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ELECTRICITY PRODUCTION BY GEOTHERMAL HYBRID – PLANTS IN LOW-ENTHALPY AREAS

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ABSTRACT

In Central Europe, the utilization of low enthalpy reservoirs for electricity production has not yet fully developed. Reliable technological experience will only be obtained from future projects. Currently, the utilization is still at an experimental stage and the failure of only a single project could easily have dramatic consequences for the continuation of other projects due to limited public interest and funding. Due to the imponderability of pure geothermal production we propose a new hybridization concept. Herewith, the probability of a success will be increased and geothermal energy can become attractive for private funding. In contrast to existing hybridization plants using geothermal to preheat working fluids of conventional plants we consider a superheating from additional fuels of a geothermal vapor cycle. Therewith, an optimum temperature can be adjusted that is less dependent on the geothermal source temperature but that is generally considerably higher than most geothermal plants. Such hybridization offers the advantage of a smooth transfer from conventional systems and allows a nearly arbitrary combination of different energy fuels. On the basis of existing data from the European EGS location in Soultz-sous-Forêts, economic estimations have been performed. Based on proper thermodynamic evaluation, our quantitative analysis demonstrates the advantage of such utilization, if already pure water is superheated. Such hybrid combination would produce electricity to an overwhelming part from geothermal resources. Using even organic working fluids, such plants even start to become economic at T~100°C under typical legal European conditions.

INTRODUCTION

Geothermal activities in Central Europe are mainly restricted to low enthalpy utilization, lacking high-temperature resources. The successful applications and spread of geothermal low-enthalpy production in many countries prove highlights the potential for this low-enthalpy use. Electricity production in these geological settings has however not been carried out. The required reservoir temperatures (>200°C) and fluid circulation rates (>50 l/s) present a strong embarrassment for exploitation in these areas. A most significant obstacle for faster geothermal power development are the high drilling costs and the expensive experimental program. In these low-temperature settings depth ranges of >5 km need to be penetrate. But also the effects of hot, highly mineralized brines require developing cost-intensive logging and experimental (i.e. packer for hydraulic and stress measurement, sampling technologies) tools to evaluate the conditions at these depths. At the Hot Dry Rock (HDR) project in Soultz-sous-Forêts (France) experience for the production of geothermal fluids from greater depth ranges has been gained over the last 10 years. This project is conducted as joint effort of the European Union and individual participation of individual countries. It also represents the culmination of European Enhanced Geothermal Systems (EGS) activities starting more than 30 years ago. Due to the successful findings of the last project phase, exploring the conditions of a ~3.5 km deep reservoir, a 5 km deep reservoir will be created in the current project phase leading to a scientific pilot plant. Currently, further EGS activities in Europe are planned with new projects in Switzerland and Germany. In spite of its success the financial engagement from industrial funds is still

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remaining on a low level. Financial support is overwhelmingly provided by government funds; industry's reluctance to enter the European geothermal arena may be explained by a potentially high risk of failure.

In this perspective, new ideas should be evaluated and more closely inspected. By combining further energy sources to geothermal, potentially lower temperature fluids could be extracted and shallower reservoirs could be exploited, thus reducing exploration costs and geological risk. Kohl et al. (2002) investigated the possibility of a hybridization of geothermal energy by superheating a binary water-vapor cycle. This paper describes now especially the possibilities and conditions of using Organic Rankine Cycles (ORC) and biomass as external fuel.

HYBRIDIZATION CONCEPT

General Idea

General electricity production is enabled by steam-based Rankine cycles, a well-established technology for the conversion of high-temperature heat into electricity. For their application to a geothermal source the necessary temperature and pressure should be high enough so that, with the help of heat exchangers, pressurized steam is produced at the entrance of the steam turbine. If the geothermal source has lower temperatures than needed for driving a steam-based Rankine cycle – conditions widely met in low-enthalpy areas – electricity production can be commonly performed by Organic Rankine cycles (ORC), which make use of an organic-based working fluid with a lower boiling point than water.

From an energy efficiency viewpoint an optimized energy production needs the use of appropriate heat sources optimized for the temperature / pressure requirements of the turbines. This brings to mind a hybrid approach, where more than one heating source is employed for a given application in order to best exploit a technology. Possible geothermal hybrid scenarios are either the utilization of geothermal energy for pre-heating water in conventionally operated power plants or superheating steam of circulating working-fluids. In a detailed investigation of the pre-heating concept, Bruhn (2002) shows that no major CO_2 reductions can be achieved and their application is rather restricted to situations when existing plants need to be renovated. Parallel for the considerations of DiPippo et al. (1978) we will investigate subsequently a hybrid power generation scheme based on a superheating concept.

Figure 1 illustrates a possible GeoHybrid system with energy transfer accomplished by means of three heat exchangers: a preheater, a steam generater, and a steam super-heater. The energy source for the first two heat exchangers is geothermal; the energy source for the third one need to supply base energy and – when selecting a renewable source – will be most likely from biomass.

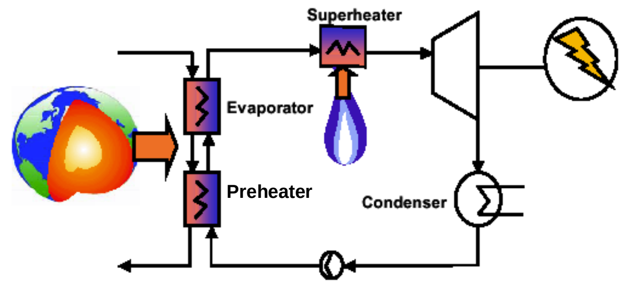

Figure 1. GeoHybrid geothermal power generation scheme (adapted from Kohl et al., 2002)

Kohl et al. (2002) have mentioned the possible advantages of the proposed hybrid power generation scheme:

- It allows the use of more energy efficient and cost effective steam-based Rankine cycles, eliminating the time and cost needed for developing other less-established conversion technologies.
- It offers the flexibility of determining the optimal steam temperature, independent of the geothermal source temperature, adding more reliability to the system design because of the uncertainty associated with the geothermal source temperature at a given depth.
- It provides a system concept for the combined generation of electricity and heat that can be designed for a decentralized application or scaled-up to a centralized application. It creates therewith a transition path to a 100% renewable electricity generation when the energy source for the super-heater is a renewable-based fuel.

System Layout for water-steam working fluid

The following considerations are based on calculations performed by Speck (2002) and Kohl et al. (2002). We applied data from the European HDR site Soultz-sous-Forêts project. During a 1997 long-term circulation test in a 3'200-3'800 m deep reservoir flow rates of 25 l/s were established at temperatures approaching 150°C (Baumgärtner et al., 1998). Already drilling but also subsequent hydraulic experiments (Kohl et al., 1997) have shown that the tectonic situation of the Rhine Graben seems to be very favorable for high subsurface permeabilities.

The nearly identical hydraulic characteristics of the boreholes GPK1 and GPK2 on the 3.5 km reservoir leads to the assumption that additional production and injection wells could linearly increase the total flow rate in the reservoir. In the following, we assume a total flow rate of 100 kg s^{-1} (i.e. 4 times the measured circulation rate) which is realized by 4 boreholes (i.e. two times the borehole layout of the 1997 circulation test), producing constantly 150°C temperatures over a considered time period of 20 yr.. produced from additional boreholes. From a purely energetic perspective, such 3.5 km deep reservoir could already be used for electricity production by binary plants, however at a considerably bad energy conversion factor.

Kohl et al. (2002) have presented the application of the GeoHybrid concept to these settings. For a small ~2 MWe plant, external fuel of 1.9 MWt should be added to the 9.5 MWt obtained from the geothermal cycle. Depending on the pressure level of the binary cycle the efficiency could be improved. Kohl et al. (2002) have assumed a turbine with minimum inlet pressure of 3 bar requiring minimum temperatures of the evaporator of 134°C. The turbine pressure furthermore has also an impact on the necessary reinjection temperatures that are as high as 128°C for 3 bars.

New calculation tool

Based on earlier experience and application, a new, more flexible calculation tool was developed. By this tool, it is now possible to combine variable geothermal production data to a variable and increasing technological database. Therewith, optimum configuration can be much easier assessed. More in detail, we now specify the following geothermal field data:

- production rate and temperature
- number of wells with borehole depth to estimate the drilling costs (Kitsou et al., 2000)
- local temperature gradient (to calculate effects when deepening a borehole)
- injection pressure to assess the pumping power for circulating fluid

Each technical device is characterized at least by costs and efficiency. Still, this calculation tool is based on the same energy transfer calculations as before. We assume that the errors introduced are acceptable within the present stage of development.

Besides the technical installations, the new tool also allows to calculate the electricity costs as function of a single variable. This way, it becomes possible to estimate the influence of

- production temperature
- borehole depth
- production rate
- turbine inlet pressure

For economic calculations, estimations of installation and further investments and of annual operation and amortization costs need to be supplied. Furthermore, the complementary utilization of the waste heat can be specified. Activating this option allows generally reducing electricity production costs. The external fuel required by the hybridization approach is currently implemented as costs per kWht. This price should cover all additional charges (installations, fuel costs, ...).

The most significant change to the earlier stage represents however the integration of organic working fluids

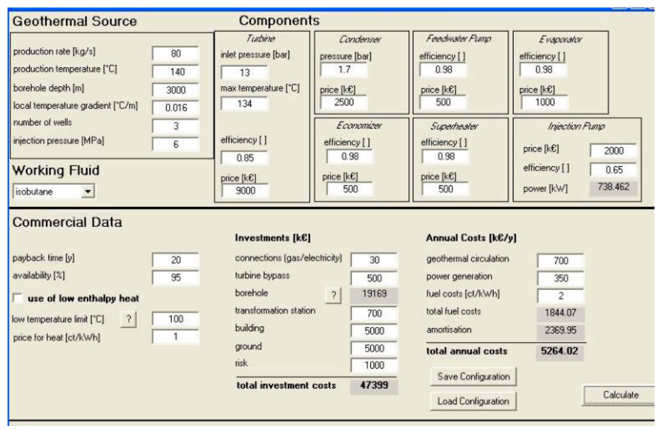

Figure 2. New GeoHybrid input scheme, used later for thermodynamic calculation

Organic Working fluids

It is a well-known fact that organic working fluids have lower efficiency for energetic transfer than water. In contrast, their operating points are more adequate to geothermal production data. In the new calculation scheme we assumed the validity and the same principles of super-heating water vapor. The individual fluid properties have been included according to the NIST database.

Currently, Hexane and Isobutane are implemented in the database, but will be continuously extended. It may be noted that the following results are preliminary, based on the validity of above mentioned assumptions. Further and more detailed studies are under way. However more sophisticated calculation schemes for complete power plant installations will not drastically change these statements. It is estimated that the results are submitted to a maximum error of 10-20%.

EXAMPLES OF UTILIZATION

In the following different typical operating points for water, Hexane and Isobutane are assumed. The geothermal cycle is assumed to produce a flow rate of 100 l s^{-1} by three boreholes at a variable temperature. Injection pressure of 6 MPa is assumed. Optimum turbine pressures are investigated, however no system is to undergo a minimum turbine pressure of 2 bars. Superheating temperatures for water is assumed to be 450°C, 234°C for Hexane and 134°C for Isobutane. Condenser pressures of 0.05 bar for water, 0.2 bar for Hexane and 4.0 bar for Isobutane are assumed.

Appropriate total investment costs for installations and three 3km well of 50 mio € are assumed, a number that is rather conservative. The real costs might be lower.

Table 1 illustrates the working points for pure water-vapor mostly for a fixed turbine pressure of 2 bars. Speck (2002) and Kohl et al. (2002) already showed that its application depends strongly on this pressure value. Minimum geothermal production temperatures of 130°C would be required for this system. At increasing temperatures, the system becomes more efficient, starting at an overall efficiency, η, of 14.4%. Possible net electric power production would start at minimum temperatures at 1.5 MW_e. As noted earlier, the strong portion of geothermal is obvious.

Table 1: Hybridization concept when superheating the working fluid "water vapor"

T [°C]	**p_s [bar]**	**P_{el} [MW_e]**	**P_{geo}/P_{ext} [MW_t] geotherm. %**	**η**
140	2	1.5	8 / 2 81%	14.4%
160	2	4.0	18 / 4 81%	17.7%
180	2	6.7	29 / 7 81%	18.7%
200	2	9.3	39 / 9 81%	19.1%
220	2	11.8	49 / 12 81%	19.4%

The possible improvements for power production using organic working fluids are illustrated in Table 2 (Hexane) and Table 3 (Isobutane). The organic working fluids generate more power than water due to the increased heat transfer in the steam generator, but have a slightly lower efficiency and decrease the geothermal percentage of the power generation.
The minimal required temperature for power generation with a water cycle is 140°C. Hexane requires at least 120°C.

The application of an isobutene cycle could start already at temperatures as low as 80°C but generates at this temperature only a low power. At production temperatures of 220°C, a net power production of 22 MWe is reached.
The application of the right working fluid needs to be carefully planned and adjusted for individual sites. A possible plant size of >5MWe is possible at considerable important portion of geothermal energy.

Table 2: Hybridization concept with Hexane as working fuid

T [°C]	**p_s [bar]**	**P_{el} [MW_e]**	**P_{geo}/P_{ext} [MW_t] geotherm. %**	**η**
120	2	3.3	18 / 11 63%	11.4%
140	2	6.2	31 / 19 63%	12.3%
160	3.5	8.0	35 /17 67%	15.3%
180	6	9.4	38 / 15 73%	17.8%
200	7	13.3	53 / 18 75%	18.7%
220	9	17	68 / 20 78%	19.7%

Table 3: Hybridization concept with Isobutane as working fluid

T [°C]	**p_s [bar]**	**P_{el} [MW_e]**	**P_{geo}/P_{ext} [MW_t] geotherm. %**	**η**
80	8	0.7	12 / 6 69%	3.9%
100	10	2.9	20 / 8 71%	7.3%
120	12	3.7	29 / 10 74%	9.5%
140	20	5.9	36 / 8 81.7%	13.5%
160	25	9.7	58 / 9 86%	14.4%
180	25	14.0	82 / 13 86%	14.7%
200	25	18.4	107 / 17 86%	14.9%
220	25	22.0	126 / 21 86%	15%

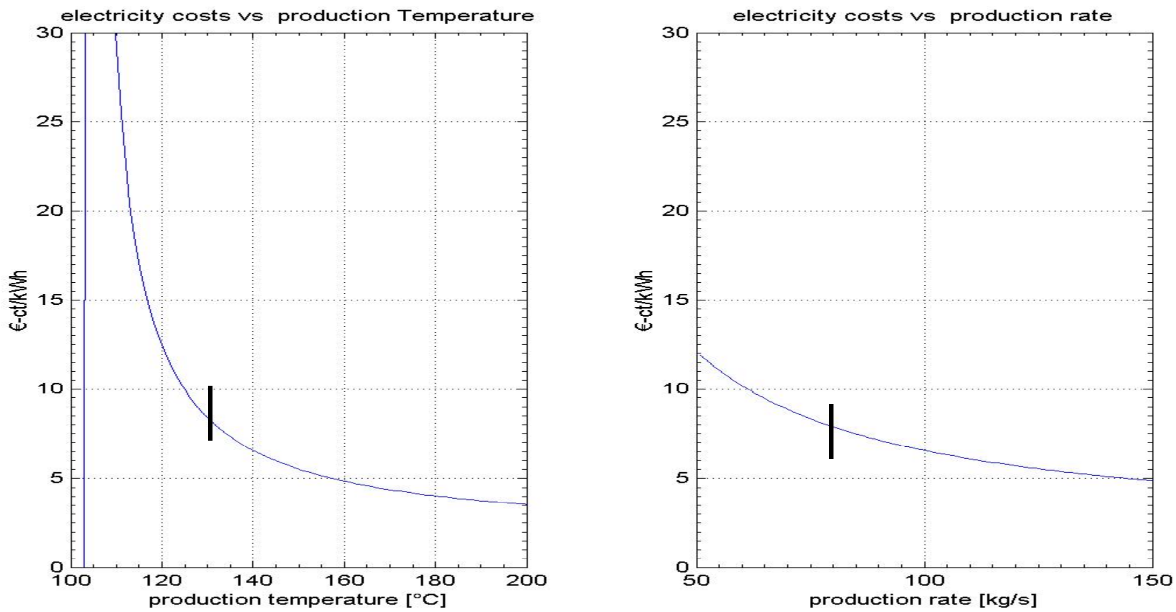

Figure 3. Dependency of geothermal production data on generation costs of electricity with isobutane as working fluid. The scenario assumed a payback time of 20 yrs, total investments of 42.4 M€ and a re-injection pressure of 4 MPa.

In addition to these thermodynamic behaviors, we roughly estimated the possible costs when externally superheating a binary cycle with Isobutane working fluids. Figure 3 illustrates the potential dependency of the described Isobutane considerations on production temperature (at a fixed production flow rate 100 l s^{-1}) and on production rate (at a fixed temperature of 130°C).

When assuming both, a fixed production flow rate of 100 l s^{-1} and a fixed production temperature of 130°C, the Isobutane hybridization would yield costs of ~9 €ct/kWh_e. Clearly, these costs depend strongly upon the geothermal production data. Especially, larger flow rates will reduce costs nearly linearly. Note, that this scenario, assumes external fuel costs of 2 €ct/kWh_t.

CONCLUSIONS

Hybridization of geothermal power shows strongly beneficial aspects in many ways. The exploration costs of low-temperature resources (Temperature gradient < 40 K km^{-1}) could be drastically reduced at lower target temperatures. Our considerations demonstrate the viability and effectiveness of hybridization. This way, steam-based Rankine cycles could become a cost-efficient solution taking advantage of much higher Carnot efficiencies at higher steam temperatures.

Especially, when using biomass as superheater two "green" band-energies are most conveniently combined. Biomass generally suffers from high production costs that present a major setback for these energy sources. However, when hybridized with geothermal energy, much smaller portion of biomass would be needed to produce the same amount of electricity. Power plants in the order of 5 MWe could become conceivable even in areas with a relative low geothermal gradient. We estimated that the amount of 2 MWt typically required for such a small unit requires a wooden area of 6x6 km^2, an area that is easily identifiable even in the strongly populated areas of Central Europe. Future studies are necessary to pinpoint further installations that could serve as database for decision-making institutions. Especially, further non-governmental funding could be easier assessed for the application of geothermal hybridization since it will strongly reduce the risk of geothermal energy production.

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