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Geothermal reserves and sustainability in the Greater Copenhagen Area

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ABSTRACT

The partners in the Greater Copenhagen geothermal license in Denmark have completed a study of the geothermal reserves in the area.

Three main sandstone reservoirs have been identified and described in 462 blocks each of an area of 4 km^2. The decrease of production temperature with time at a geothermal plant with moderate, but commercial production rates has been modeled over 500 years. The results show, that the production temperature decreases relatively slowly due to a significant flow of heat from the layers above and below the reservoirs partly reheating the injected water. The production can thus be continued for many decades when commercial at a lower production temperature than the initial reservoir temperature.

The modeling was also used to establish a generalized correlation between production temperature as fraction of initial temperature and produced fraction of heat in gross reservoir. Another computer program estimating geothermal heat production costs was used to establish a generalized relation between transmissivity and a lower temperature limit for commercial production.

These two generalized relations were then combined with an assessment of the transmissivity and the initial temperature and heat in place in each of the 462 blocks to calculate the commercially producible heat from each block.

The thus producible heat at a chosen commercial cut off heat price in the Greater Copenhagen area reaches 60.000 PJ. Compared to the district heat consumption for the area of 40 PJ/year, the underground is seen to have a capacity to supply whatever heat is needed for thousands of years.

A simulation of the reheating of reservoirs to estimate the temperature distribution with depth after 5000 years shows that the reheating of the reservoirs by then has given a substantial contribution to the reserves.

1. INTRODUCTION

In 1999 a geothermal Joint Venture was established between 5 energy companies, and in 2001 the Energy Agency assigned to these companies a license to explore and produce geothermal energy in the Greater Copenhagen area. The license covers the existing district heating network in Greater Copenhagen with more than a million consumers as well as areas north of Copenhagen where new consumers might be connected in the future.

With the grant of the license a conditional work program followed. First part of the program was fulfilled by establishing a geothermal demonstration plant in Copenhagen starting commercial production in August 2005.

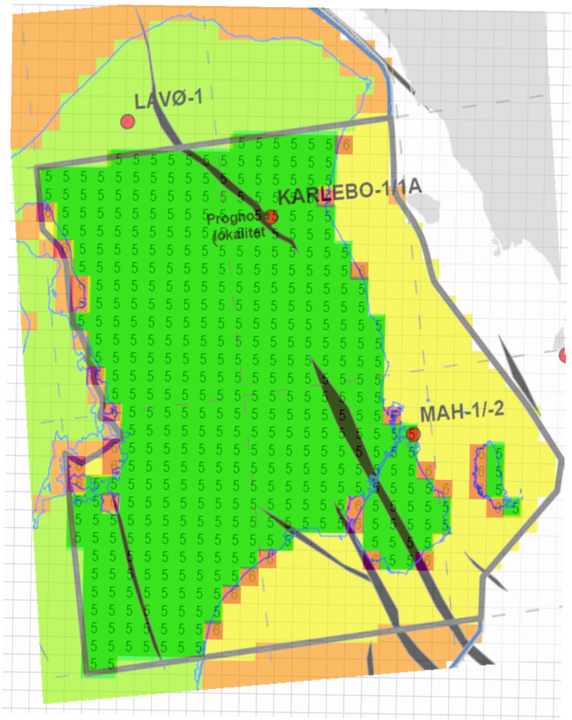

Figure 1: License area covering Greater Copenhagen area and part of North Zealand, Denmark

Next part of the program was to evaluate the reserves and their distribution in the license area. The main purpose was to point out the best localities for further investigations in the years to come; but also to evaluate the geothermal potential in near and far future. A study of the reserves was completed end of 2008. This paper describes the method used and results obtained.

2. METHOD FOR ESTIMATION OF RESERVES

Before the study commenced some assumptions were made which influence the frames and method of the study.

Initial investigations showed that production could be maintained in the area for hundreds of years. This long term perspective removed ties to excising network and plants as the lifespan for all these installations would be overrun long time before even a minor part of the geothermal reserves were produced. Future geothermal plants are assumed able to supply heat to local district heating networks and have access to driving heat for absorption heat pumps all over the license area.

Reserves are in the study defined as the amount of heat from the underground that can be produced at a competitive price at the time of production.

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A competitive price today is approximately 75 DKK/GJ or 10 €/GJ = 36 €/MWh, but prices are expected to rise in the future due to lack of fossil fuels and CO_2 quotes. In the study a price of 100 DKK/GJ or 48 €/MWh has been used as competitive or commercial price limit.

To perform the study 3 models were established and combined to reach an estimation of reserves:

1. A geological model used to asses typical aquifer data and estimate transmissivities and initial temperatures as function of depth in the aquifers,

2. A reservoir simulation model calculating produced heat and drop in production temperature used to establish a generalized relation between accumulated heat production and decreasing production temperature, and

3. A plant simulation model calculating heat production costs used to establish a standardized relation between transmissivities and lowest commercial production temperature.

By combining these models an estimate is obtained of the amount of heat that can be produced at a price less than or at the maximum commercial heat price of 48 €/MWh.

2.1 The geological model

To get a relatively fine meshed description of the license area, which has a size in average of 58 km x 32 km, the area was divided into 462 blocks each of the size of 2 km x 2 km or 4 km^2.

Previous seismic surveys, wells outside the license area and data from the 2 wells at the geothermal demonstration plant were the basis for the geologists at GEUS (the Geological Survey of Denmark and Greenland) to set up a model for each of the main sandstone reservoirs present in the area. Descriptions were made for each of the main sandstone reservoirs in each 4 km^2 block.

In relation to the thickness of reservoirs 3 different definitions were used:

1. The reservoir gross-thickness, which normally can be mapped via seismic surveys, is the total aquifer thickness including productive sandstone layers in mixed with non productive sandstones and claystones limited by the top and bottom of productive layers.
2. The reservoir netsand-thickness constitutes the productive sandstone layers. It is measured in wells and defined as a fraction of the reservoir gross-thickness and local variations of the fraction in the area are estimated primarily based on the assumed geological development.
3. The reservoir continuous netsand-thickness constitutes the fraction of reservoir netsand-thickness which has a hydraulic connection between a plant's production and injection well. The continuous netsand-thickness is the thickness of sandstone to be used in technical and economical calculations, when the price of heat is estimated. In the study a distance of 1 km between wells has been used to describe the fraction of sandstone with hydraulic connection. This fraction, expressed as a continuity factor, is dependent on the areas geological model, the thickness of the individual sandstone layers and nearby situated fault zones.

For each block the geologists described the sandstone layers including the netsand-thickness, continuity factor, mid reservoir depth, shape of grains, mid grain size, sorting and cementation. Combining general porosity-depth curves from the area with the geologist's descriptions the reservoir engineers modeled the permeabilities and transmissivities. The initial production temperatures were estimated from general temperature-depth curves in the area.

The area has 3 main reservoir formations generally dipping from S towards N and NW:

- Bunter sandstone formation at depths of 2.0 – 3.7 km has temperatures between 61 – 108 ^{0}C and continuous netsand-thickness between 15 – 50 m.

- Gassum sandstone formation at depths of 1.5 – 2.6 km has temperatures between 48 – 77 ^{0}C and continuous netsand-thickness between 25 – 35 m.

- Lower Cretaceous and lower Jurassic sandstone formation at depths of 1.3 – 2.1 km has temperatures between 43 – 69 ^{0}C and continuous netsand-thickness between 15 – 90 m.

2.2 The reservoir simulation model

In general an exploitation of geothermal heat is linked to a configuration of production and injection wells with a suitable distance between the wells so the production temperature can be considered constant during a lifetime of the plant of say 30 years. But even if the reservoir temperature drops during a prolonged period new wells and installations and reuse of older wells and installations can continue production as long as the price of heating is not higher than the maximum commercial heat price.

To investigate how the production temperature would drop during long term production reservoir simulations were performed based on average parameters of each of the 3 main reservoirs. The reservoir simulations were performed using Eclipse.

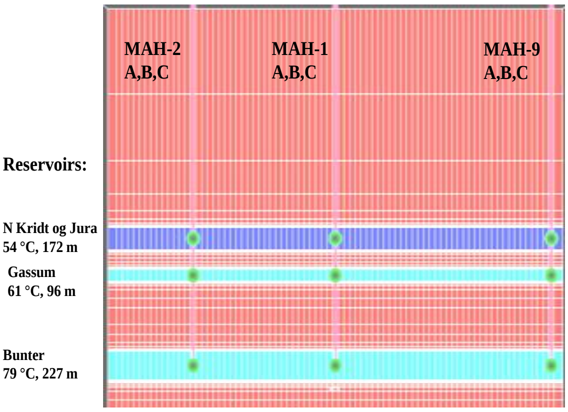

Figure 2: A vertical view of the 3 modeled reservoirs shoving the reservoir gross-thickness

The calculations and reservoir simulations were performed on a Star Plant which is a plant with several wells stretching in all directions from one well site at the surface to different locations at reservoir depth. The Star Plant configuration will probably be the preferred configuration in densely populated areas to avoid new network installations between wells outside the plant site.

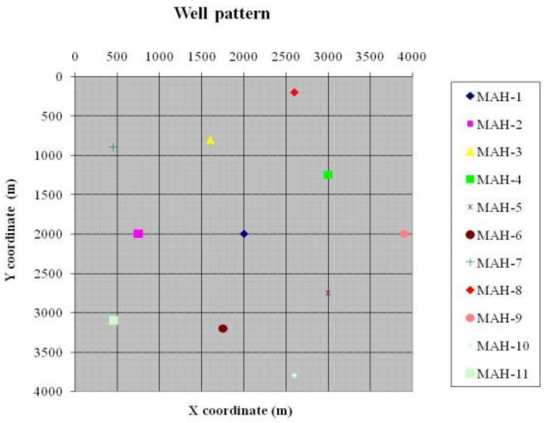

Figure 3: A Star Plant well configuration at reservoir depth.

The simulations were performed on a configuration with 1 vertical injection well, 5 production wells in an inner ring and 5 additional injection well in an outer ring. The simulations were performed at 4 adjacent blocks covering 16 km^2 isolated from the surroundings and production were simulated on all 3 main reservoirs simultaneously to include a balanced heat inflow to the reservoirs from layers between and avoid including the same heat more than once.

The 3 reservoirs were produced at typical commercial production rates of 105 – 200 m^3/h. Production continued for 500 years to investigate the long term drop of production temperature.

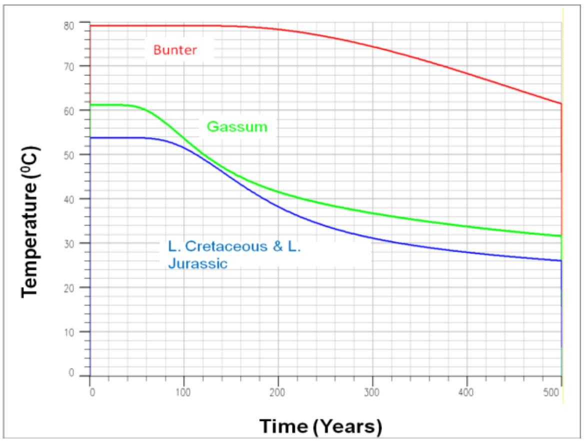

Figure 4: Production temperature decrease with time.

Calculations show that the amount of water in the continuous netsand-thickness of the reservoirs in the 4 blocks have been produced and injected 5 – 9 times during the 500 years and still the production temperatures are considerably higher than the injection temperature at about 18 ^{0}C. The heat contribution from surrounding layers by conduction is thus substantial.

The simulations show that the temperature drop has a shape with time which is interpreted as an initial period with constant temperature until the first cold water reaches the production well followed by a period with temperature decline when the share of cooled water is increasing. At a later stage the temperature drop decreases which mainly is due to the decrease in heat extracted as the production of water is constant.

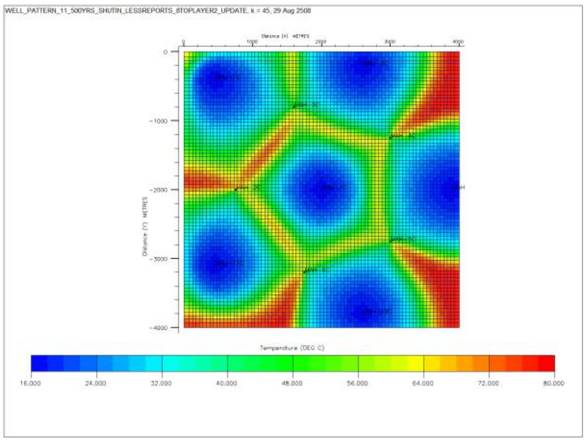

Figure 5: Bunter gross-thickness reservoir. Horizontal view of the temperature distribution after 500 years of production.

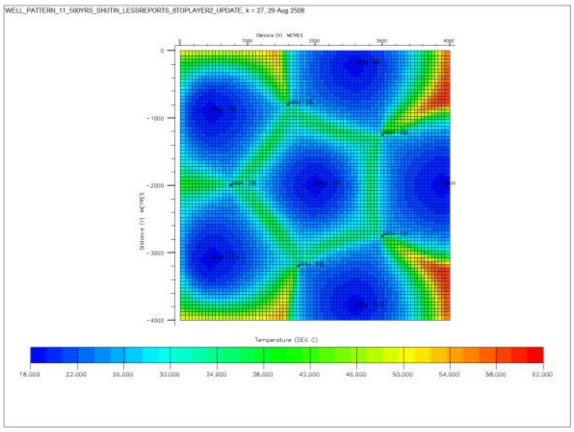

Figure 6: Gassum gross-thickness reservoir. Horizontal view of the temperature distribution after 500 years of production.

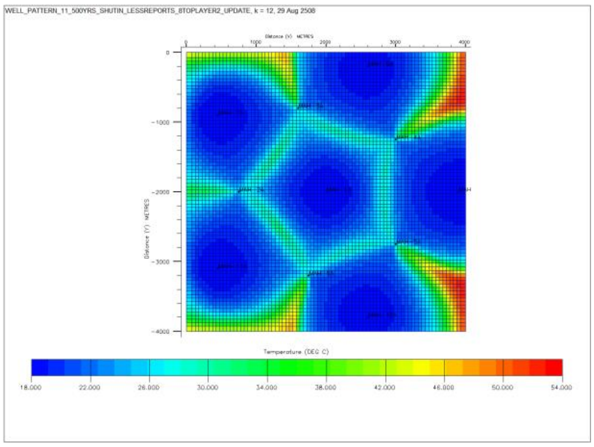

Figure 7: Lower Cretaceous and lower Jurassic gross-thickness reservoir. Horizontal view of the temperature distribution after 500 years of production.

The general result of the simulations is that if a lower production temperature than the initial temperature can be accepted, production can continue for centuries.

The heat produced as fraction of the initial heat in the 3 reservoirs has been calculated from the simulations as well as the combination of the reservoirs produced together pronounced as the Field.

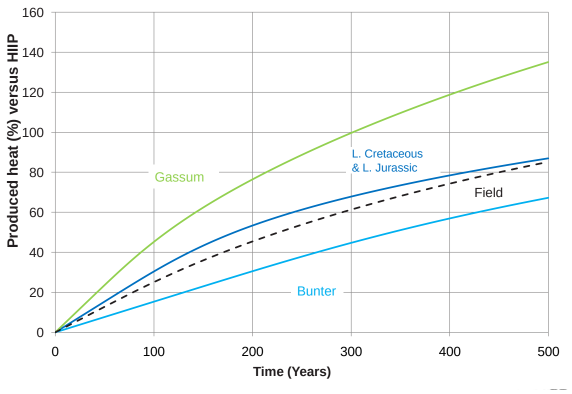

Figure 8: Development of heat produced as fraction of initial heat in place with time.

The Field curve was combined with the average development of the Field temperature as fraction of the initial temperature to establish the below curve.

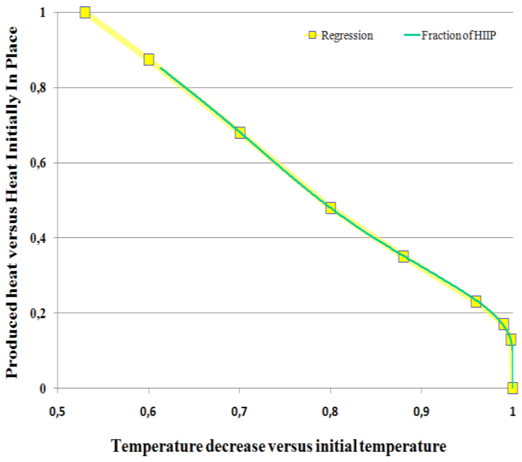

Figure 9: Produced fraction of heat initial in place in total reservoir gross-thickness versus production temperature as fraction of initial temperature.

2.3 The plant simulation model

Star Plants were used above to include influence from nearby wells, but heat production costs for each of the 2 x 2 km blocks were calculated for doublet plants.

The heat production costs were calculated based on average reservoir parameters to establish a generalized relation between transmissivity and commercial temperature limit.

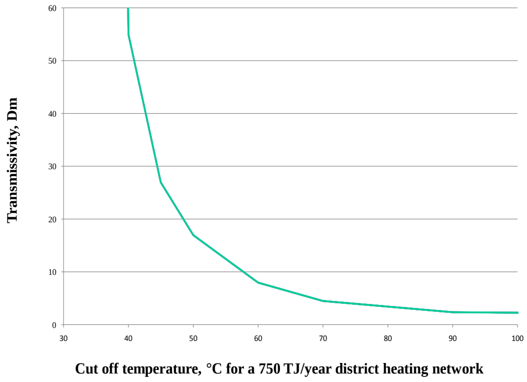

Figure 10: Lower production temperature limit as function of transmissivity at commercial heat production cost limit = 48 €/MWh.

The doublet plant was assumed to produce heat to a district heating network with a heat demand at 750 TJ/year and supply / return temperatures at 80 / 49 ^{0}C. The lowest production temperature giving the heat production cost at the 48 €/MWh was found at the different transmissivities optimizing the geothermal water flow to minimize the heat production cost including investment costs as a 25 year indexed loan with 5,5 % real interest paying for the plant.

The heat was assumed transferred by heat exchangers and absorption heat pumps driven by cost neutral heat from other producers to the district heating network. The heat from the underground would e.g. cover about 30 % of the heat demand with a summer production at about 25 -45 % of the winter production.

3. RESERVE ESTIMATES

In each of the 462 blocks in the license for each of the 3 reservoirs the transmissivities and initial temperatures were estimated as well as the heat initially in place. Based on the local transmissivity the commercial temperature limit and the initial temperature defines the fraction of temperature decrease and from this the fraction of heat to be produced commercially which is equal to the reserves.

The results are shown for each block as a reserve in GJ/m^2.

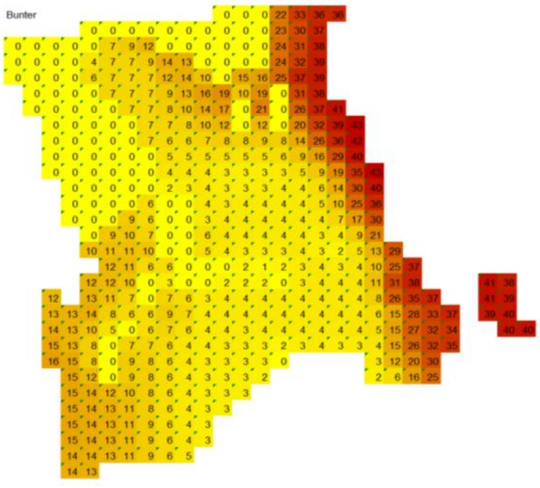

Figure 11: Reserves from the Bunter reservoir (GJ/m^2).

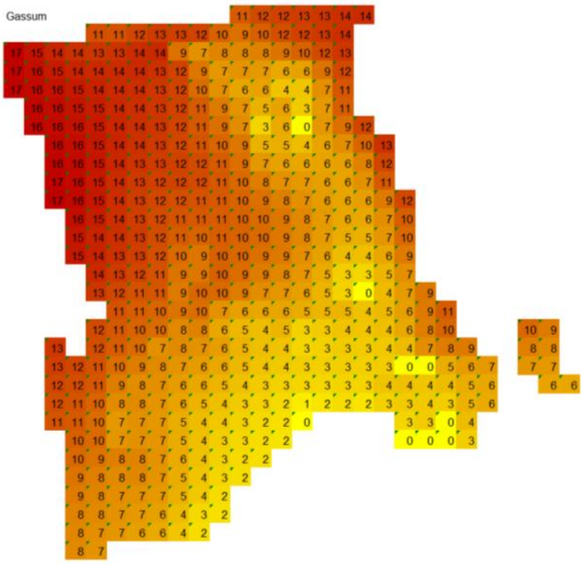

Figure 12: Reserves from the Gassum reservoir (GJ/m^2).

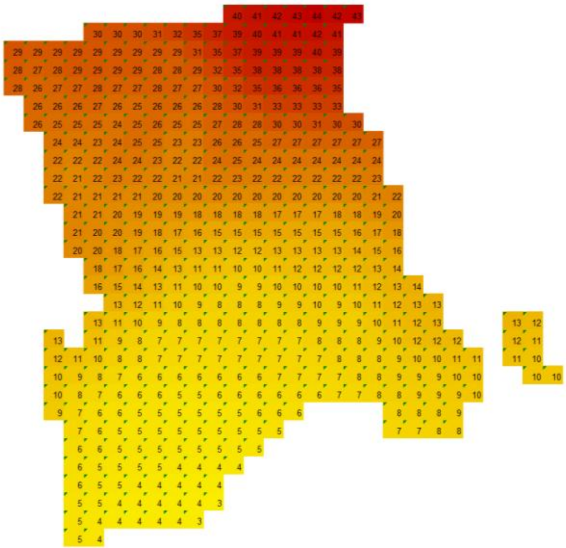

Figure 13: Reserves from the Lower Cretaceous and lower Jurassic reservoir (GJ/m^2).

Total reserves from the 3 reservoirs add up to more than 60.000 PJ. As the total consumption in the area is approximately 40 PJ/year and assuming that 30 - 50 % could be covered by geothermal heat the reserves will last for thousands of years.

The reserves are very dependent on the commercial heat price limit. Considering the time span 48 €/MWh seem to be a reasonable limit, but the reserves were also estimated at a commercial price limit of 75 DKK/GJ or 36 €/MWh which is a competitive price today. The estimated reserves become then 23.000 PJ. This shows that geothermal heat already today is an alternative to other heat sources and should massively be incorporated in the authorities heating plan for Greater Copenhagen Area.

The reserves are not limited to what can be produced at the initial temperature, but the reserves are dependent on what decline in temperature that can be accepted guided by the heat price competitive to the alternatives. If the heat price can endure a small increase due to a drop in production temperature the reserves will increase dramatically.

The investigations show that the geothermal resources in the area are not just limited to the heat content in the reservoir gross-thickness, the netsand-thickness or continuous netsand-thickness, but that heat in huge volumes of layers above and below will contribute to the resources. Gringarten has in 1975 described the substantial supply of heat coming from the adjacent layers when production continues at declined temperature, so the mechanism are not a new discovery, but the study has put this mechanism into a commercial frame when estimating the reserves.

In the Atlas of Geothermal Resources of Europe issued by EU in 2002 the resources are assessed based on net sands, and the reserves are based on a theoretical sweep of heat not allowing any drop of production temperature. Using this method the reserves in the license area from Lower Cretaceous and lower Jurassic and the Gassum sandstone layers were assessed to less than 1.000 PJ. Compared to reserves at 46.000 PJ estimated in the same layers by the method of the study presented in this paper this shows, that the reserves are drastically underestimated in the area. This conclusion can be expanded to the area of Denmark and probably also to most parts of Northern Europe.

The study and the comparison with former estimations have shown that geothermal heat might be available at much higher quantities than previous anticipated. This perception is important because this means that geothermal heat can play a much bigger role in Europe’s effort towards a future with less consumption of fossil fuels.

4. REHEATING AFTER PRODUCTION PERIOD

Simulations were made to assess the reheating simulating temperatures during and after a production period.

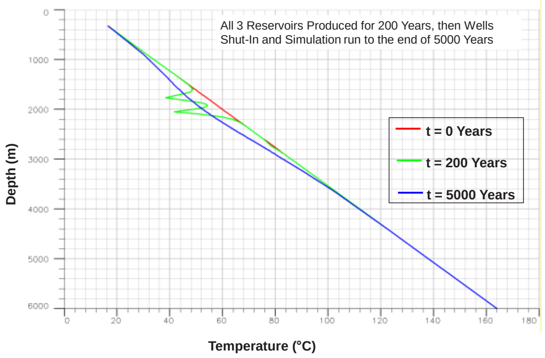

Figure 14: Vertical temperature distribution at production well location after 200 years of production and 4.800 years of reheating

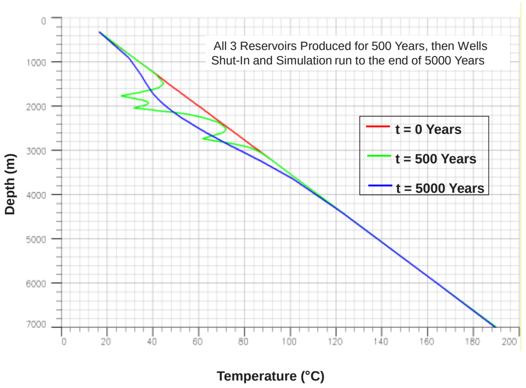

Figure 15: Vertical temperature distribution at production well location after 500 years of production and 4.500 years of reheating

As can be seen the temperatures and thus reserves have been partly regained so new commercial production could be established. This supply of heat have not been added to the reserve estimate of 60.000 PJ but is regarded as an upside showing that the reserve estimate is not an optimistic evaluation.

It can be seen that the entire volume of layers at between around 800 and 3.600 m depth contribute to the reheating of the 3 reservoirs with an average total continuous netsand-thickness less than 100 m.

5. SUSTAINABILITY IN THE LICENSE AREA

Considering the vast reserves of geothermal heat in the area that can cover whatever the need may be in thousands of years and considering the efforts being done to minimize heat consumption in new houses and via renovation of older houses that will stretch the reserves even further the utilization of geothermal heat is truly sustainable.

6. CONCLUSIONS

The study has shown that by combining geology models on reservoir sandstones with reservoir simulation models on accumulated heat produced and temperature decrease and with a plant simulation model an estimate of the reserves were possible.

The reserve estimate is 60.000 PJ at 48€/MWh and 23.000 PJ at 36€/MWh.

If a decline in production temperature can be accepted the reserves are substantially increased compared to a traditional evaluation solely based on a standard doublet draining of heat in the reservoir netsand-thickness.

Conduction of heat from the adjacent layers of the reservoirs implies that estimates on the resources should include layers of thicknesses in the order of kilometers.

Former reserve estimates are often far too low, and a reevaluation of sustainable production of reserves may lead to a potential for a much bigger role for geothermal heat in a Europe.