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Energy Consumption for Geothermal Wells

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ABSTRACT

Drilling and completing geothermal wells is connected with a high consumption of energy depending on size and depth of the individual borehole. In the hydrocarbon industry, energy consumption represents a rather negligible factor when drilling wells referring to the energy balance of the resource exploitation. This is mainly due to the much higher specific energy density of the exploited resource.

A sensitivity study was performed to determine the magnitude of the energy input and the parameters of influence. Datasets from the oil and gas- and the geothermal industry were used for the study. New geometry-, formation- and process specific energy consumption key figures were derived. Based on the findings, site-specific saving and optimization potentials can be analysed and retrieved. The results can be readily integrated into practical well planning and design work. Especially, for deep wells exploiting low-enthalpy reservoirs the latter is mandatory in order to increase the overall efficiency of the geothermal energy recovery system.

1. INTRODUCTION

In Germany, geothermal energy use for power generation purposes requires deep wells. The depth to get to a sufficient temperature depends on the geothermal gradient, that is temperature increase with depth, at the specific site: the smaller the gradient, the deeper the required depth of the well. When the depth of the well is fixed, the direct energy demand for drilling the well depends on the diameter of the well, the used drilling mud, the capacity of the drilling rig, the final well completion and, of course, the geological setting.

Direct energy demand plays no decisive role in exploitation of hydrocarbon reservoirs since the energy costs make only a small share of the total well costs (5% - 10%, share decreases with vertical well depth; Legarth 2003) and the recovered energy of the reservoir (hydrocarbons) is distinctly higher compared to the energy consumption for drilling the wells (energy pay-back time is less than one week)[1]. Due to these issues, data for the energy consumption is rarely available.

Regarding geothermal wells, the situation changes: Compared to conventional oil (HC) reservoirs, a low-enthalpy geothermal (GT) reservoir ends up with a heat value relationship of the produced media of approximately 25:1[2] (HC:GT). The relationship increases with the decrease of the specific energy density (or enthalpy) of the geothermal reservoir. This figure indicates that for the assessment of a geothermal resource the energy demand is an important issue.

The direct energy demand has to be distinguished from the cumulative energy consumption for the wells. The latter includes all upstream as well as downstream processes and used resources. Calculation of the cumulative energy consumption can be carried out following the VDI guideline 4600. Teuber et al. (1999) determined the cumulative energy consumption for hydrocarbon wells with vertical depths up to 3 km. The study includes also figures for the specific primary energy consumption (in GJ/m) for well drilling.

In the following, a case study is carried out based on analysis of two deep, onshore hydrocarbon wells located in the North German basin. The data was provided by a German E&P company (Ruttmann 2001). The direct energy demand depending on the factors mentioned above is calculated and plotted in figures. Comprehensive figures, e.g. the specific energy demand per meter, are derived and will help to make estimates for comparable wells. The figures include only the direct energy demand, that is the energy needed at the drill site for drilling, completion, mud handling and other drill site operations.

Any upstream process chains remain not respected. They are part of comprehensive energy balances (Rogge et al. 2002). Thus the determined energy consumption values represent minimum values.

The analysis will not only include quantitative data but will also cover qualitative characteristics to discuss energy saving potentials and site specific issues.

2. ENERGY CONSUMPTION DURING DRILLING

Drilling wells costs energy. The energy consumption increases with well depth and number. For the exploitation of deep geothermal reservoirs it becomes a significant factor of the overall energy recovery process efficiency. Therefore, the energy consumption has to be estimated and their sensitivity has to be analysed. This enables us to draw conclusions on energy saving potentials.

In order to better compare and transfer energy consumption values, they exclusively incorporate the energy consumption for the drilling process itself.

[1] „energetic pay-back period" represents the time needed to produce the equivalent energy consumed for the development of the reservoir (for low-enthalpy geothermal applications this period can reach a year or more)

[2] heating value diesel* (HC) : 42 MJ/kg; heating value geothermal fluid (GT) : 1,7 MJ/kg for water with T=423 K und cp=4 kJ/kgK; *crude oil input (refinery specific) not accounted for

2.1 Definitions and general issues

The energy consumption of a well can be directly determined during the drilling phase. It is the sum of all processes involved in drilling and completing the well:

- Drilling (driving and moving the drill string)
- Completion (installing casings and cementation procedures)
- Mud Handling (pumping mud for cooling and cleaning purposes, actuating downhole tools; mud conditioning)
- Drill site operations (mob- and demobilization, transport, auxilaries)

The rig's energy is supplied either by diesel-electric drives or by mains supply (directly from the local power grid). According to Teuber et al. (1999) the energy consumption for operations mentioned above represents roughly 20 % of the cumulative energy consumption of a 3 km well (calculated for diesel-electric drives).

In general, a deep well has a telescopic profile. The time/depth relationship (drilling progress) decreases with depth. This is due to increasing roundtrip times and decreasing rates of penetration (ROP) in deep and compacted rock (Legarth et al. 2003). Based on these facts, the energy consumption share in the cumulative energy consumption will increase with well depth. Moreover, the material usage is reduced by decreasing borehole and casing diameters. The latter might be balanced by increasing downhole tool wear in harsh drilling environments, thus representing a rather site specific factor that is not suited for generalization purposes.

Due to targeted geothermal application characteristics (deep wells for power generation) and the lack in quantity and quality of existing datasets, comparable energy consumption values are determined for wells reaching a depth of 5 km. For this purpose datasets of two comprehensively documented hydrocarbon wells (KW1 and KW2) with diesel-electric drives (KW1) and mains supply (KW2) will be analysed (tab. 1).

Table 1: borehole and casing profiles of the two reference wells

KW1	KW1
Bit Dia (") - Depth (m)	Casing Dia (") - Depth (m)
20 - 31	20 - 31
16 - 950	13 3/8 - 950
12 1/4 - 4078	10 3/4 x 9 5/8 - 4078
8 3/8 - 4709	7 5/8 x 7 - 4709
5 7/8 - 5048	4 1/2 - 5048
KW2	**KW2**
Bit Dia (") - Depth (m)	Casing Dia (") - Depth (m)
30 - 62	30 - 62
23 - 963	18 5/8 - 963
17 1/2 - 2639	16 - 2639
14 3/4 - 4180	13 3/8 - 4084
12 1/4 - 4503	7 5/8 x 7 - 4674
8 3/8 - 4620	4 1/2 - 5100
5 7/8 - 5100	

The analysis will present depth, formation and geometry specific parameters of the energy use that are being normalized for transfer purposes to different well profiles and sites. The analysis will not only include quantitative data but will also cover qualitative characteristics in order to discuss energy saving potentials and site specific issues.

The data used represent the specific energy consumption of the drilling operations. The equivalent primary energy consumption can be back calculated from the given values.

In case of mains supply this is done using data of the mean energy efficiency for power generation in the grid. The values depend on the plant characteristics supplying power to the grid. Here a value of 35.5% was used. It represents the German power grid characteristics (VDEW 2002).

In case of the diesel-electric driven rig the dataset consists of the fuel consumption per time interval (days). A heating value was assigned to the diesel fuel (see footnote above). The electric power consumption was then calculated by assuming an efficiency of the diesel-electric drive unit of 40%. Consequently, the two rigs with different power supply concepts could be directly compared. In case of rigs with mains supply an additional amount of fuel is required for the operating the drill site, leading to the following table:

Table 2: definitions of the reference standards

reference standard	rig type			
	mains supply		diesel-electrive drive	
total energy consumption [MWh]	a	electric power consumption (transformer)	a	fuel consumption
	b	fuel for drill site operations		
equivalent primary energy consumption [GJ]	a / mean specific energy efficiency + b / mean heating value		a / mean heating value	

This extra amount is low compared to the overall energy consumption. For the rigs compared it reaches absolute values of approximately 0.3 m³ Diesel per day (2.8 % of the overall energy consumption).

2.2 Database and Correlations

Fig.1 shows the depth dependency of the specific energy consumption. It can be correlated to a drilling performance (rate of penetration – ROP). The ROP is inversely proportional to the energy consumption (Legarth 2003). From the data, weighted average values can be identified and compared in different depth intervals. All values of the specific energy consumption per unit meter or cubic meter exclude completion work (casing running, cementation etc.). They exclusively cover the drilling process itself (including roundtrips).

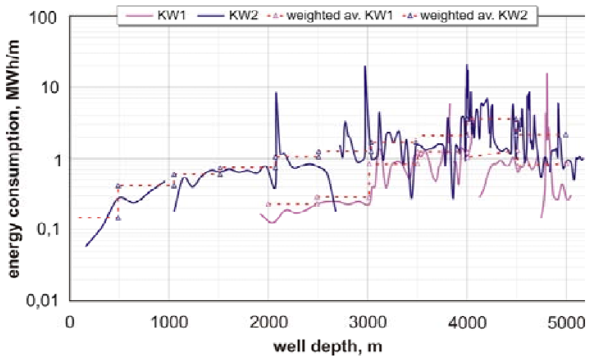

fig. 1: depth specific energy consumption for two reference wells

Although the wells bear a similar final depth (well KW1: 5048 m, well KW2: 5100 m) the drilling is associated with a different energy consumption. This is caused by different well profiles (tab. 1) and rig capacities (fig. 4).

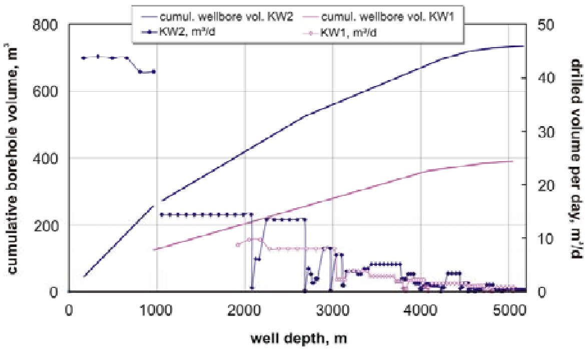

fig. 2: development of the cumulative and specific borehole volume with depth

The drilled volume at final depth in case of well KW2 is almost twice as big as the drilled volume of well KW1. 50% of the drilled volume is already reached in a depth of 1.5 km (KW2) and 2 km (KW1) respectively. A look at the rig capacities yields a similar picture.

The rig peak load differs from the Horsepower Rating usually provided as technical specification. The rating represents the constantly available power for driving the rig. A higher value as peak load can be caused by excessive pumping as demonstrated in fig. 3a and 3b.

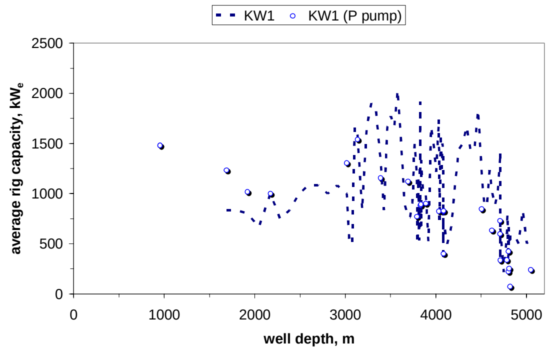

fig. 3a: average rig capacity development with depth given as total (line) and hydraulic power (dots) output (well KW1)

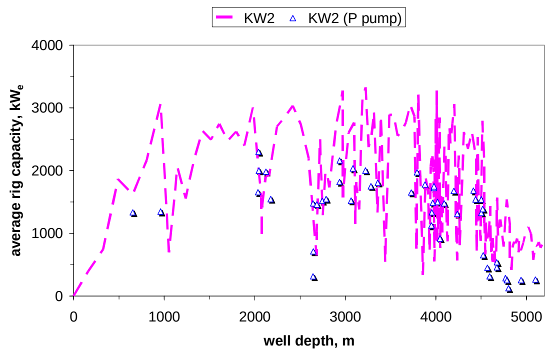

fig. 3b: average rig capacity development with depth given as total (line) and hydraulic power (dots) output (well KW2); KW2 shows a significantly higher power output (capacity) compared to KW1 (fig. 4a)

The average rig capacity (energy consumption divided by the well completion time) for well KW1 reached a value of 970 kW and 1480 kW for well KW2. The individual hydraulic power outputs (power for pumps) are represented by dots in fig. 3a and 3b. Their average values are higher. This is caused by cumulatively less operating time. High hydraulic power outputs are caused by high pumping rates and pressures.

Thinking about energy saving potentials a first step has to consider the reduction of pressure losses in the system. This has to be achieved at the surface (e.g. flow lines, valves etc.) and down hole (e.g. drill string, bit etc.). A determination of these saving potentials requires a thorough investigation and optimization of the individual drilling set-up on site and therefore will not be covered in this study.

Using the data from fig. 1 through fig. 3b the overall energy consumption for the two wells can be determined (fig. 4).

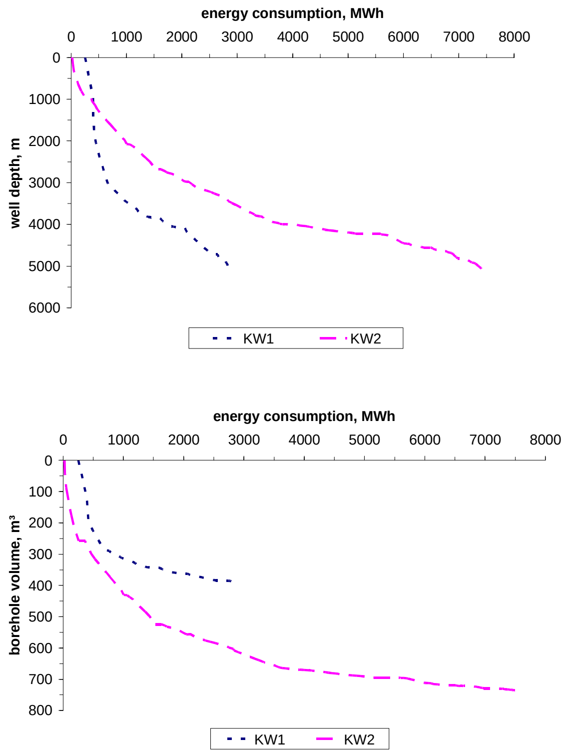

fig. 4: cumulative energy consumption versus vertical borehole depth (top) and volume (bottom) for the wells KW1 and KW2; in both cases there exists an exponential correlation

From fig. 4 – showing the electric power consumption - the equivalent primary energy consumption can be approximated and compared to other studies by multiplying the values with the factor b to receive GJ.

$$b = \frac{3{,}6GJ}{1MWh} \cdot \frac{1}{\eta_e}$$

Using a value for energetic efficiency (η_e) of 35.5% as mentioned above one ends up with a factor of approximately 10.

Moreover, fig. 4 shows that the energy consumption increases exponentially with borehole depth and volume. The two wells differ significantly in size (volume) and rig capacities (power output).

$$\frac{V_{KW2}}{V_{KW1}} = 1{,}9 \qquad \frac{P_{KW2}}{P_{KW1}} = 1{,}6$$

Dividing the KW2 values by the sum of the two factors reasonable curve fits can be achieved. This indicates that the type of power supply (mains supply or diesel-electric) plays a minor role for the energy consumption.

Horizontal sections in the curves represent phases with no drilling progress (e.g. casing and cementation operations, round trips). It can be clearly seen that these phases do not dominate the overall energy consumption at all. Furthermore, fig. 4 reveals that the specific values are strongly deviating from well to well.

3. ENERGY DEMAND ESTIMATION AND DATA TRANSFER

Based on this, neither representative figures for the energy consumption of an arbitrary 5 km well can be determined nor can parameters be transferred to other sites. The well geometry (volume and depth) determines the rig capacity and has the strongest influence on the energy demand. Thus, for transfer purposes the data has to be normalized. The normalization leads to a key figure E_n that can be used to estimate the energy consumption – as the parameter of interest.

$$E_n = \frac{\sum EC}{z \cdot V_b \cdot \overline{P}_r} \qquad (1)$$

$$\overline{P}_r = \frac{\sum EC}{t}$$

$$E_n = \frac{t}{z \cdot V_b}$$

In the given case, E_n is determined from the recorded individual energy consumptions of two wells (according to tab. 2). This was possible by evaluating high quality data sets that allowed the determination of the values. As mentioned beforehand, P_r is the average power required to drive the rig, drill and complete the well. It is not equal to the Power Rating of the rig. Here P_r was determined as weighted average from the daily power record data. For a known energy consumption P_r can be estimated as being the energy consumption divided by the required well completion time t. The analysis (Table 3) also revealed that P_r in both cases reaches a value of approx. 45% of P_{max} (with P_{max} equal to the peak load given in fig. 3a and 3b).

With an average value of the empirically derived key figure E_n of 1.42 kWh m^{-1} m^{-3} MW_e^{-1} a reasonable estimate of the overall energy consumption is possible. For better accuracy the given individuals En for small and large capacity can be used. This can be done with a defined borehole volume V_b, depth z and average rig capacity P_r. The E_n values were determined for two wells with optimum design. Thus they can be regarded as benchmarks for wells with a similar depth range. Further data from additional wells is needed to calibrate and verify the key figures.

Table 3: energy consumption in KW1 and KW2

	EC, MWh$_e$	*z, m*	*V_b, m³*	*P_r, MW$_e$*	*t, d*
KW1	2852	5048	390	0.974	119
KW2	7511	5100	735	1.483	211

small capacity well (KW1): E_n = 1,49

large capacity well (KW2): E_n =1,35

3.1 Influence of Borehole Size

Another possibility to determine the energy consumption for the whole well or well intervals is by using values of the specific energy consumption per unit volume (fig. 5).

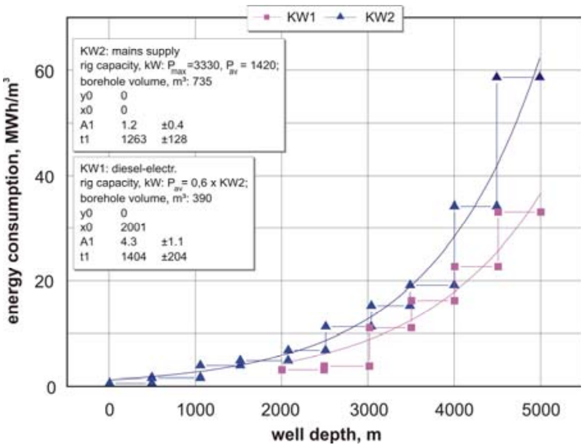

fig. 5: development of the energy consumption per unit volume with depth; P_{max} stands for the peak load of the rig

From curve fits individual exponential functions can be derived of the type:

$$f(x) = y_0 + A \cdot e^{\frac{(x - x_0)}{t}} \qquad (2)$$

To receive the energy consumption per drilled meter in order to make it comparable to other well profiles, the exponential functions of fig. 5 have to be combined with conventional borehole calipers (bit sizes). The calipers are multiplied with the volume specific consumption. The results for selected borehole calipers are shown in fig. 6.

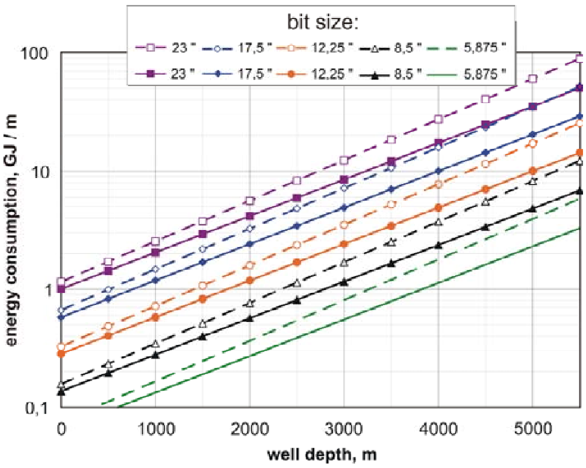

fig. 6: development of the caliper dependent energy consumption with well depth; dashed lines with hollow symbols represent large capacity wells, solid lines with filled symbols represent small capacity wells

Using fig. 6 the energy consumption per well section (EC_{Ai}) can be approximated according to a given well profile. Exact values are found by applying a integral function.

$$EC_{Ai} = \left[\int_{x_0}^{x_e} f(x)dx \right] - \left[(x_e - x_0) \cdot f(x_0) \right] \quad (3)$$

with

$$f(x) = a \cdot e^x \quad (4)$$

and

x_e: interval end, m

x_0: interval start, m

$_{A,\,i}$: subscripts representing the intervals

A rough approximation can be found by using the arithmetic average.

$$EC_{Ai} = \frac{f(x_e) + f(x_0)}{2} \cdot (x_e - x_0) \quad (5)$$

The sum of the individual sections delivers the overall energy consumption.

$$EC = \sum_{i=1}^{x} EC_{Ai} \quad (6)$$

In this context, it has to be emphasized that reducing the borehole volume to reduce the overall energy consumption has to be regarded as an option that is always limited by the production efficiency, especially looking at geothermal applications. As mentioned at the beginning, geothermal wells are usually produced at high flow rated requiring large conduits in order to avoid excessive pressure losses. Nevertheless, this does not implicate that in general a larger borehole volume than for hydrocarbon wells is needed. Excluding surface installations, it is rather the profile of the production casing/tubing that has to show minimum flow restrictions and appropriate inner diameter values.

3.2 Influence of Geology

Besides the issues already discussed the energy consumption also depends on the geology or the type of drilled formation (fig. 7 and 8). The formation specific energy consumption varies significantly. Quantitatively it is incorporated in the rig capacity and can be directly correlated to the drillability of the formation and the specific well costs (Legarth et al. 2003): Energy intensive formations are often also cost intensive formations. Both should be avoided when drilling. The latter can only be achieved by

- intense exploratory work (searching sites where the critical formations are not existing or less developed)
- optimum drilling design (bit and mud selection, continous drilling process control, analysis and optimization – Ruttmann et al. 2001)

Principally, both practices are already routinely implemented in geothermal and oil industry. Their extent is controlled by the individual project budget. For the first practice an innovative approach could incorporate the re-processing of geophysical data in terms of rock drillability.

Adapting the drilling path (directional drilling) as a third option has a much less practical implication. Directional drillings means longer paths resulting in higher energy consumption. Moreover, in geothermal exploration, it is sometimes very difficult to locate drilling sites since naturally fractured zones are targeted. In this case directional drilling becomes even more complicated. On the other hand, if the energy intensive formation is stratified distributed in between surface and the target zone, it has to be drilled anyway.

In this case the database only allows qualitative conclusions. This is due to the fact that in the two wells comparable formations occur in different depths and facies types. Further, investigations using data from additional wells should fill this gap in order to be able to draw quantitative conclusions as it was done for the parameters before. Figs. 7 and 8 are presented to give a first impression how much the formation influence the specific energy consumption.

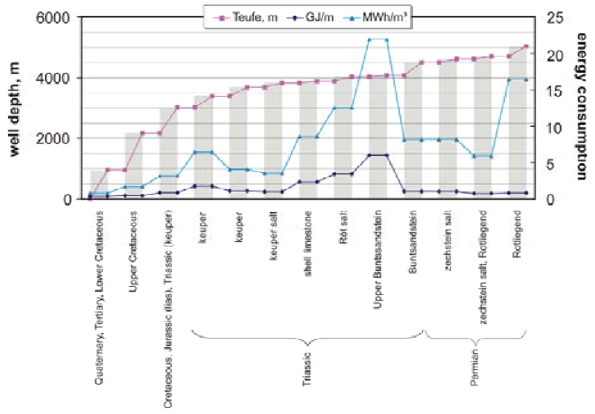

fig. 7: values for the formation specific energy consumption of well KW1

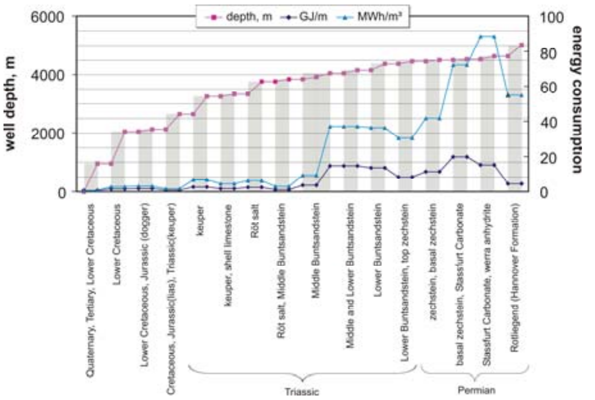

fig. 8: values for the formation specific energy consumption of well KW2

4. CONCLUSIONS

The energy consumption for geothermal wells is an important parameter. This is mainly due to the energy efficiency.

The overall energy consumption as well as specific values were determined for two reference wells. From these an empirically key figure was derived that can be used to estimate the energy consumptions for wells in a similar depth range. Because of the high quality data sets used the key figures can be used as benchmarks.

Attention has to paid when trying to extrapolate energy consumption figures to other borehole depths and volumes. This is due to the exponential correlations. Using lump sum values for practical energy estimates is therefore not allowed.

For a well with 5 km vertical depth and smaller volume and rig capacity approximately 2700 MWh are consumed by the drilling progress. The drilling alone (rock penetration and tripping) is responsible for the mayor part of that consumption. Completion work and other drill site operations play a minor role. This is mainly due to the smaller time share of the processes and their lesser energy intensity.

Furthermore, the energy consumption was correlated with the geology. It was found that there exist energy intensive formations that agree well with cost intensive formation (except salt structures).

The energy consumption for wells can be reduced in several ways:

- increasing the overall drilling process efficiency (optimize well design, tool selection, minimize frictional losses)
- realizing an “as-slim-as-possible” well design
- selecting drill sites and paths with less developed energy intensive formations

Of course, all options remain restricted. Especially, the slim well design has to obey the requirements of an efficient fluid production. Reducing well depths for energy saving issues is very effective but strongly influenced by the local geothermal gradient. In any case, the energy efficiency should never be overemphasized and has to remain in consensus with the effectiveness of the drilling process that determines the overall costs.

Yet, the analysis was based on a limited oil well dataset. Therefore, further studies with data from additional wells, especially geothermal wells, should be conducted in order to extend and verify the findings. Comparing horizontal wells to vertical ones would be another interesting and important issue.

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