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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. This makes geothermal plants more expensive to build than 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. Obtaining accurate costs for 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. Accurate well cost records also make it possible to carry out an 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 high temperature geothermal wells that allows for 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 a price book where all the unit costs are listed. 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 pricing a geothermal well. There is surprisingly little published data available on the breakdown of geothermal drilling costs due to the competitive nature of the geothermal drilling industry and confidentiality clauses. As a result, the data used for the price book for this model are estimated based on best guess values. The cost model divides the well cost into three major parts: pre-spud, drilling, and completion costs. The pre-spud costs include all the costs prior to spud-in, while the drilling costs are all the costs incurred while making the hole. This includes the rig rental cost, materials and the supervision cost. This is where the bulk of the cost lies. Finally the completion costs are the costs incurred after achieving total depth, prior to rig release. The model does not include the cost of monitoring the well after drilling nor that for flow testing.

1. INTRODUCTION

The goal of any geothermal drilling project is to drill the well to completion as per the drilling programme while ensuring the safety of the drilling staff, the drilling rig and to complete the well with minimum cost. The drilling programme includes the geoscientific studies which are conducted to determine the location of the well and the targets to be reached, the design of the well, the drilling technology to be applied and the well measurements and logging to be conducted while drilling and upon completion.

Drilling geothermal wells 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 labour intensive operation with most of the jobs being performed 24 hours a day, seven days a week, in all weather conditions. The work is strenuous and hard and in Kenya is performed in a traditional 12 hour shift on a two-week on and off rotation. Only extreme weather, mechanical failure or lack of supplies 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, depending on the geological conditions. Accurate costing of these geothermal wells is, therefore, very important.

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. 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 organisation, 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 well drilling costs. The realization that the drilling process with the bit on the bottom takes about 50% of the total time, and the rate of penetration cannot be significantly increased, has led to the option of trying to reduce the non-drilling time. The challenge is to increase rig availability and reduce the time of “flat spots” where there is no depth progress. The “flat spots” are due to rig-up time, running in and cementing the casing, and solving drilling problems mainly caused by loss of circulation or a stuck pipe. One success story has been the development of drill bits which can stay in the hole longer and drill more depth, thereby reducing the rig time.

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 (ESMAP and World Bank, 2012). 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 as follows;

i. Studies of surface manifestation: This phase involves the collection of information from previous geoscientific studies made in the area and analysing it. It also involves conducting surface exploration by mapping the geothermal manifestation in the area to determine the existence of a commercially viable geothermal reservoir and to estimate its exploitable potential.

ii. Detailed exploration: The detailed exploration phase consists of surveys to further confirm the findings from the preliminary resource assessment. An exploration plan is generated. This plan includes the geochemical, geological and geophysical exploration, heat flow measurements, hydrogeological and baseline environmental studies. Interpretation of old information and results from new surveys are used to develop the first basic conceptual model.

iii. Exploratory well drilling: This is the last phase of the exploratory phases. Based on the environmental studies done and the developed conceptual model, 3 to 5 exploratory drill sites are selected and the first wells are drilled and tested. This is followed by drilling the appraisal wells. The appraisal wells are mainly drilled in order to determine the size, characteristics and potential of a reservoir and, therefore, the size of the power plant to be developed.

iv. Feasibility studies: The results from the test drilling will enable the completion of the feasibility study, including all the financial calculations. At this point it is considered possible to determine the most economically advantageous project size and the investment necessary.

v. Developmental phase: This marks the beginning of the actual development of the power project. It consists of drilling production and re-injection wells. The time needed to drill a geothermal well not only depends on a well's total depth, but also on the geology of the area and the capability and capacity of the drilling rig being used. Production drilling is a time consuming and expensive activity. Delays during the drilling phase can, therefore, seriously affect the financial viability of a project. The environmental impact assessment for the project is carried out concurrently with the detailed power plant design.

vi. Construction, start-up and commissioning: This phase comprises the installation of a steam gathering system and the separators, installation, start-up and commissioning of the power plant with the turbine, generator and the cooling system. The cooling system consists mainly of a condenser, cooling tower, and a re-injection system.

vii. Operation and maintenance: This includes the operation and maintenance of both the steam field which includes the geothermal wells, steam pipelines and infrastructure and the power plant which includes the turbine, generator and cooling system. Proper maintenance of all of these facilities is crucial as it ensures availability of the power plant and steady steam production from the geothermal wells.

3. PHASES OF GEOTHERMAL DRILLING

The entire drilling project from well planning, designing, and drilling right to 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:

3.1 Pre-spud phase

The pre-spud phase constitutes mainly the designing, planning and preparation of the infrastructure. It extends from the start of a drilling contract to the well spud. The pre-spud phase has several sub-phases as discussed below.

Well design: The number of casing strings, casing diameter 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 well control considerations. When selecting the type of casing to be run in the hole, several parameters are considered as well. These parameters include:

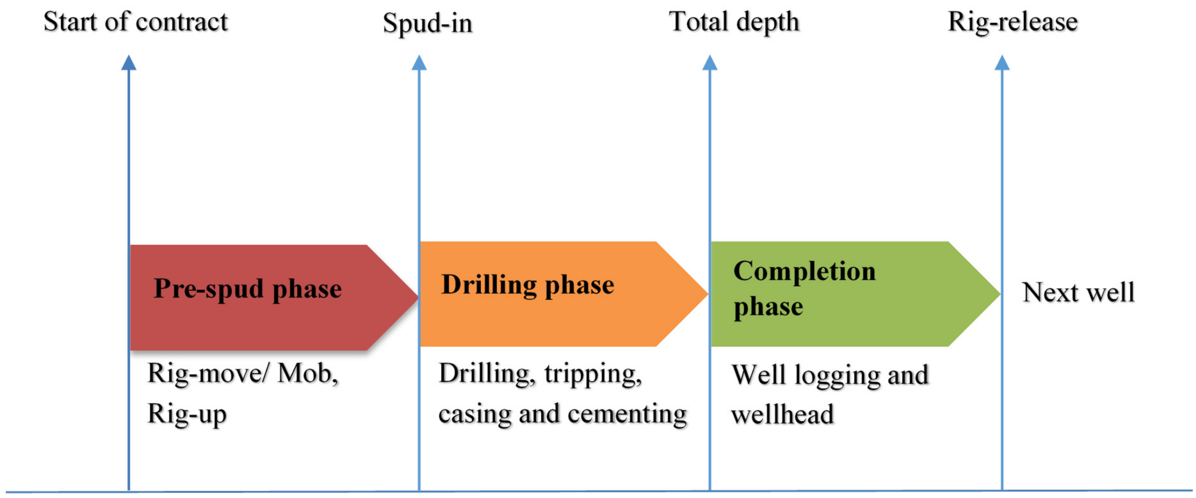

FIGURE 1: Summary of geothermal drilling phases

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. Well trajectory;
iv. Length of individual casing interval;
v. Brine chemistry; and
vi. The need for special casing material or connections.

Wells are generally designed from the bottom up to the surface casing, which is to say that the expected depth of the production zone and the expected flow rate will determine the casing programme. Most of the drilling equipment requirements will follow from these criteria.

The next important step is the preparation of a drilling programme. This programme 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 consumable specifications and selection, for example the wellhead, drilling fluid, cement and cement additives.

Construction of access roads: Construction of the access roads follows. It involves clearing vegetation, removal of the top soil, excavation, grading, murrum dumping, final grading and compacting and provision of drainage. Earth moving equipment is used for this purpose. In new geothermal fields this can take quite a long time and can also be expensive.

Well pad preparation: This is the preparation of a stable, well compacted drilling site that will accommodate the drilling rig, its associated equipment, all the offices and accommodation facilities and the drilling crew. A large discharge pond which is big enough to accommodate the discharged fluids is also prepared. This is done according to a designed access road route and well pad layout. The process involves marking the sites, clearing the vegetation and removing the top soil, taking spot heights and fixing depth of cut while excavating the pad area. The process of levelling, dumping of murrum, final grading, and compacting of the pad using earth moving equipment follows:

Cellar construction: A cellar is a concrete structure that provides working space for well head equipment for the rig such as the blow out preventer (BOP) and later for the production wellhead. Construction of the cellar includes marking the cellar area, excavation and either bringing in a precast cellar or by making it on site from concrete, and laying drainage pipe. The cellar design usually depends on the size of the drill rig and the rig floor height.

Laying water lines: Water for the drill fluid is key during the drilling of geothermal wells although its availability close to drilling sites is limited in most geothermal fields in the world. The water is mostly sourced from nearby rivers, lakes or boreholes. This water has to be pumped from the source to the drill site. The pipeline route is first surveyed and approved. The length of pipeline can be more than 10 km and the change in elevation several hundred metres. This is followed by laying the pipe, installing the pumps and arranging for water storage. The flow meters are then installed and finally the water line is tested for any leakages.

Rig mobilization/ demobilization: This involves the transportation of the drill rig to a new geothermal field. This is usually a one off cost. The cost may be borne entirely by the first well drilled or shared amongst several wells to be drilled. Mobilization cost is, therefore, highly variable.

Rig move, rig up and transport costs: Rig move is the transport of the drill rig from one drill site to the next. It includes the rig down, rig move and rig up on the new site. This is usually the case when the drill rig is drilling within the same geothermal field or different fields within the same region.

3.2 Drilling phase

The drilling phase includes all the activities carried out from when the well is spudded until the total depth is reached. Typically, geothermal wells today are drilled to depths ranging from 400 to 2000 m depth for low to medium temperature systems and from 700 to 3000 m depth for high temperature systems. Both vertical and directional wells are drilled. An example of a typical regular diameter well profile and trajectory for wells drilled in Olkaria geothermal field is shown in Figure 2.

Drilling 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 uses a perforated uncemented liner which allows the geothermal fluids to pass into the pipe (Semancik and Lizak, 2009).

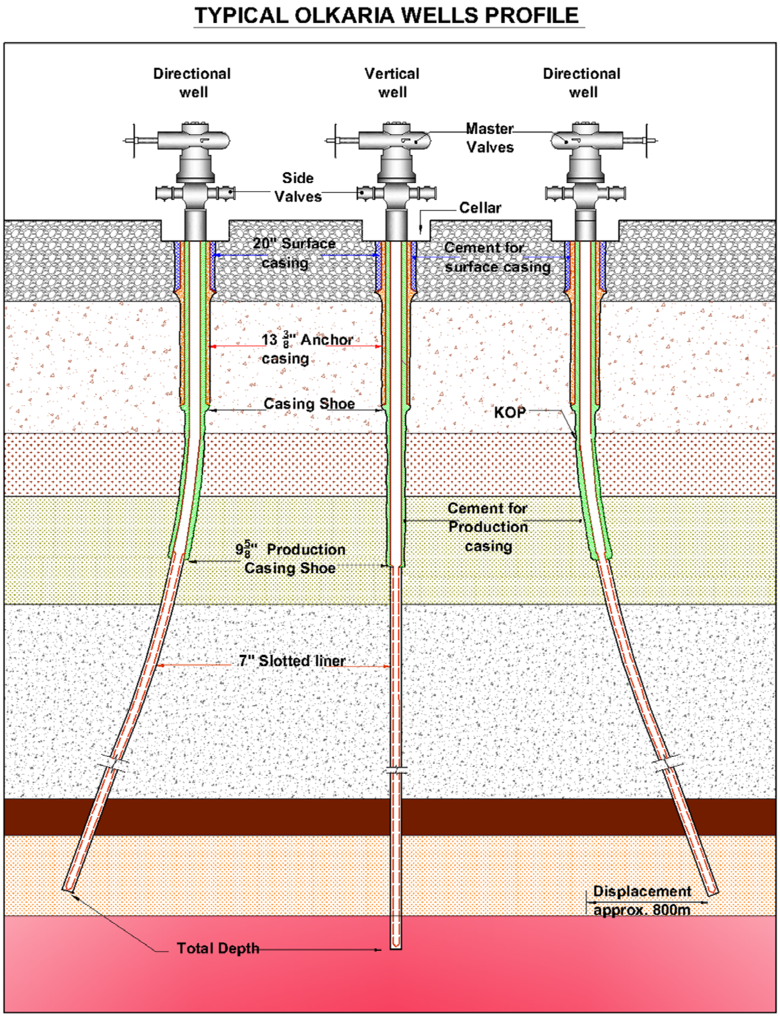

FIGURE 2: Typical regular diameter well profile in Olkaria

3.2.1 Casing programme

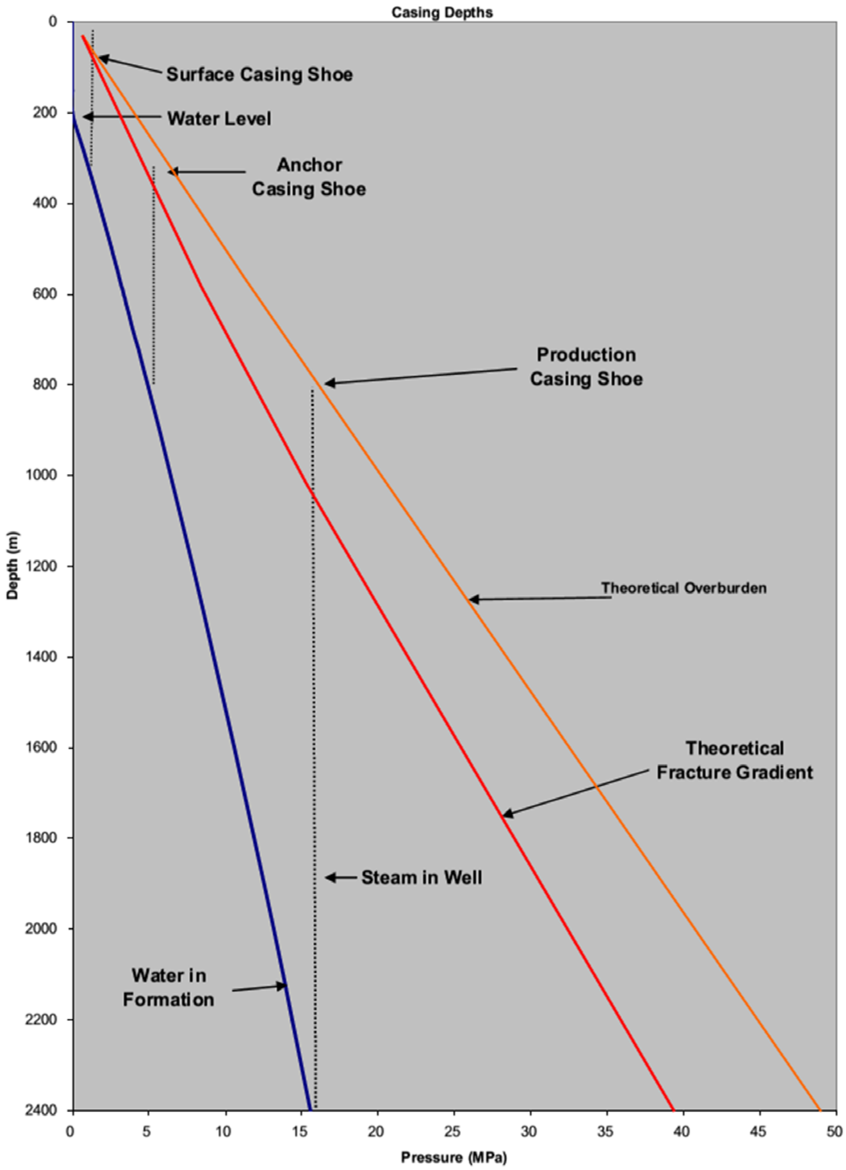

FIGURE 3: Theoretical minimum casing depth selection (Hole, 2008a)

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 analysing 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. Figure 3 illustrates how the shoe depth may be chosen as per the New Zealand Standard 2403:1991. It assumes a boiling point for depth fluid pressure conditions from a nominal water level at 200 m depth; and a uniform formation fracture gradient (overburden) from the surface to the total depth of 2400 m. From this model, the production casing shoe would need to be set at about 800 m, the anchor casing shoe at approximately 350 m, and a surface casing at around 50 m depth.

Casing diameters:
The casing diameters will be dictated by the desired open hole production diameter. A typical regular diameter geothermal well as discussed by Thórhallsson (2013) would include:

i. Surface casing (20"or 18-5/8" casing): These are the largest casings which are set at a shallow depth and are used to prevent loose near surface materials from collapsing into the hole. They are also utilized to support the initial drilling wellhead or blow out preventer and to contain the circulation drilling fluid. The setting depth of the casing shoe will be estimated from geological deductions but may be altered to reflect conditions found during the course of drilling.

sii. Intermediate or anchor casing (13-3/8”casing): This string of casing isolates the surface aquifer from contamination while providing anchorage for the wellhead. It also seals off loss zones and protects the shallow formation from deep reservoir pressure, thus preventing blowouts. The setting depths are usually chosen from expected formation rock and fluid conditions to provide adequate permanent anchorage and additional security against drilling problems, including blowouts.

iii. Production casing (9-5/8" casing): This casing is smaller in diameter and is set at greater depth than the previous casing. It primarily acts as the conduit for the reservoir fluid to the surface, protecting the shallow formation from deep reservoir pressure, thus preventing blowouts, and isolating the cooler shallow water from degrading the reservoir fluids. The depth of this casing string is chosen on the basis of the expected depths and temperatures of fluids to be included and excluded from production. A common criterium for high temperature wells is to accept only fluids above 210°C, as the inflow of lower temperature fluid may have an unstable flow or even no self-flow.

iv. Slotted liner (7" casing): This is primarily run to prevent the reservoir wellbore from collapsing and blocking the well flow path. The liner depth is from 10-20 m up into the production casing (overlap) and to the well's total depth.

The competence of the rock and the incidence of drilling circulation fluid losses are likely to govern final casing depths. The final decision on casing depths is, however, made on site, considering the actual well conditions and the design.

Casing material and connections:
The casing material 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 thickness which has a higher burst and collapse resistance than the calculated value is selected. The casing material most commonly used is steel, based on the petroleum industry standard API SPEC 5CT. The preferred API steel grades are K-55, L-80, and C-75 (Thórhallsson, 2013).

Casing connections:
The compressive stress imposed on a casing string undergoing heating after well completion is extreme. As an example, an 800 m length of casing undergoing heating from the cement setup temperature of about 60°C to the final formation temperature of about 210°C would freely expand. If uniformly constrained over the full length, the compressive strength induced would be about 360 MPa; the minimum yield strength of grade K-55 casing steel is 379 MPa. 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, for a square section thread form to be chosen; this is typically the API Buttress threaded connection (Hole, 2008b).

3.2.2 Cementing programme

Geothermal well cementing is the process of mixing and pumping a cement slurry down the casing and then up the annulus to totally fill the annular space between the casing string and the formation. Upon setting, the cement will establish a bond between the casing and the 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 dry mixed into the cement 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. Sometimes mica flakes are added to form bridging for lost circulation. The cement is usually mixed with 35-40% silica flour for temperature resistance. This ensures longevity of the cement (Bett, 2010).

Other additives besides the silica flour may include:

i. Retarders are used to prolong the thickening time of the cement slurry, thus avoiding premature setting at elevated temperatures. The retarder concentration is based on the expected or measured bottom hole circulation temperature (BHCT) and the pumping time. The exact retarder concentration is, however, decided upon after a cement laboratory test on the same batch of cement.

ii. Lightweight additives or extenders are used to reduce the slurry density for cementing jobs where the hydrostatic head of the cement slurry may exceed the fracture strength of the formation. In reducing this slurry density, the ultimate compressive strength and thickening time is reduced. The most commonly used extender is expanded perlite or glass microspheres and bentonite.

siii. Friction reducer includes dispersants used to lower the yield point of the slurry, thereby allowing the cement slurry to go into turbulent flow at a lower velocity.

iv. Fluid loss control additives are used to prevent dehydration of cement slurry and premature setting.

v. Loss of circulation additives are used to prevent the loss of slurry into the formation. Mostly used are the mica flakes.

vi. Accelerators are added to the cement slurry to shorten the setting time. These are mostly used when cementing the surface casing where temperature is low, resulting in the cement taking too long to set. An example is calcium chloride.

3.2.3 Bit selection

The drill bit is the most critical part of the bottom hole assembly. Drilling efficiency largely depends on the drill bit's life and the rate of penetration. There is 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 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 the 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 latter three factors.

3.2.4 Drilling fluids

Drilling fluids are very important when drilling geothermal wells as they contribute to the success of the drilling project. They are required in order to remove cuttings from the well, cool and lubricate the bit and the drill string and control the formation pressures during drilling. Various drilling fluids are selected depending on the diameter of the well, loss of circulation, temperature and the technique of drilling employed. It is important, therefore, to select a drilling fluid that will provide the best results in terms of cost, safety and performance so as to attain the desired depth and output of the well. The drilling fluids most commonly used when drilling geothermal wells include water-based mud, water alone, aerated mud or water and foam. The upper section of a geothermal well is usually drilled with water-based bentonite mud, thereby maintaining the pH above 9. As drilling proceeds and temperature increases, the viscosity of the mud is controlled with the addition of 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 loss persists. If none of these methods work, 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). In the open hole section, water alone is used as the drilling fluid and, in many areas, compressed air is added to achieve a pressure balance, especially after encountering losses. High viscosity polymer pill sweeps are used, especially before adding a new drill pipe, to aid in hole cleaning should there be a large fill-in.

3.2.5 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 well pad allows for fewer drill sites, less surface area disturbance as well as making it easier to exploit the resources being drilled. Additional equipment and expert services from "directional drillers" are, however, required when drilling a directional well as opposed to a vertical well. They include:

i. Tools for changing the course of the well bore from vertical to the desired direction, such as downhole motors. They are of two types, either having a bent-sub above the "straight" motor, or the mud motor housing itself having a bend a short distance above the bit. The latter type is more versatile as it can either be deployed in a "sliding" mode to increase the angle or "rotation" to drill straight to stay on track, but the straight motor and bent-sub can only increase the angle and then the bent sub has to be removed to drill straight with a new BHA.

ii. Surveying equipment run on a wireline such as magnetic-single shot equipment, magnetic multi-shot equipment and the gyroscopic multi-shot. Measurement while drilling tools (MWD) are used in the BHA above the motor to transmit by mud pulse technology the toolface, inclination and azimuth.

These tools enable a change in the course of the wellbore from vertical to the desired direction and inclination 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 (KOP). The factors that determine the choice of tool to use is identified by Miyora (2010) as the degree of deflection needed, formation hardness, depth of the well, encountered temperature and economics.

3.2.6 Hole problems

These are any occurrences which may cause a time delay in the progression of planned drilling operations. Included are the time required to solve the problems 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 thereby reducing well costs. That is not to say that actual times cannot be reduced by eliminating inefficiencies. The most common down-hole problems when drilling geothermal well are discussed below.

Loss of circulation
This is one of the most expensive problems routinely encountered when drilling geothermal wells. It is the loss of drilling fluid to pores or fractures in the rock formation being drilled. Ideally the well should have no losses until the casings have been cemented, but in the open hole section big losses indicate good future production potential and are, thus, highly desirable. Loss of circulation is quite harmful for the drilling process for several reasons:

i. Drilling without returns can leave the formation pressure unbalanced, which can allow the hole wall to fall in. Also, the cuttings that do not enter the fracture accumulate inside the well cavities. At breaks in circulation, for example when adding a new pipe and without much warning, the material can jam the drill string. This can cause a stuck pipe, twist offs, or even loss of the well.

ii. Flow of the drilling fluid with cuttings into the formation can damage the formation's permeability and reduce well productivity.

iii. Lost circulation that occurs during the cementing of the well can cause incomplete cement jobs that can in turn lead to casing failure.

iv. The drilling fluid used, for example bentonite, is usually quite expensive and losing it into the formation instead of re-circulating it is costly.

vi. Lost circulation can suddenly lower the fluid level in a well. Decreasing the static head of drilling fluid in a hot formation can allow the formation fluids to enter the wellbore, causing loss of well control.

vii. Placement of cement plugs is made difficult because the top and bottom of the loss zone are often not well known.

viii. Time lost in attempts to regain circulation adds to the cost of the well.

Stuck pipe
This refers to the mechanical sticking of a drill string. It is caused by chips and cuttings collecting on top of the drill string. The pipe can also be held against the wellbore wall by the differential between the drilling fluid pressure and the pore pressure. Sticking directly affects the cost of the well as it can extend the time it takes to complete the well.

Fishing
A fishing operation is an attempt made to remove stuck or broken objects from the well which prevent further drilling. Fishing may take up to 20% of the time incurred when drilling a geothermal well. Each rig is equipped with various fishing tools. Fishing jobs require high skill and specialized equipment. Most companies find it more economical to rely on service companies to furnish the tools and specialized personnel when the need arises (Ngugi, 2008).

Other well problems may include twist-offs (broken drill sting), hole stability problems, well control problems, cementing, casing problems and directional drilling problems.

3.3 Completion phase

The completion phase covers the time from when the total depth is achieved to rig release. Immediately after a geothermal well is drilled to total depth, a slotted liner is 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 conditions (Hole, 2008c). In addition, these tests determine the physical properties of the reservoir. 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 during the completion phase include: injection tests, well logging, running in the slotted liner and installation of the master valve.

3.4 Rig release, rigging down and rig move

After the master valve is installed, the rig is released and rig down is 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 vary from 5 to 14 days, mainly depending on the type and size of the rig and the distance involved. Drilling companies usually charge a fixed price for the rig move to the next well.

4. WELL COSTS

4.1 Elements of well costs

Well costs are a major component of the total cost of developing any geothermal project. It is estimated to be about 40% of the total investment cost for a new high temperature geothermal plant (Thórhallsson and Sveinbjörnsson, 2012). 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 well cost may include the geographical location of the drill site, well design, whether vertical or directional, the down hole problems encountered and finally the well measurements and well logging employed.

Well costs are divided into three major items: the pre-spud, the drilling and the completion costs. The pre-spud costs are the costs incurred during the pre-spud phase for infrastructure and rig mobilization. The drilling cost, on the other hand, is the sum of the total costs incurred when making the hole. This includes the cost of the drilling rig rental, 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 drill site 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 charge for the rig with crew and associated equipment. This rig rate varies depending on the type and size of rig, length of contract, and of course the market conditions as reflected in a tender. The well design will dictate the type of rig to be hired and the extra equipment that comes with it. It may also include the costs for the 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, drilling detergent, diesel, lubricating oil, cement and cement additives and drilling mud. The quantity of these consumables will entirely depend on the well design and the working days.

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. The purchasing of materials is usually by an open tender process or integrated in the drilling contract. When calculating the cost of casings for a particular well, for example, each casing string for each hole size is costed and the total is summed up to give the total casing costs for the well.

iv. Services costs: There are several services provided 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 services, air drilling services and well logging.

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

The total drilling cost is, therefore, the sum of all of these costs. The costs incurred during the completion phase include the well logging and equipment rental and the associated service charge. These costs depend primarily on the type of well measurements and logging programme 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 consists of both productive and non-productive time. It is a sum of the following:

i. The time spent on making the 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. The detailed time estimate is then prepared for each section of the well by considering the individual operations involved. The drilling time is affected by several factors as discussed below.

i. Drilling rate - rate of penetration (ROP)
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 the bit, the rotary speed, bottom hole cleaning and the type of drilling fluid being used. A study done by Miyora (2010), a UNU fellow, in which 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 57 m per day when drilling in Iceland versus 48 m per day when drilling in Olkaria.

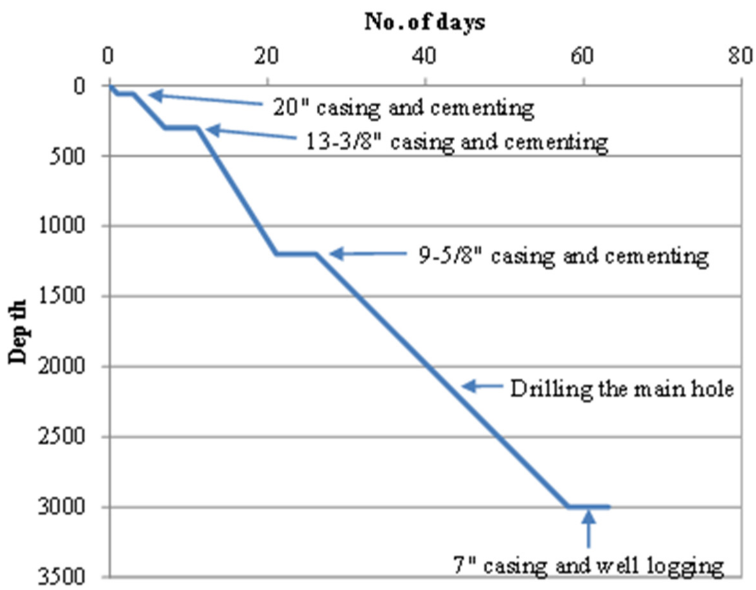

FIGURE 4: Drilling time - depth vs. days

ii. Well design
The target total depth and design of the well will have an effect on the drilling time. It takes a shorter time to drill a shallow well to total depth than a deep well. The time to drill a "regular" geothermal well and a "large" diameter geothermal well is, however, virtually the same.

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 required if cement returns are not received on the 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 in Iceland where the calliper logging is carried out to estimate the cement volume and temperature logs to locate the main loss zones.

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 directional control of a well that has deviation tendencies. This increase in time in Kenya is usually from the many directional surveys conducted and the need to correct well angle and azimuth if need be by changing the BHA, compared to Iceland where a MWD tool and a steerable motor is used, allowing the drilling to go on without interruption.

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 lithological logging. These measurements aid in obtaining information which lead to a better understanding of 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 occur before the well is spudded-in while rig-down and rig move-out occur after completion of the well. The size of the drilling rig, therefore, is a major determinant of the rig moving costs. For the present model, the cost for the rig move is a fixed sum.

4.3 Drilling contracts

Geothermal drilling contracts mainly fall under four main categories:

i. Day rate contracts
This is the most commonly used contract worldwide. The drilling contractor in this case is paid a specified sum by the company for each day that he spends on the well. Most drilling contractors prefer this type of contract as there is little downside for them. The day rates are usually broken down into three: Operating day rate, which is applied to the day rate when the contractor's equipment and personnel are fully utilized; The second is the standby day rate in which case the contractor's equipment and personnel are not being fully utilized. This rate is usually a slightly lower than the operating rate: Finally, the zero day rate is when no payment is made at all to the drilling contractor, e.g. if rig maintenance exceeds agreed limits.

ii. Footage contracts (metre rates)
In this case, a specified rate per metre drilled is negotiated for a well of a certain design. Certain operations are, however, charged at a day rate or a fixed rate. With this type of contract, the contractor has an incentive to drill the well faster. This type of contract has been employed in mature geothermal fields which are reasonably well known, for example in Iceland.

iii. Integrated drilling contracts
An integrated contract is made with the drilling contractor for the provision of all drilling services and materials, under one contract.

iv. Turnkey contracts
With this type of contract, the company pays the contractor a lump sum to drill a well of a certain depth in a given field. It is, therefore, up to the drilling contractor to procure all the drilling materials and to organise the required third party services in order to deliver the well. The company has no input on the day to day drilling operations unless of course if it is stated in the contract.

The scope of work of a drilling service contract will define the split of responsibility between the owner and the contractor. Operational responsibility, control and risk are all interlinked. Operational responsibility implies operational risks, but imposes operational risk, as depicted by Hole (2006) in Figure 5.

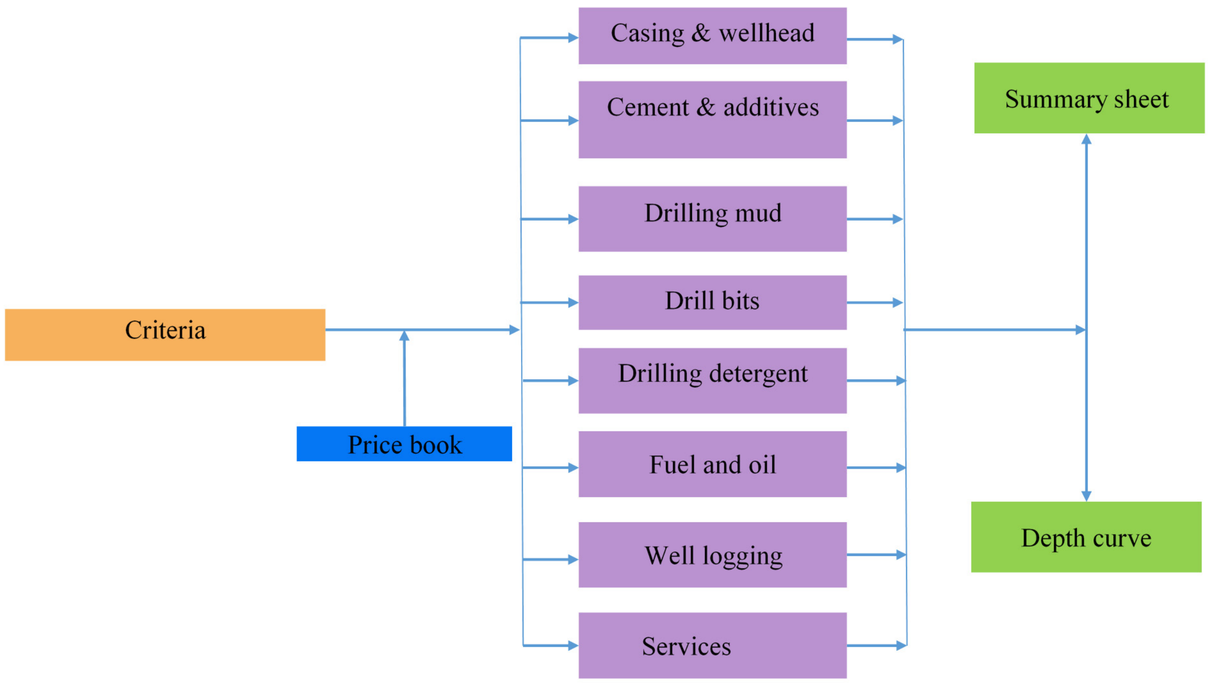

FIGURE 5: Summary of cost model parameters (Hole, 2006)

5. COST MODEL STRUCTURE AND PARAMETERS

The need to make an accurate estimation of well costs led to the development of a well cost model known as the Wellcost Lite in the United States of America. This model was used to determine the most important factors behind drilling costs for geothermal wells. The model allows for the input of a casing design programme, rate of penetration, bit life and trouble map for each well interval. The model then calculates the time to drill each interval including rotating time, trip time, mud, and related costs and the end of interval costs such as casing and cementing and well evaluation. The cost of materials and the time required to complete each interval is calculated. The time is then multiplied by the hourly cost for all rig time –related cost elements such as tool rental, blow out preventers (BOP), and supervision. Each interval is then summed to obtain a total cost. The cost components of the well are presented in a descriptive breakdown and on the typical authorization for expenditure (AFE) form used by many companies to estimate drilling costs (Augustine and Petty, 2006). The Wellcost Lite model is, however, not yet available.

The EXCEL based spreadsheet cost model developed as a part of this study divides well costs into six major components: the pre-spud costs, daily operating costs, drilling consumables, casing, wellheads, and services costs. For this case study, a 3000 m deep regular diameter well (9 5/8" production casing) was selected, similar to wells drilled in Kenya. The general design of the well is as described in the criteria in Table 1. With the case of a large diameter well or a slim hole, the various casing diameters and setting depths need to be entered into the criteria inputs. The number of days taken to drill each section of the well is inputted, based on best knowledge, and the rate of penetration is then automatically calculated. This is summarised in Figure 6.

TABLE 1: Criteria showing each depth interval, duration and calculated rate of penetration

Criteria inputs	**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	75
13-3/8" casing and cementing	0	298.5	4.1	-
Drill 12-1/4" hole	300	1,200	10	120
9-5/8" casing and cementing	0	1,198.5	5	-
Drill 8-1/2" hole	1,200	3,000	32	93.8
7" casing	1,174.5	3,000	2	
Completion tests			2	
Breaking Tubulus/Rig release			1	
TOTAL			**63.1**	

5.1 Pre-spud costs

The pre-spud costs consist 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 therefore depends on the number of days taken to move the rig. These actual costs vary depending on the location of the geothermal field and the size of the drilling rig being used. These costs were input into the price book for this model as a fixed cost based on recent experience.

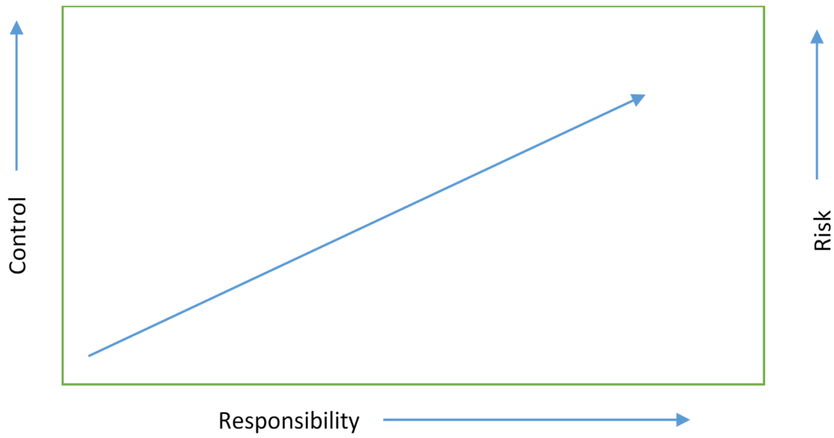

FIGURE 6: Responsibility, control and risk matrix

5.2 Daily operating costs

The daily operating costs consist of the rig rental, together with the drilling crew and all the associated rig equipment, but not such equipment 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 a contract basis. This cost was, therefore, calculated by multiplying the total drilling time from spud in to total depth by the unit daily costs.

5.3 Drilling consumables

The cost of the drilling consumables includes 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 costs 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 for the final price used for the various drilling materials.

TABLE 2: Cost of bits used

Rock bits	Life (m)	No.	Unit cost (USD)	Total cost (USD)
26"	180	1	30,000	30,000
17-1/2"	300	1	25,000	25,000
12-1/4"	350	3	15,000	45,000
8-1/2"	400	5	8,000	40,000
Stabilizers add 30% to bit cost				42,000
SUM				182,000

i. Rock bits
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 expected depth life of the respective bit size as shown in Table 2. The depth life of bits is assumed as shown in Table 2. It may vary, however, depending on the formation and type of bit being used.

ii. Drilling mud
For this example, an assumption was made that bentonite mud was only utilized when drilling the top sections of the well down to about 300 m and a reserve is kept in the mud tanks when drilling the next section, just in case there is need for the drilling mud for sweeps.

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 assumed to be twice the theoretical value for the well, to cover losses into the formation. This was added to the amount of drilling mud reserved on the two mud tanks. As a rule of thumb, the total capacity of mud tanks on rigs should be about three times the well volume. Table 3 below shows how the calculations were made.

TABLE 3: Cost of drilling mud

	Depth		**Capacity**	**Hole volume**	**Excess**	**Hole volume w. excess**	**Mud tanks**	**Total mud weight**	**Cost per tonne**	**Total cost**
	From (m)	**To (m)**	**Hole (l/m)**	**(L)**	**(%)**	**(L)**	**(L)**	**(Ton)**	**(USD)**	**(USD)**
26" hole	0	60	342.5	20550	100	41,100	100,000	9.9	800	8,000
17-1/2" hole	60	300	155.2	46560	100	93,120	100,000	13.5	800	10,900
12-1/4" hole	300	1,200	76.04	91248	0	0	0	0.0	800	0
8-1/2" hole	1,200	3,000	36.61	109830	0	0	0	0.0	800	0
SUM										**18,900**

iii. Drilling detergent

Drilling detergent (drilling soap) is added to the compressed air for pressure balance drilling after loss of circulation is encountered during drilling. It is quite difficult to estimate how much drilling detergent is needed for a particular well. The amount depends on the geological conditions encountered and the amount of aerated drilling employed and, therefore, varies from location to location. For this example, however, it was approximated that two drums 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, as shown in Table 4.

TABLE 4: Cost calculation for drilling detergent

	From (m)	**To (m)**	**Usage (L/day)**	**Total usage**	**No. of drums**	**Unit cost**	**Total cost**
Drilling 26" hole	0	60	420	0	0	500	0
Drilling 17-1/2" hole	60	300	420	1680	8	500	4,000
Drilling 12-1/4" hole	300	1,200	420	4200	20	500	10,000
Drilling 8-1/2" hole	1,200	3,000	420	13440	64	500	32,000
SUM				**19320**	**92**	**500**	**46,000**

iv. Cement and cement additives

The amount of cement required for each well section was then calculated. This was done by first calculating the total theoretical annulus 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. To cover losses and volume in cavities and washouts, an excess was added. The excess depends on the geology of the area and the losses encountered during drilling. For the cost model an excess of 120 % is used (theoretical volume of the open hole * 2.2, but with no excess in the casing-casing annulus). The amount of dry neat cement required was then calculated as shown in Equation 1 below, based on a slurry yield of 75.8 L/100 kg.

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

This was then divided by 1000 to get the weight of cement in tonnes as shown in Table 5.

TABLE 5: Cost calculation for neat cement

	Depth (m)	**Capacity (l/m)**	**Excess (%)**	**Total vol. /L)**	**Neat cement (Tonne)**	**Cost/tonnes (USD)**	**Total cost (USD)**
26" x 20"	60	139.8	120	18,454	24.35	250	6,100
Backfill	25	139.8	50	5,243	6.92	250	1,800
Plug job	10	342.5	20	4,110	5.42	250	1,400
17-1/2" × 13-3/8"	300	64.5	120	42,570	56.16	250	14,100
Backfill	100	64.5	20	7,740	10.21	250	2,600
Plug job	30	155.2	20	5,587	7.37	250	1,900
12-1/4" × 9-5/8"	1,200	29.1	80	62,856	82.92	250	20,800
Backfill	600	29.1	0	17,460	23.03	250	5,800
Plug job	100	76.04	120	16,729	22.07	250	5,600
SUM				**180,748**	**193.35**		**60,100**

For the cement additives, the amount by weight of blended cement used was calculated. For this example, the cement additives considered were retarder and water loss with 0.3 and 0.5 percent by weight of cement (BWOC), respectively. This was calculated as shown in Table 6.

TABLE 6: Cost of cement additives

	% BWOC	Cement w. additives (Tonne)	Total weight (Tonne)	Unit cost (USD)	Total cost (USD)
Water loss	0.5	163	0.82	12,000	9,900
Retarder	0.3		0.49	8,000	4,000
SUM					**13,900**

v. Diesel and Lubricating oil

The daily consumption of diesel fuel 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 on average 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 7 shows the calculations for the cost of diesel and lubricating oil.

TABLE 7: Cost of diesel and lubricating oil

	Volume/day (L)	Tot. volume (L)	Unit cost (USD)	Total cost (USD)
Diesel	5000	315500	1.5	473,300
Lubricating Oil	-	-	-	23,700
SUM				**497,000**

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. 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, casing accessories and consumables and wellhead equipment is shown in Tables 8, 9 and 10, respectively.

TABLE 8: Cost of casing

	Depth (m)	Length (m)	Unit cost (USD)	Total cost (USD)
20" casing	60	58.5	375	22,000
13-3/8" 54.5 lb/ft casing	300	298.5	150	44,800
13-3/8" 68 lb/ft casing, top two casings	24	24	195	4,700
9-5/8" 47 lb/ft casing	1,200	1198.5	135	161,800
7" 26 lb/ft casing slotted	3,000	1,826	105	191,700
7" 26 lb/ft casing plain inside prod. casing	24	24	75	1,800
SUM				**426,800**

TABLE 9: Casing accessories and consumables

	Number	Unit cost (USD)	Total cost (USD)
For 20" casing:			
Casing shoe	1	900	900
Float collar	1	1800	1,800
Cement plugs, Top/bottom	1	200	200
Casing dope	1	150	150
For 13-3/8" casing:			
Casing shoe	1	800	800
Float collar	1	1500	1,500
Cement plugs, Top/bottom	1	200	200
Centralizer	13	200	2,600
Casing dope	1	150	150
For 9-5/8" casing:			
Casing shoe	1	700	700
Float collar	1	1300	1,300
Cement plugs, Top/bottom	1	150	150
Centralizer	43	150	6,450
Casing dope	1	150	150
For 7" casing:			
Casing hanger	1	12000	12,000
Guide shoe	0		
Casing dope	2	150	300
SUM			**29,400**

TABLE 10: Wellhead equipment

	Number/Sets	Unit cost (USD)	Total cost (USD)
Master valve 10" Class 900	1	45000	45,000
Casing head flange	1	10000	10,000
Adaptor flange	1	3000	3,000
2-1/16" Side valve, 5000psi	1	4500	4,500
Adaptor spool	2	8000	16,000
Ring gasket and bolts	3	350	1,050
SUM			**79,600**

5.5 Services

Various services are required during the drilling of any geothermal well regardless of the contract type. For this example, the service costs were as follows:

i. Drilling supervision;
ii. Civil construction supervision;
iii. Directional services;
iv. Air drilling services;
v. Mud engineering services;
vi. Cementing services;
vii. Geological services including site geologist;

viii. Reservoir engineering / well logging;
ix. Maintenance engineering;
x. 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, integrated with the drilling contract, or any mix of these.

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:

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

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:

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

For a mature geothermal field this can be summarised as:

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

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:

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

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. 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 as shown in Table 11.

7. CONCLUSION

Costing geothermal wells can be a fairly simple task if one has a clear understanding of all activities and operations involved from well planning up to when it is completed, and knowing the unit prices, so as to obtain an accurate figure of the total well cost. For this study, an Excel spreadsheet model was created.

By defining the casing programme and time required for drilling each section, the model calculates the material requirements and total well cost. The unit costs for materials and services are entered centrally in a "Price Book" so they can easily be updated later to reflect actual costs. The cost numbers shown in this report are not based on actual prices but are approximate values and used for the creation of the model only, and do not reflect KenGen prices.

TABLE 11: Summary sheet

	Unit	**Total** (USD)
Pre-spud costs		
Drillsite preparation	Fixed	400,000
Rig mobilisation and transport (1/5)	One-off	400,000
Sum		**800,000**
Daily operating costs		
Rig rental with crew	Day rate	2,208,500
Rig rental with crew-standby	Day rate	210,000
Air compressors, balanced drilling	Day rate	16,000
Cementing equipment	Day rate	24,000
Maintenance Engineering	From table	24,000
Drill stem inspection	Fixed	300,000
Transportation and cranes	Day rate	12,000
Directional drilling equipment rentals	Day rate	157,800
Water Supply	Day rate	126,200
Waste disposal, clean up and site maintenance	Day rate	12,620
Lodging, catering (camp and food)	Day rate	151,500
Sum		**3,242,700**
Drilling consumables		
Rock bits	From table	182,000
Drilling detergent	From table	46,000
Diesel & lubricating oil	From table	497,000
Cement	From table	60,100
Cement additives	From table	13,900
Drilling mud	From table	18,900
Sum		**817,900**
Casing and wellhead		
Casing	From table	426,800
Casing accessories and consumables	From table	29,400
Wellhead Equipment	From table	79,600
Sum		**535,800**
Services		
Drilling supervision	From table	24,000
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		**99,000**
TOTAL		**5,495,400**
TOTAL +10% CONTINGENCY		**549,600**
PROJECT TOTAL		**6,045,000**

It is also imperative to note that proper and reliable data is vital when costing geothermal wells. This, therefore, calls for systematic accounting to make the unit costs available internally within the company for such modelling. Only then will the estimation of the well cost become as accurate as possible.

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

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