goal of any geothermal drilling project is to drill the well to completion as per the drilling program while ensuring safety of the drilling staff, the drilling rig and the well with minimum cost. The geoscientific studies conducted determines the location of the well, the design of the well, the drilling technology to be applied and eventually the well measurements and logging to be conducted while drilling and on completion.

Drilling of geothermal wells is a complex process that uses very expensive drilling 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 manually, 24 hours a day, seven days a week, in all weather conditions. The work is strenuous and hard and is performed in a traditional 12 hour shift on a two-week on and off rotation basis. Only extreme weather or mechanical failure will warrant the shutting down of these operations. Although the physics of drilling is the same everywhere in the world, wells vary widely in complexity and type. Accurate costing of these geothermal wells is therefore very important.

Several factors affect the cost of geothermal wells. These factors include the well design, the total depth of the well and the type of the drilling rig used. Other parameters may include efficiency of the drilling operation and the optimization of the drilling variables. These translate to the total time taken to drill the well. The total well time constitutes both the drilling and the non-drilling time. There are several factors and events which influence the well drilling time. Measurable factors include the physical characteristics of the well, geology of the area and the drilling parameters employed. The indirect factors on the other hand include well planning, drilling operator experience, execution team communication and organization, leadership and project management skills. These indirect factors will however be considered to be beyond the scope of analysis for this paper.

Many advances have been made with the aim of reducing these well drilling costs. The realization that the penetration rates cannot be significantly increased has led to the option of trying to reduce on the non-drilling costs by increasing rig availability and developing drill bits which can stay in the hole longer and therefore drill more depth thereby eliminating expensive rig time and excessive trips.

2. GEOTHERMAL PROJECT DEVELOPMENT

Geothermal projects have seven key development phases before the actual operations and maintenance phase commences. It is said to take approximately seven years to develop a typical full size geothermal project with, for example, a 50 MWe turbine as a first step. However the project development time may vary, depending on the country's geological conditions, available information about the resource, institutional and regulatory climate, and access to suitable funding among other factors. The phases as outlined by (Mwangi, 2005) are listed as follows;

i. Studies of surface manifestation

ii. Detailed Exploration

iii. Exploration well drilling

iv. Feasibility studies

v. Development phase

vi. Construction, start-up and commissioning

vii. Operation and maintenance

3. PHASES OF GEOTHERMAL DRILLING

The entire drilling project from well planning, designing, drilling upto the delivery of a geothermal well can be divided into three main phases; the pre-spud phase, drilling phase and the completion phase as summarized in Figure 1 below.

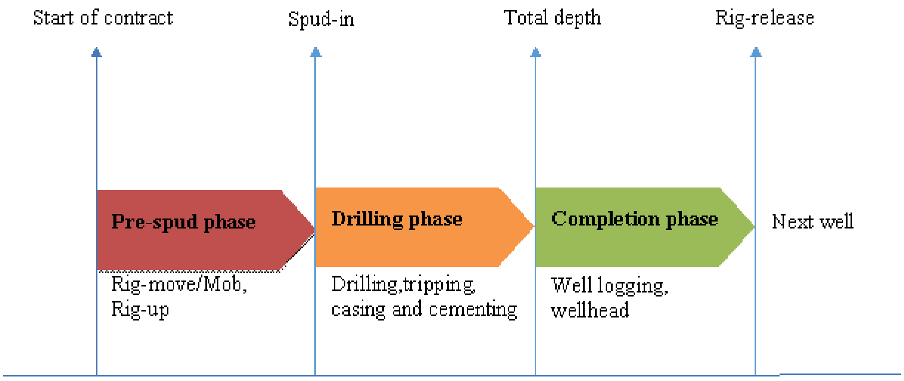

Figure 1: Summary of the phases of geothermal drilling

3.1 Pre-spud phase

This is mainly the planning phase. It extends from the start of a drilling contract to well spud. The pre-spud phase has several sub-phases as discussed below.

Well design

Casing selection and casing setting depths are important factors to consider when designing a geothermal well. The depth of each casing string is determined by several factors including the geological properties of the area, the total depth of the well, formation fluids as well as the well control considerations. When selecting the type of casing to be run in hole, several parameters are considered as well. These parameters include:

i. The nominal production rate from the well and the casing diameter implied by that flow rate;

ii. The depth of the production zone and expected temperature;

iii. Brine chemistry;

iv. Well trajectory;

v. Need for special casing material or connection and

vi. Length of individual casing interval.

The next important thing is the preparation of a drilling program. This program contains the primary objective of drilling the well and a step by step schedule giving detailed procedures on how to carry out each activity when drilling the well. It also outlines most of the anticipated drilling problems and how best to handle them (Karewa, 2012). Other factors put into consideration may include other drilling materials and consumables specification and selection for example the wellhead, drilling fluid and cement and cement additives.

Other costs considered in the pre-spud phase may include construction of access roads costs, costs incurred during well pad preparation and cellar construction, Laying of water lines, rig mobilization/ demobilization, rig move, rig up and transport costs.

3.2 Drilling phase

The drilling phase includes all the activities carried out from when the well is spud-in until when the total depth is achieved. Typically, geothermal wells today are drilled to depths ranging from 200 to 1500 meters depth for low to medium temperature systems and from 700 to 3000 meters depth for high temperature systems. Both vertical and directional wells are drilled. An example of a typical regular diameter well profile for wells drilled in Olkaria geothermal field is shown in Figure 2.

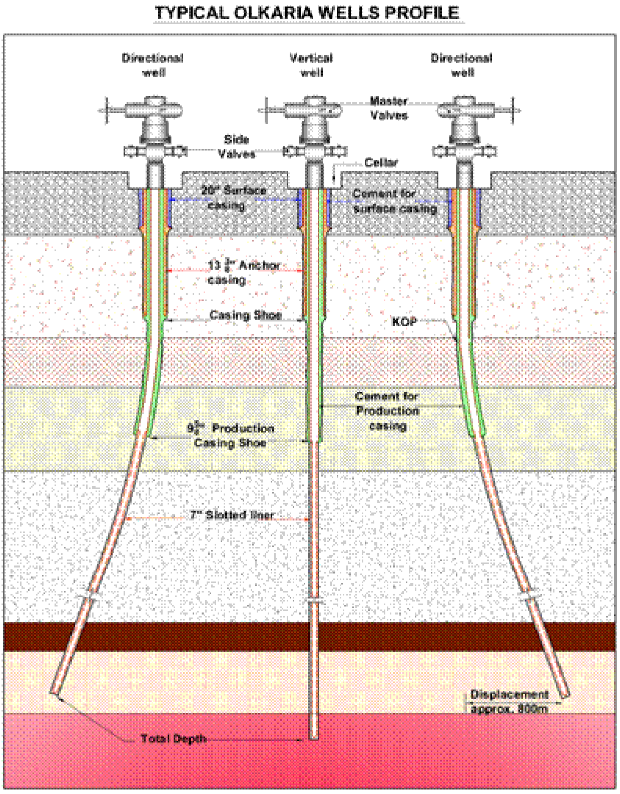

Figure 2: Typical regular diameter well profile

Drilling of geothermal wells is carried out in a series of stages with each stage being of smaller diameter than the previous stage, and each being secured by steel casings, which are cemented in place before drilling the subsequent stage. The final section of the well use a perforated uncemented liner which allows the geothermal fluids to pass into the pipe. (Semancik and Lizak, 2009)

i. Casing Programme

The first design task in preparing the well plan is selecting the depths to which the casings will be set and cemented. These depths are determined such that the casings can safely contain all well conditions encountered as a result of surface operations and from the behaviour of the formations and fluids encountered as drilling proceeds. Casing shoe depths are determined by analysis of data from adjacent wells. This includes rock characteristics, formation and formation temperatures, fluid types, composition and pressures and in particular, the fracture gradient data that is gathered from nearby wells.

Casing Diameters

The casing diameters will be dictated by the desired open hole production diameter. A typical regular diameter geothermal well as discussed by Thorhallsson (2013), would include a 20" surface casing, 13-3/8" intermediate or anchor casing, 9-5/8" production casing and finally 7" slotted liners.

The competence of the rock and the incidence of drilling circulation fluid losses are likely to govern final casing depths, and thus the number of casing strings needed to allow the target depth to be reached most economically.

Casing material and connections

The casing material and connection is determined in two steps. First, the operational scenarios which will result in burst, collapse and axial loads are defined and their magnitude calculated. From the calculated values, the casing material which has a slightly higher burst and collapse resistance than the calculated value is selected. The casing material most commonly used is steel and is selected from the petroleum industry standard API. The preferred API steels are J-55, K-55, L-80, C-75, and N-80 (Thorhallsson, 2013). In cases where special conditions are encountered, such as severely corrosive fluids, use of other specialised materials is warranted.

Casing connections

The compressive stress imposed on a casing string undergoing heating after well completion is extreme. As an example, an 800m length of casing undergoing heating from the cement setup temperature of about 60ºC to the final formation temperature of about 210 ºC would freely expand. If uniformly constrained over the full length, the compressive strength induced would be about 360MPa; the minimum yield strength of grade K-55 casing steel is 379MPa. This illustrates that the axial strength is critical and it is therefore important that the casing connection exhibits a compressive strength at least equivalent to that of the casing body. It is usual therefore that a square section thread form is chosen, and this is typically the API Buttress threaded connection (Hole, 2008b)

ii. Cementing Program

Geothermal well cementing is the process of mixing and pumping cement slurry down to fill the annular space between the casing string and formation. Upon setting, the cement will establish a bond between the casing and formation. The slurry is made by mixing cement with water and other additives. The additives are used to tailor cement for a specific application. They are mixed into the cement slurry to alter the properties of both the slurry and the hardened cement. These additives adjust the density, thickening time, and viscosity of the cement slurry, control filtration and cost per unit volume while bridging for lost circulation and specific applications. The cement is usually mixed with 35-40% silica flour for heat resistance. This ensures longevity of the cement. (Bett, 2010) Other additives besides the silica flour may include; Retarders, lightweight additives, friction reducer, fluid loss control, loss of circulation materials and accelerators.

iii. Bit selection

The drill bit is the most critical part of the bottom hole assembly. Drilling efficiency largely depends on the drill bit life and the rate of penetration. There exists a relationship between the bit cost, bit life and the bit performance. For a drill bit to have a longer drilling life, more advanced technology needs to be applied during manufacturing, thereby resulting in higher bit costs. Most drill bit manufacturers however tend to play with these factors to strike a balance between cost effectiveness and bit performance. For geothermal wells, drill bits with tungsten carbide inserts, gauge protection and journal bearing are most commonly used (Cherutich, 2009). The factors that affect bit life are lithology, the bottom hole assembly design, well trajectory and drilling parameters employed. Although one has no control over the lithology of the area, the bit life can be significantly improved by making intelligent changes in the last three factors.

iv. Drilling Fluids

Drilling fluids are very important when drilling geothermal wells as they contribute to the success of the drilling project. They are required to remove cuttings from the well, cool and lubricate the bit and the drill string and control the formation pressures during drilling. The upper section of a geothermal well is usually drilled with simple water based bentonite mud. As drilling proceeds and temperature increases, the viscosity of the mud is controlled with the addition of simple dispersants. If loss of circulation is encountered above the production casing shoe depth, attempts will be made to seal these losses with loss of circulation materials (LCM), and cement plugs. If the losses cannot be controlled easily, then drilling blind or drilling with aerated fluid commences. Once the production casing shoe has been run in hole and cemented, and drilling into the production part of the well commences, mud is no longer used as drilling fluid as it has the potential to damage the permeability and thus the production potential of the well (Chemwotei, 2011).

v. Directional Drilling

Directional drilling is a special drilling operation used when a well is intentionally curved to reach a bottom location. It is the most widely used method of drilling geothermal wells due to its various advantages. Drilling multiple wells in the same wellpad allows for fewer rig moves, less surface area disturbance as well as making it easier to exploit the resources being drilled for. Additional equipment is however required when drilling a directional well as opposed to a vertical well. These tools enable a change in the course of the wellbore from vertical to the desired direction while allowing the driller to know the position and course of the hole as drilling progresses. The principle is to orient the drill bit in the required direction at the kick-off point. The factors that determine the choice of tool to use as identified by Miyora (2010) are the degree of deflection needed, formation hardness, depth of the well, encountered temperature and economics.

vi. Hole problems

These are any occurrence which may cause a time delay in the progression of planned drilling operations. It includes the time required to solve that problem and the time it takes to bring the operation back to the point or depth at which the event occurred. It is very common to experience these problems when drilling geothermal wells. The ultimate goal of any drilling organization is to improve drilling performance by reducing unscheduled events and therefore reducing well costs. That is not to say that actual times cannot be reduced by elimination of any inefficiencies. The most common hole problems when drilling geothermal well are lost circulation, stuck pipe and fishing

3.3 Completion phase

The completion phase covers all time from when total depth is achieved to rig release. Immediately after a geothermal well is drilled to total depth, slotted liners are run into the open hole production section of the well. It is a usual practise to carry out a series of completion tests on the well, utilising the drilling rig and equipment, and in particular the rig pumps before rigging down and releasing the rig from the drill site. These completion tests and measurements are designed to identify potential feed zones in the well, provide an estimate of the total effective permeability of the well, and to establish a baseline dataset of the casing condition (Hole, 2008a). In addition, these tests determine the physical properties of the reservoir and of the reservoir fluid near the well. A significant amount of information which will add to the characterization of the reservoir and the well, can only be obtained in the period during and immediately after drilling activities are completed. The activities in the completion phase include well logging, running in the slotted liners and installation of master valve.

3.4 Rig release, rigging down and rig move.

After the master valve is installed, the rig is released and rig down commenced. The rig components are dismantled and loaded to trucks for transportation to the next drill site. The time taken to rig down, transport and finally rig up on the new site determines the cost of a rig move operation. This time will of course vary with the size of rig. It is common practise among companies to charge the cost of the rig move to the next well.

4. WELL COSTING

4.1 Elements of well costing

Well costs are a major component of the total cost of developing any geothermal project. There are several factors that affect these well costs. They include the depth of the geothermal resource together with the nature, structure and hardness of the rock formation. These parameters automatically influence the initial and final well diameter, the number of casing strings required, the rate of penetration and drilling speed, and eventually the total time required to complete the well. Deeper wells also require larger and thus more expensive drilling rigs. Other factors that influence the well cost may include the geographical location of the drillsite, the downhole problems encountered and finally the well measurements and well logging types employed.

Well costs are divided into three major costs; the pre-spud, the drilling and the completion costs. The pre-spud costs are the costs incurred during the pre-spud phase. The drilling cost, on the other hand is the sum of the total cost incurred when making the hole. This includes the cost of drilling materials and consumables and the cost of services offered depending on the contract. The drilling cost although quite predictable can vary according to the drilling contract, the size and rating of the drilling rig being used, the well design and to a lesser extent the remoteness of the drillsite and proximity to suppliers.

Drilling costs are further categorized into four components, namely;

i. Daily operating costs: These are the costs incurred when operating the drilling rig on a day to day basis. It includes the daily rig rate which is the rental charges for the rig with crew and associated equipment. This rig rate varies depending on the type and size of rig, length of contract, supervision, and of course the market conditions. The well design will of course dictate the type of rig to be hired and not to mention the extra equipment that comes with it. It may also include the costs for the rig maintenance, water supply, catering and accommodation, drill site maintenance and waste disposal.

ii. Drilling consumables costs: These are the costs inclusive of VAT and transport and handling of the drilling consumables that are used when drilling a geothermal well. These consumables include the rock bits, the drilling detergent, diesel, lubricating oil, cement and cement additives and drilling mud. The quantity of these consumables will entirely depend on the well design.

iii. Casing and wellhead costs: These are the cost of the steel casing, casing accessories and wellhead equipment inclusive of VAT and transport to the drilling site. The cost of these drilling materials can be easily estimated. When calculating the cost of casings for a particular well for example, each casing string for each hole size is costed and the total added up to give the total casing costs for the well. The same applies to each item which requires selection and breaking into individual groups for example drill bits when calculating the drilling consumable costs.

iv. Services costs: There are several services offered during the drilling of a geothermal well. These services vary depending on the well design and the drilling contract in place. These services include drilling supervision, planning and logistics, civil engineering, geological services, cementing services, directional drilling, and well logging. The total cost of services is usually costed for each individual hole section and the total cost summed up.

v. Non-productive costs: These are the costs incurred from delays due to encountered downhole problems.

The total drilling phase cost is therefore the sum of all of these costs. The costs incurred during the completion phase include the well logging tools and equipment rental charge and the associated service charge. These costs depend primarily on the type of well measurements and logging test employed.

4.2 Drilling Time

Drilling time is a key measure of the technical performance when drilling a geothermal well. The total time spent on a well consist of both productive and non-productive time during drilling. It is a sum of the following:

i. The time spent on making hole. This includes the actual drilling time and the associated activities for example circulation, directional drilling, wiper trips and reaming or hole opening.
ii. The flat time that is spent on tripping, running in casing and cementing it in place, making up BOPs and wellheads.
iii. The time spent on conducting the well completion tests.
iv. Time taken to move the rig to location, rig up and rig down once the well is drilled to completion and the rig released.
v. The non-productive time.

A graph of well depth is plotted against the total drilling time, usually in days as shown in Figure 4 below.

The detailed time estimate is then prepared for each hole section by considering the individual operations involved. The drilling time is affected by several factors as discussed below.

<u>i. Drill rate</u>

This refers to the rate at which the drill bit penetrates the formation. This drill rate depends primarily on rock type and the type of bit selected. Hard-rock drilling needs significantly more drilling time than soft rock drilling. Other factors may include the type of bit used, weight on bit, the rotary speed, bottom hole cleaning and the type of drilling fluid being used. A study done by Miyora, (2010) A UNU fellow where he compared the time required to drill 12 directional wells from the Olkaria geothermal field in Kenya to 14 similar wells of regular diameter from the Hengill geothermal field in Iceland shows an overall advance from start to finish of drilling to be about 57m per day for Iceland versus 48m per day for Olkaria.

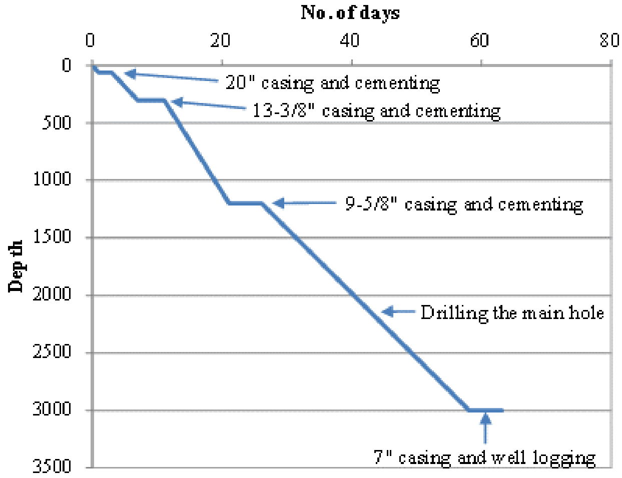

Figure 4: Depth vs days

ii. Well design

The target total depth and design of the well will have an effect on the drilling time. It may take a shorter time to drill a shallow well to total depth as compared to a deep well.

iii. Casing and cementing

This is the time required to run the casing into the well, and cement it in place. The casing and cementing time is highly dependent on the casing size and length, hole conditions and crew efficiency. From the study done by Miyora, (2010), cementing wells takes about one and a half times longer in Kenya than in Iceland. This could be due to the large number of backfill jobs done if cement returns are not received on surface in Kenya as compared to Iceland. Another possible cause deduced was the cementing programme, where no calliper logging was done in Kenya to accurately ascertain the capacity of the annulus unlike the case in Iceland where the calliper logging is carried out.

iv. Directional drilling

Directional control of a well requires an increase in the drilling time. Whether it is an attempt to drill a well directionally or in maintaining vertical control of a well that has deviation tendencies. This increase in time is usually from the many directional surveys conducted and the need to correct well angle and azimuth if need be.

v. Completion logging

Well completion test and logging for geothermal wells vary in complexity and therefore have a significant variation in the duration. The most common well logging done are the temperature, pressure and the lithological logging. These measurements aid in obtaining information which lead to a better understanding of the subsurface conditions. The efficiency of the associated personnel and their experiences with the type of well logging being done have a major impact on the required completion time.

vi. Rig move

Rig transportation is an important part of the drilling process. There are two types of rig transportation, rig mobilisation and rig move. Rig mobilisation is where the rig is transported either from the rig manufacturers workshop or overseas contractor yard, whereas rig-move refers to the movement of the rig from one completed well to the next drilling site within the same geothermal field (Cherutich, 2009).

Rig move-in and rig-up occurs before the well is spudded-in while rig-down and rig move-out occur after the completion of the well. Rig moving affects several areas of the cost estimate and must therefore be considered in the time projections. The total time required for rig move affect the rig move cost, supervision cost and of course the overhead allocations. The size of the drilling rig therefore is a major determinant of the rig moving costs.

5. COST MODEL STRUCTURE AND PARAMETERS

The EXCEL based spreadsheet cost model divides well costs into six major component; the pre-spud costs, daily operating costs, drilling consumables, casing and wellheads and services costs. For this case study, a 3000m deep regular diameter well was selected. The general design of the well is as described in the criteria in Table 1 below. With the case of a large diameter well or a slim well, the various casing diameters and setting depths need to be input in the criteria. The number of days taken to drill each section of the well were input into the model and the rate of penetration automatically calculated.

Table 1: Criteria showing depth, duration and rate of penetration.

Criteria Inputs (shaded grey)	**Depth (m)**		**Duration**	**ROP**
	From	**To**	**Days**	**(m/day)**
Drill 26" hole	0	60	1	60
20" casing and cementing	0	58.5	2	-
Drill 17-1/2" hole	60	300	4	60
13-3/8" casing and cementing	0	298.5	4	-
Drill 12-1/4" hole	300	1,200	10	90
9-5/8" casing anc cementing	0	1,198.5	5	-
Drill 8-1/2" hole	1,200	3,000	24	75
7" casing	1,174.5	3,000	2	
Completion tests			2	
Breaking Tubulus/Rig release			1	
TOTAL:			**55**	

5.1 Pre-spud costs

The pre-spud costs consisted of the drillsite preparation cost which is a fixed cost and the rig mobilization, rig demobilization and rig move costs. This is however a day rate cost and it therefore depends on the number of days taken to move the rig. These costs vary depending on the location of the geothermal field and the size of drilling rig being used. These costs were input into the price book. The cost used for this model was however estimated on the basis of recent experience. It does not represent actual market values. This is due to the fact that well costs are not normally made public by companies. Therefore obtaining actual costs was a challenge.

5.2 Daily operating costs

The daily operating costs consisted of the rig rental together with the drilling crew and all the associated rig equipment such as the cementing equipment, directional drilling, air compressor and fishing tools. Most of these items are day rate based except for the drill stem inspection which is a fixed one-off cost and is done on contract basis. This cost was therefore calculated by multiplying the total well time from spud in to total depth by the onsite daily costs.

5.3 Drilling consumables

The cost of the drilling consumables include the cost of rock bits, drilling detergent, diesel, lubricating oil, cement and cement additives and finally drilling mud or bentonite. The unit price for all of these materials is the cost of the material on site that is inclusive of VAT, transport and handling cost and shipping. Although VAT, shipping and transport and handling vary greatly, the example in this model used the estimated values assuming the field to be in Olkaria Kenya and the port to be Mombasa.This was worked out in the price book and the final price used in the various drilling materials.

<u>i. Rock bits</u>

The total number of bits required to drill each section of the well was calculated by dividing the depth of the well section, which was picked from the criteria, by the depth life of the bit as shown on Table 2below. This depth life was approximated from experience and research. It may vary however depending on location and type of bit being used.

Table 2: Cost of bits used

Rock bits	Life (m)	No.	Unit cost (USD)	Total cost (USD)
26"	180	1	30000	30000
17-1/2"	300	1	25000	25000
12-1/4"	350	3	15000	45000
8-1/2"	400	5	8000	40000
Stabilizers add 30% to bit cost				42000
SUM				182000

ii. Drilling Mud

For this example, an assumption was made that drilling bentonite was only utilized when drilling the top section of the well and a reserve is kept in the mud tanks when drilling the next section, just in case there is need for the drilling mud.

When calculating the total amount of drilling mud required, the capacity of the hole which was obtained from Gabolde and Nguyen, (2006) was multiplied by the depth of the well and an excess added. The excess is added because the actual volume of drilling mud required is twice the theoretical value due to losses into the formation. For this example, one hundred percent excess was used. This was added to the amount of drilling mud reserved on the two mud tanks. As a rule of thumb, the capacity of the mud tanks is three times the hole volume.Table 3 below shows how the calculations were made.

Table 3: Cost of drilling mud

	Depth		Capacity	Hole Vol.	Excess	Vol. with excess	Mud tanks	Weight	Cost per ton	Total Cost
Hole Diameter	From (m)	To (m)	Hole (l/m)	L	(%)	L	L	Ton	USD	USD
26" hole	0	60	342.5	20550	100	41,100	59,256	7.2	800.00	5754.00
17-1/2"	60	300	155.2	46560	20	55,872	50,000	7.4	800.00	5928.83
12-1/4"	300	1,200	76.04	91248	0	0	0	0.0	800.00	0.00
8-1/2"	1,200	3,000	36.61	109830	0	0	0	0.0	800.00	0.00
SUM							14.6	14.6	11682.832	170610.70

iii. Drilling detergent

Drilling detergent is used when loss of circulation is encountered during drilling. It is quite difficult therefore to approximate how much drilling detergent is needed for a particular well. The amount depends on the geological conditions encountered and therefore varies from location to location. For this example however, it was approximated that twodrums with a capacity of 210 litres each were used daily. This is a very rough estimation. This was then multiplied by the time it takes to drill that section of the well.

iv. Cement and cement additives

The amount of cement required for each hole section was then calculated. This was done by first calculating the volume in litres. To obtain this volume, the hole capacity which was obtained from Gabolde and Nguyen, (2006) was multiplied by the depth of the section of the well to be cemented, and an excess added. The excess depends on the geology of the area and the losses encountered during drilling although 120 percent excess was a more realistic figure for this example.The amount of dry neat class G cement was then calculated as shown in Equation 1 below.

$$\text{Amount of cement} = \frac{\text{Volume in litres} * 100}{75.8} \quad (1)$$

This was then multiplied by 1000 to get the weight of cement in tonnes.

v. Diesel and Lubricating oil

The daily consumption of diesel will greatly vary with the horsepower rating of the drilling rig. For this model, it was estimated that about 4 tonnes of diesel is required per day under normal drilling operations and 6 tonnes per day when using the air compressors. The total cost of lubricating oil required for the rig and associated equipment during the entire period from spud-in to rig release was estimated to be about 5 percent of the cost of diesel. Table 4 shows the calculations for the cost of diesel and lubricating oil

Table 4: Cost of diesel and lubricating oil

Item	Volume per day (L)	Total volume (L)	Unit Cost (USD)	Total cost (USD)
Diesel	5850	369135	1.9	701356.5
Lubricating Oil	-	-	-	35067.825
SUM				736424.325

5.4 Casing and wellhead

This includes the cost of the casing, casing accessories and consumables and the wellhead equipment together with the associated consumables. For the casing, the length of casing required for each well section was determined from the criteria and the number of casing pipes calculated assuming that one pipe is approximately 12 m long. The number of the different casing accessories and consumables were identified and input into the table, and the cost calculated. What constituted the total cost of the casings is shown in Table 5.

Table 5: Cost of Casing

Casing	Depth (m)	Length (m)	Unit Cost USD	Total Cost USD
20" casing	60	58.5	225	13162.5
13-3/8" 54.5 lb/ft casing	300	298.5	175	52237.5
13-3/8" 68 lb/ft casing, top two casings	24	24	190	4560
9-5/8" 47 lb/ft casing	1,200	1198.5	145	173782.5
7" 26 lb/ft casing slotted	3,000	1,826	170	310335
7" 26 lb/ft casing plain inside prod. casing	24	24	110	2640
SUM				556,718

5.5 Services

Various services are required during the drilling of any geothermal well regardless of the contract type. For this example, the services costed were drilling supervision, civil construction supervision, geological services including site geologist, reservoir engineering, maintenance engineering, planning and logistics.

These activities and processes may be provided to the well owner under a large number of totally separate service contracts, under one lead contract, or any mix between these two extremes.

6. DISCUSSION

This paper has discussed the various elements of well costing and the various factors that affect these elements. The well costs for this model were divided into three major costs and may be summarised as follows;

$$\text{Cost of well} = \text{Pre pud costs} + \text{drilling costs} + \text{completion costs}$$

Where *the pre-spud costs* were described to be the costs incurred during site preparation and rig mobilisation, rig move and rig-up. It can be summarised as follows:

$$\text{Pre pud costs} = \text{site preparation} + \text{Rig mobilisation} + \text{Rig move} + \text{Rig up}$$

For a mature geothermal field this can be summarised as:

$$\text{Pre pud costs} = \text{Rig move} + \text{Rig up}$$

The drilling costs were described as the total cost incurred when making the hole. The cost can be summarised as follows:

$$\text{Drilling costs} = \text{daily operating costs} + \text{cost of drilling materials} + \text{service costs}$$

The daily operating costs are mainly day rate costs which are multiplied by the total well time.

Drilling materials were subdivided into drilling consumables, casing and wellhead.

The completion costs were identified to include the well logging tools rental charge and the associated service charge. They are often said to be a day rate charge for the period of time the well logging and measurements will last. The completion costs can be summarised as follows:

$$\text{Cost of well} = \text{Pre pud costs} + \text{drilling costs} + \text{completion costs}$$

Where

$$\text{Completion costs} = (\text{daily charge} \times \text{completion time}) + \text{service cost}$$

The primary objective was to come up with a cost model that allows the estimation of well costs from a few key input variables such as well depth, number and size of casing intervals, and well trajectory. The model has two input parameters, the criteria where the well design is established and the price book where all the costs are listed down. The cost model then calculates the amount of all the drilling materials required to drill the specified well to completion. The cost of these materials is then automatically calculated using the unit cost that is automatically picked from the price book. The summary sheet then gives the total cost of the well.

7. RESULTS

Table 6: Summary Sheet

Description	**Unit**	**Total** ($)
Pre-spud costs		
Drillsite preparation	Fixed	70,000
Rig mobilisation, demobilisation and transport	One-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
Rental tools, fishing	Day rate	0
Maintenance Engineering	From table	24,000
Drill stem inspection	Fixed	300,000
Transportation and cranes	Day rate	0
BOP rentals + H2S alarms	Day rate	0
Directional drilling equipment rentals	Day rate	1,250
Welding services and others	Day rate	0
Water Supply	Day rate	0
Waste disposal, clean-up and site maintenance	Day rate	0
Lodging, catering (Camp and food)	Day rate	82,030
SUM		2,667,780
Drilling consumables		
Rock Bits	From table	182,000
Drilling Detergent	From table	46,000
Diesel & Lubricating Oil	From table	736,424
Cement	From table	39,674
Cement additives	From table	3,967
Drilling mud	From table	170,610
SUM		1,178,676
Casing and wellhead		
Casing	From table	556,718
Casing accessories and 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 and logistics	From table	12,000
Logging services	Fixed	30,000
SUM		105,000
Non-productive time		
Fishing	Day rate	
Lost Circulation	Day rate	
Others	Day rate	
SUM		0
TOTAL		5,107,074
TOTAL +15% CONTINGENCY		766,061
PROJECT TOTAL		5,873,135

8. CONCLUSION

Costing of geothermal wells can be a fairly simple task if one has a clear understanding of all activities and operations involved from well planning upto when it is completed. If that is the case, it will be possible to factor all costs associated with the drilling of a geothermal well to obtain an accurate figure of the well cost.

It is also imperative to note that proper and reliable record keeping is vital when costing geothermal wells. This therefore calls for a systematical documentation related to costs of items spent on the well so that determination of the well cost can be as accurate as possible.

Accurate well costing help quantify the substantial costs associated with development of geothermal projects. It will also help to investigate the costs of drilling and completion of wells and relate these costs to the economic viability of the geothermal project.

REFERENCES

Bett, E.K., 2010: Geothermal well cementing, materials and placement techniques. Report 10 in: Geothermal training in Iceland 2010. UNU-GTP, Iceland, 99-130

Chemwotei, S.C., 2011: Geothermal drilling fluids. Report 10 in: Geothermal training in Iceland 2011. UNU-GTP, Iceland, 149-177

Cherutich, S.K., 2009: Rig selection and comparison of top drive and rotary table drive system for a cost effective drilling project in Kenya. Report 8 in: Geothermal training in Iceland 2009. UNU-GTP, Iceland, 65-84

Gabolde G., and Nguyen, J.P., 2006: Drilling Data Handbook (8th edition). InstitutFrancaisdu P´etrole Publications, Paris.

Hole, H., 2008a: Geothermal well completion tests.Presented at “Petroleum Engineering Summer School”, Dubrovnik, Croatia workshop 26, 5pp

Hole, H., 2008b: Geothermal deep well drilling practices- An introduction. Presented at “Petroleum Engineering Summer School”, Dubrovnik, Croatia workshop 26,6pp

Karewa, N. O., 2012: Reporting and efficiency analysis in geothermal well drilling. Report 16 in: Geothermal training in Iceland 2012. UNU-GTP, Iceland, 293-328

Miyora, T. O., 2010: Controlled directional drilling in Kenya and Iceland. Report 20 in: Geothermal training in Iceland 2010. UNU-GTP, Iceland, 365-390.

Mwangi, M., 2005: Phases of geothermal development in Kenya. Presented at “Workshop for decision makers on geothermal projects and managements”, Naivasha Kenya, 11pp

Semancik, P., Lizak, F., 2009: Geothermal resources. Presented “Environmental Impacts of Power Industry”, Pernink, University of West Bohemia, Czech Republic, 6pp

Thórhallson, S., and Sveinbjornsson, B., 2012: Geothermal drilling cost and drilling effectiveness. Short course on Geothermal Development and Geothermal Wells organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 11-17, 2012. 10 pp.

Thorhallsson, S., 2013: Geothermal drilling Technology. UNU-GTP, Iceland, unpublished lecture notes.