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D14.2 Report on the impact of OPTIDRILL on LCOE

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EXECUTIVE SUMMARY

The OPTIDRILL project developed a drilling advisory system utilising machine learning methods to predict ROP, lithology, and drilling problems uniting those under one system for drilling process optimisation and intelligent decision-making. The drilling advisory system advises drillers on optimum drilling parameters to improve efficiency. It recommends drilling parameters to reduce mechanical specific energy (MSE), i.e., the most efficient drilling in terms of energy consumed. MSE is a key performance metric representing the energy required to remove a unit volume of rock.[1] It provides a measure of the efficiency of the drilling process, helping operators assess and optimise the performance of the drill bit and overall drilling system. Optimising MSE minimises wasted energy during drilling, reducing fuel usage and carbon footprint. MSE optimisation also results in improved ROP (rate of penetration) and reduced wear on tools. It also reduces non-productive time (NPT) by lowering operational expenses, including rig rental, fuel, and personnel costs.

In this deliverable, we evaluated OPTIDRILL technologies' economic impact for a case study: a hypothetical greenfield geothermal power plant at the Rhine Graben, Germany. The levelised cost of energy (LCOE) methodology was used in the evaluation. Drilling performance considered is based on the lithologies in the case study areas. The economic evaluation shows that with OPTIDRILL technologies, drilling time is reduced by 3.31% - 8.22% and drilling cost is reduced by 2.43% - 6.03%, contributing to a 1.69% - 4.19% reduction in LCOE.

[1] Xiao, H., Liu, S., & Tan, K. (2019). Experimental Investigation of Force Response, Efficiency, and Wear Behaviors of Polycrystalline Diamond Rock Cutters. Applied Sciences, 9(15).

1. INTRODUCTION

The OPTIDRILL drilling advisory system was demonstrated by integrating it into the drill-rig of a drilling project in Bochum, Germany. However, the specific requirements of that project prevented us from thoroughly testing the advisory system by checking the impact of recommended drilling parameters. ***Table 1*** shows the lithology profile at the demo drilling. The rock formations found at the wellbore are Claystone, Claystone/Sandstone, and Sandstone, all of which are soft rocks.

Table 1: Lithology profile at the demo site in Bochum, Germany

Lithology	Depth [m]
Claystone	29.99
Claystone/Sandstone	65
Claystone	77.98
Claystone/Sandstone	94.99
Sandstone	100
Claystone	140.32

We have evaluated the data gathered from the demonstration. The goal of the drilling advisory system was MSE minimisation, i.e., improving drilling efficiency. As shown in ***Table 2*** and ***Table 3***, the MSE value, which should directly impact bit life, was reduced in over 97.57% of the cases by an average of 27.34%.

Table 2: Actual and expected MSE

	Actual MSE	Expected MSE
Average MSE [N/mm2]	74.61	48.90
Standard deviation [N/mm2]	45.10	14.75
Min. MSE [N/mm2]	1.12	1.02
Max. MSE [N/mm2]	726.7	233.67

Table 3: MSE optimisation results

	Value
Average MSE enhancement [N/mm^2]	25.73
Average MSE enhancement [%]	27.34
Decreased MSE values	7791
Increased MSE values	194
Constant MSE values	0

Table 4 shows the measured, predicted, and expected ROP. The measured ROP is from the drill rig data stream. The predicted ROP is the value the ML model predicted using the actual drill rig measurements. The expected ROP is calculated based on the recommended drilling process parameters. The expected ROP value is theoretical and based on the model predictions. We have used the following formula to calculate the expected ROP.[2]

$$MSE = \frac{WOB}{Bit\ Area} + \frac{2\pi * RPM * Torque}{Bit\ Area * ROP}$$

[2] *Teale R. "The Concept of Specific Energy in Rock Drilling." International Journal of Rock Mechanics. 2. (1965): 57-73*

Table 4: Statistical overview of measured, predicted and expected ROP

	Measured	Predicted	Expected
Average ROP [m/h]	13.31	13.44	14.43
Standard deviation [m/h]	5.74	4.3	4.44
Min. act. ROP [m/h]	1	2.27	2.54
Max. act. ROP [m/h]	40	38.9	42.59
Percentile 50%	12.5	12.47	13.64
Percentile 75%	16	14.8	15.93
Percentile 90%	21.3	19.13	20.64
Percentile 95%	25	23.15	24.34
Percentile 99%	30	27.51	28.36

As can be seen from ***Table 5***, *predicted ROP also increased in over 60% of the cases by an average of 10.73% and expected ROP increased in over 73% of the case by an average of 18.88%.*

Table 5: ROP optimisation results

	Predicted ROP	Expected ROP
Average ROP enhancement [m/h]	0.13	1.12
Average ROP enhancement [%]	10.73	18.88
Increased ROP values	4805	5852
Decreased ROP values	3169	2119
Constant ROP values	11	14

However, the improvement of the ROPs is calculated based on the predictions of the ROP model, which have a certain error. ***Table 6*** *shows* an overview of the prediction errors made by the model and some common error metric values. From these values, we can see that, while having quite good error metric values indicating a good performance, the model tends to predict higher ROPs with an average error of around 2 m/h more often than lower ROP values. This leads to more optimistic results for the ROP and MSE optimization.

Table 6: Overview of the prediction errors made by the model

Metric	Value
Mean Absolute Error [m/h]	2.24
Root Mean Squared Error [m/h]	3.11
R^2-Score	0.72
Instances with positive error	4805
Average positive error [m/h]	1.97
Instances with negative error	3169
Average negative error [m/h]	-2.66

Due to the shallow drilling depth, we were unable to test OPTIDRILL drilling advisory system's impact on equipment wear.

The current deliverable evaluates OPTIDRILL technologies' economic impact using levelized cost of energy methodology. The analysis aims to identify the economic benefits (if any) of OPTIDRILL technologies with respect to state-of-the-art drilling technologies. The levelized cost of energy (LCOE) methodology estimates the representative cost of generating electrical power from a plant over its lifetime and compares different methods of electricity generation. It is the ratio of all the discounted costs over the power plant lifetime divided by the discounted sum of the actual energy delivered, i.e., the average revenue per unit of electricity (in €/kW-hr or €/MWh) that would be required for a power plant to break even.

2. METHODOLOGY

A hypothetical greenfield geothermal power plant was used to evaluate the economic performance of OPTIDRILL drilling advisory system. As presented in ***Table 7*** the hypothetical plant is in the Upper Rhine Graben basin, Germany. The goal of this analysis was to evaluate drilling OPTIDRILL optimisation technology. Therefore, we have kept other sub-systems of the geothermal plant the same. Also, we did not consider transmission lines in the analysis.

Table 7: Case study power plant

	Case study
Resource temperature	200°C
Well depth	5 km
Conversion technology	Double flash
No of production wells	10
Project life	30 years
Capacity factor	95%
Transmission line length	0 km

The rate of penetration (ROP), i.e., how fast we are drilling a wellbore and bit lifetime, depends on rock formation and drilling depth. The economic benefits of new drilling technologies come from drilling faster or replacing worn-out drill bits less often. ***Table 8*** presents the rock formations to 5500 meters in the case study locations. The upper 1000 meters in the Upper Rhine Graben are different soft rock types; the rest is hard rock.

Table 8: Rock formation in the case study [3]

Rock formation	**Depth (meter)**
Tertiary and Jurassic sediments	750
Keuper (dolomite, shales, or claystone)	50
Shelly limestone	200
Coloured sandstone	400
Granite	4100
Basalt rock	4500

Table 9 presents rock types, ROP, and bit life collated from a literature review. Soft rocks can be drilled faster with longer bit life than hard rocks. ROP and bit lifetime are also impacted by sub-optimal drilling, in-situ drilling conditions at the bit/ bottom hole. The demonstration drilling encountered claystone and sandstone, which are soft rocks. Hence, we lack data on the ROP improvement in other rock types, e.g., Granite, from utilising the OPTIDRILL drilling advisory system. Therefore, this analysis considers ROP improvement in line with the Bochum demonstration (***Table 5***). Though we have found the use of tricone bit for drilling wellbores in the study location, we have assumed PDC bit for the bottom 4000 meters in the case study to compare with PDC bit technology. For the top 1000 meters, we are considering tricone as it is optimal for drilling soft rocks. Though we expect the drill bit lifetime to improve due to MSE optimisation, we have assumed the same bit lifetime for the analysis as the data gathered from the Bochum demonstration was insufficient to evaluate drill bit lifetime improvement.

[3] Genter, Albert & Baujard et al., Geology, Geophysics and Geochemistry in the Upper Rhine Graben: the frame for geothermal energy use

Table 9: Drilling performance data [4] [5] [6] [7]

Rock type	Drilling technology		ROP (meter/hr)		Drill bit lifetime (meter)	
	Existing technology	OPTIDRILL	Existing technology	OPTIDRILL	Existing technology	OPTIDRILL
Tertiary and Jurassic sediments	Tricone	OPTDIRLL drilling advisory system	4.5	ROP improvement in line with Table 5	2000	Same as existing technology
Keuper (dolomite, shales, or claystone)						
Shelly limestone						
Coloured sandstone						
Granite	PDC		7.16		164	

Table 10 presents the configuration of wellbores drilled to extract geothermal resources for the case study.

Table 10: Wellbore configuration[7]

Section	Section depth from surface (meter)	Hole diameter (inch)
Conductor casing	100	30
Surface casing	600	24
Intermediate / Anchor casing	1800	17.5
Production casing	3200	12.75
Perforated Liner	5000	8.5

Drill bit costs of different diameters are calculated from reference bit cost (***Table 11***), assuming a linear relationship between drill bit size and cost. ***Table 12*** presents other data used to estimate wellbore drilling costs.

Table 11: Reference drill bit cost[7]

Drill bit size (inch)	Drill bit type	Drill bit cost
12.75	Tricone	USD 60,000

Table 12: Other data

Drill rig	3,000 hp
Diesel consumption	15,000 litre / day
Cost of diesel	€1.77 / litre
Trip speed	200 meters

Wellbore drilling cost depends upon the speed at which the drill bit penetrates rocks (ROP) and the cost and time spent replacing damaged drilling components like the drill bits. Services like drill rigs are rented daily, and faster drilling reduces such costs. Therefore, drilling technology that can remove rocks faster and dill longer without replacing components will spend more time on actual drilling and reduce overall drilling costs. ROP and bit life is dependent on the rock formation being drilled. Progress is slower in harder rocks, and lifetime is also lower. Therefore, the wellbore model must consider rock formation encountered in every section of the wellbore and the expected ROP and life there. *Figure 1* presents the methodology used for estimating drilling performance and cost for technologies under consideration, and *Figure 2* presents the simplified view of the wellbore model. First, we break down rock formation

[4] Baujard, Clement & Hehn at el., Rate of penetration of geothermal wells: a key challenge in hard rocks.
[5] Logan Hackett at el., Analysis of Drilling Performance Using PDC Bits, Fallon FORGE Well 21-31x.
[6] Sverrir Thorhallsson al el., Iceland Deep Drilling Project (IDDP): The challenge of drilling and coring into 350-500°C hot geothermal systems and down to 5 km
[7] Collected for H2020 Geo-Drill and reported in D9.1 impact of Geo-Drill on LCOE

contributions to different wellbore sections and feed these, including drilling performance and component cost data (***Table 9***, ***Table 11***, ***Table 12***), into the wellbore model for drilling performance and cost for each rock formation-wellbore section combination. Finally, these are added for overall drilling performance and cost.

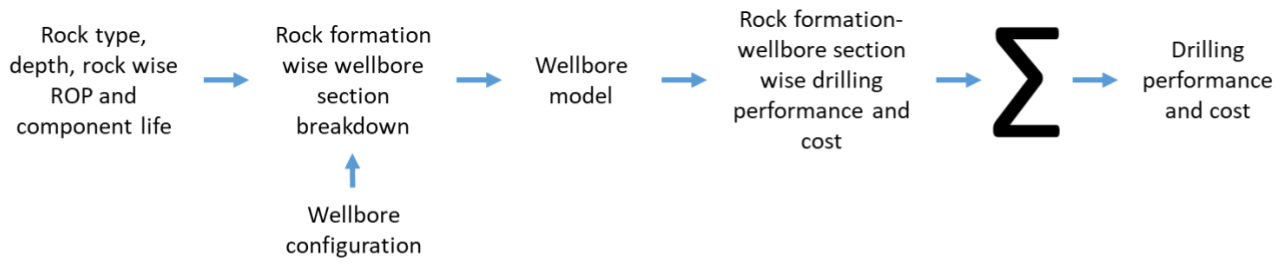

Figure 1: Methodology of estimating drilling performance and cost (developed in Geo-Drill project)

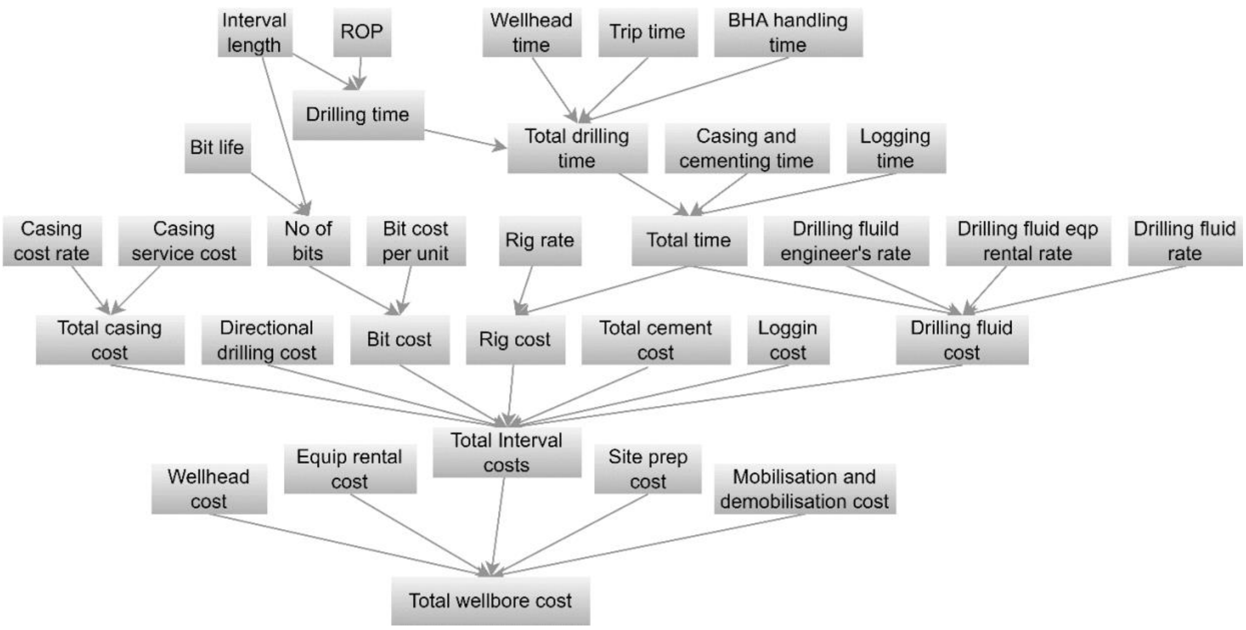

Figure 2: Simplified view of TVS wellbore model (developed in Geo-Drill project)

The economic assessment was performed using TVS geothermal LCOE framework developed in the H2020 Geo-Drill project. The framework considers different components of a geothermal power plant and different phases of plant development. Costs are estimated for the activities in each phase, and power generation over the plant lifetime is used to calculate LCOE. The LCOE framework considers capital costs for all phases of geothermal power plant development and is summarised in *Figure 4*. The goal of the study was to evaluate OPTIDRILL technologies. Therefore, the focus was on collating data relevant to wellbore drilling. We have used GETEM[8] defaults for the rest. This approach still provides us with a suitable comparison of the OPTIDRILL projects' impact on the economic performance of geothermal power plants. The number of production wells forms the basis of the study. From there, we estimated the performance of the reservoir, wellbore, geofluid gathering system, and power plant size, which in turn gives us capital and operating costs. Discounted cash flow (DCF) methodology is finally used to estimate LCOE.

[8] https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model

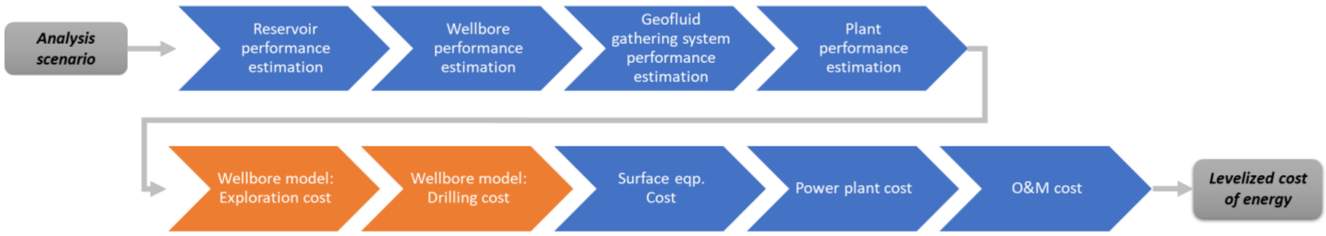

Figure 3: TVS LCOE framework (developed in Geo-Drill project)

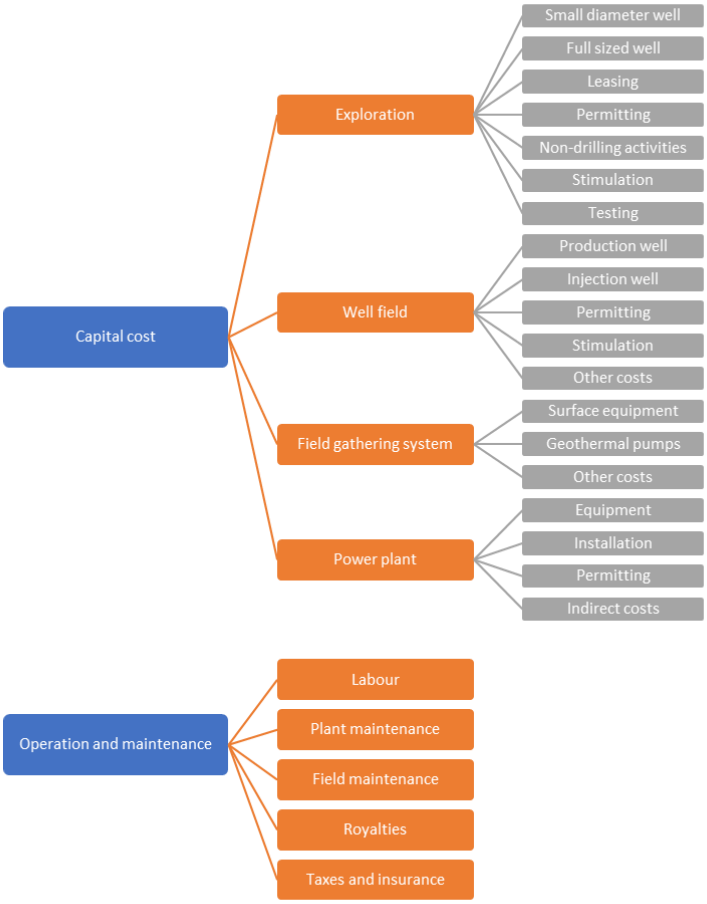

Figure 4: Cost considered in LCOE estimation (developed in Geo-Drill project)

Assumptions used in the economic impact analysis:

a) Production or injection wells are identical.
b) Resource temperature declines with time while the geothermal flow rate remains unchanged.
c) Power sales are estimated monthly to account for the impact of resource temperature decline and determined for each period based on the temperature decline.
d) Makeup drilling will occur if the temperature decline is excessive and the production temperature returns to the initial value.
e) The present value of costs and revenues are determined at start-up using specified discount rates for each project phase.
f) Geothermal sector incentive is not applied.
g) Multiple prospects will be evaluated and drilled to develop a successful project.
h) Full-size wells at one or more sites will be drilled to verify commercial potential.
i) Default costs are based only on those incurred at the successful site, including initial exploration activities, permitting and leasing, drilling of small-diameter wells, and the drilling and testing a limited number of full-size wells to establish that the resource is commercially viable.
j) Exploration cost is independent of project size.

k) All production and injection wells have the same depth and cost regardless of whether they are successful or not.
l) Drilling success rate (75%) determines how many wells are drilled.
m) Unsuccessful production wells will be used to supplement injection.
n) Each well has an associated cost for surface equipment, determined using the average distance between the plant and well and pipe size.
o) Well-stimulation is not required for any wellbore.
p) The setting, depth, and size of the production pump are based on the casing configuration, flow rate, well depth, geofluid temperature, and productivity index
q) Injection pump is in a single location.
r) Flash power plant costs and performance estimates are based on flash pressures determined using the GETEM model.
s) Installation multiplier methodology of Electric Power Research Institute's Next Generation Geothermal Power Plants study (EPRI 1996).
t) Different phases and activities in project development have costs, such as planning and management, limited testing of exploratory wells, and engineering. These indirect costs are estimated as a percentage of the total cost for the activity or phase, and this tool uses GETEM defaults.
u) A contingency of 15% is applied to all capital costs.
v) Operation and maintenance costs are specified as a fraction of the capital costs. The power plant, well field, and field gathering system arre 1.8%, 1.5%, and 1.5%, respectively.

3. OPTITDRILL IMPACT ON LCOE

Table 14 presents the results of the LCOE case study, and ***Table 13*** summarises the results. The study shows that with the OPTIDRILL drilling advisory system, wellbore drilling cost is reduced by 2.43% - 6.03% and drilling time is reduced by 3.31% - 8.22%, contributing to the reduction of LCOE (1.69% - 4.19%). This reduction comes from increased drilling speed, resulting in less time to do actual drilling. We expect the improvement will be even higher from less wear due to efficient drilling in terms of energy consumed, i.e., reduced MSE results in longer drilling time between trip out.

Table 13: Summary of the LCOE study

		State-of-art	Predicted ROP		Estimated ROP	
LCOE	*€/ kWh*	0.220	0.217	-1.69%	0.211	-4.19%
Drilling	*€/ kWh*	0.093	0.091	-2.43%	0.088	-6.03%
Drilling time	*Day/well*	39.83	38.51	-3.31%	36.56	-8.22%
Well Cost	*€million per well*	16.32	15.92	-2.43%	15.34	-6.03%

Table 14: LCOE results

			State-of-art	Predicted ROP	Estimated ROP
	LCOE	***€/ kWh***	0.220	0.217	0.211
	Power Sales	*MW*	42.80	42.80	42.80
	LCOE contribution of Drilling	*€/ kWh*	0.093	0.091	0.088
Exploration	Exploration Drilling Costs (full-sized)	€	78,341.15	76,435,396.20	73,614,673.11
	Small Diameter Exploration Drilling	€	2,250,520.80	2,250,520.80	2,250,520.80
	Non-Drilling Exploration Costs	€	475,175.80	475,175.80	475,175.80
	Permitting & Leasing Costs	€	307,403.92	307,403.92	307,403.92
	Other Indirect Costs	€	4,123,218.46	4,022,915.59	3,874,456.48
	Total exploration cost w/o cont	€	85,497,469.80	83,491,412.31	80,522,230.12
Drilling	Number Production Wells		10	10	10
	Number Injection Wells		3.74	3.74	3.74
	Wells Drilled to Complete Field		15.66	15.66	15.66
	Drilling time	*Day/well*	39.83	38.51	36.56
	Well Cost	*€/well*	16,321,073.09	15,924,040.87	15,336,390.23
	Permitting Costs	€	1,036,269.15	1,036,269.15	1,036,269.15
	Production Well Costs	€	174,091,446.26	169,856,436.00	163,588,162.48
	Injection Well Costs	€	81,463,642.05	79,481,928.60	76,548,778.23
	Non-Drilling Costs	€	13,668,006.58	13,340,810.60	12,856,525.13
	Total drilling cost w/o cont	€	270,259,364.04	263,715,444.34	254,029,734.98
Field gathering system (FGS)	Total Production Flow	*kg/s*	800	800	800
	Flow per well	*kg/s*	80	80	80
	Production Pumping	*MW*	2.40	2.40	2.40
	Total Injection Flow	*kg/s*	676.10	676.10	676.10
	Injection Pumping	*MW*	5.10	5.10	5.10
	Wells Used for Injection		7.66	7.66	7.66

	Surface Equipment Costs	€	8,519,572.74	8,519,572.74	8,519,572.74
	Total Production Pump Costs	€	1,556,612.62	1,556,612.62	1,556,612.62
	Total Injection Pump Costs	€	2,243,444.43	2,243,444.43	2,243,444.43
	Indirect Costs	€	1,679,949.52	1,679,949.52	1,679,949.52
	***Total FGS cost w/o* cont**	€	13,999,579.31	13,999,579.31	14736399.27
Power Plant	Generator Nameplate	*MW*	53.61	53.61	53.61
	Power Plant Net Output	*MW*	50.30	50.30	50.30
	Geothermal Pumping Power	*MW*	7.50	7.50	7.50
	Power Plant Cost (per net MW)	*€/MW*	2.04	2.04	2.04
	***Total power plant cost w/o* cont**	€	102,454,629.03	102,454,629.03	102,454,629.03
Total capital cost		€	472,211,042.19	463,661,064.99	451,006,173.44
Total capital cost with cont		€	492,958,262.64	484,344,160.62	471,594,357.38
O&M cost (annual)		€	12,349,824.76	12,190,890.94	11,955,651.67

4. CONCLUSION

LCOE analysis for a case study was performed to evaluate the economic performance of the OPTIDRILL technologies. The case study power plant was designed based on rock formations in Rhine Graben, Germany. Due to the shallow drilling of the OPTIDRILL technology demonstration, we could gather data on the ROP improvement only, not lifetime improvement due to less wear. Therefore, though we expect equipment lifetime to improve, this study considered ROP improvement from the OPTIDRILL drilling advisory system only. The study shows that OPTIDRILL technologies will reduce actual wellbore drilling time by 3.31% - 8.22% and drilling costs by 2.43% - 6.03%, contributing to a 1.69% - 4.19% reduction of geothermal power plant LCOE. This study reveals that adopting the OPTIDRILL drilling advisory system will reduce wellbore drilling costs and increase the viability of geothermal power plants.