Bulletin d'Hydrogéologie No 17 (1999)
Centre d'Hydrogéologie, Universitd de Neuchâtel
EDITIONSPETER LANG

Efficient geothermal-fossil hybrid electricity generation: geothermal feedwater preheating in conventional power plants

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ABSTRACT

Hybrid steam power plants with geothermal feedwater preheating enable the utilisation of geothermics in electricity generation in Germany. In order to estimate the potential of geothermal-fossil hybrid power plants with geothermal feedwater preheating, we examine the application of this concept in the examples of two modem power plant assemblies. In addition, energy output and economic efficiency calculations will be compiled for this concept utilising the thermal water data of an existing geothermal heating installation.

The process of geothermal feedwater preheating as a means of improving performance forms both an alternative and an extension to the electricity generation methods based on renewable energy, for example photovoltaics or wind power, which tend to be high in costs and/or low in availability. **An** electricity cost of around **300** DM/MWh appears to be attainable. In countries with the appropriate prerequisites, a considerable benefit in efficient electricity generation and environmental protection can be expected with this concept.

Nomenclature

F	fluid consumption (in kg/kWh)
in	thermal water mass flow rate (in kg/s)
P_{eigen}	power consumption for thermal water cycle (in MW)
P_{el}	net electric power output (in MW)
$P_{net, sol}$	net additional power output from geothermal heat supply (in MW)
0_{sol}	geothermal heat flow (in MW)
V	thermal water volume flow rate (in m^3/h *or* l/s)
W	primary energy flow (in *MW)*
v	productivity of thermal water reservoir (in m^3/hMPa)
z	depth (in m)
ß	electrical output ration (dimensionless)
$\bullet^{TM}_{sol}$	primary energy flow saved by means of geothermal heat supply (in MW)
$\lceil_{net}$	net energetic (1st law) efficiency (dimensionless)
k	conversion factor (dimensionless)
k′	equivalent conversion factor (dimensionless)
δ	density (in kg/m^3)

KEYWORDS

Power plant, geothermal, Ranhine cycle hybrid, electricity generation, extraction steam, low enthalpy, hot dry rock, thermal water

Geothermal electricity generation and geothermal-fossil hybrid power plants

Geothermal installations with the appropriate technology belong to the most environmentally benign forms of electricity generation facilities (DIPIPPO 1991). The main advantage in utilising the Earth's internal heat in comparison to other renewable energy sources is the fact that this resource is almost perpetually available throughout the lifetime of such a power plant.

A combination of geothermal energy and fossil fuels for electricity generation in so-called hybrid power plants provides significant thermodynamic advantages in comparison to a separated approach. For steam-based power plants, three principal concepts for hybridisation may be distinguished (DIPIPPO 1997):

1. Fossil superheating of geothermal steam - gas turbines may be used for this purpose leading to hybrid combined cycle plants (BIDINI et al. 1998).
2. Geothermal feedwater preheating in conventional steam power plants (KESTIN et al. 1978).
3. So-called compound geothermal fossil power plants (DIPIPPO et al. 1981).

Of these three concepts, only the process of geothermal feedwater preheating can be considered a valid possibility for Central Europe with the possible exception of some special locations with higher temperature resources. In addition to geothermal feedwater preheating, a geothermal heat supply for district heating is also possible in combined heat and power plants.

In steam power plants, the feedwater for the boiler is usually preheated with steam extracted from the turbine. This is termed regenerative preheating because part of the enthalpy otherwise lost in the condenser is recovered in the process. As a result of this preheating process, the heat influx in the steam generator can occur at a higher temperature, which, according to the laws of thermodynamics, facilitates a higher power plant efficiency.

The geothermal feedwater preheating process can be implemented in the feed loop of conventional steam power plants. An additional heat exchanger is integrated into the feed loop of an existing plant (*see* figure 1) in a bypass to one or more of the conventional preheaters. In a plant designed as a hybrid plant, some of the conventional preheaters may be reduced in size or may be left out altogether, reducing the investment cost. Part of the boiler feedwater is then preheated geothermally. As a result, the steam flow required for feedwater preheating can be saved upon. The extraction steam which thus remains in the turbine leads to an increased output in the low pressure part of the turbine. By means of this process, on the one hand, an increase in the electrical output can be attained (booster operation) or on the other hand, combustible fuels may be saved at a constant power output (fuel-saver operation). Not only geothermal energy is to be considered in this model, but also other energy sources, such as industrial waste heat, solar energy, etc. BRUHN (1999) made a systematic investigation of this concept in steam power plants, with the example of solar energy supply from high temperature collectors (also compare BRUHN & ZÖLLNER 1996). A comparison of the integration of solar and geothermal heat is given in BRUHN et al. (1999).

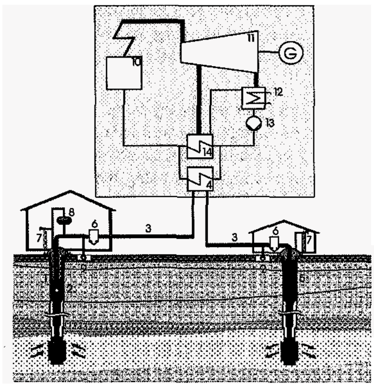

Figure 1: Principle of geothermal preheating (geothermal extraction steam saving) in a steam power plant and scheme of a thermal water cycle for high salinity waters. Extraction well (1), downwell pump (2), transmission pipe (3), heat exchanger (4), injection well (5), filters (6), inert gas protection system (7), constant pressure system (8), slop pits (9), steam generator (boiler)(10). steam turbine (11), condenser (12), feedwater pump (13), conventional preheater (14).

Performance parameters

The power plant efficiency, defined as a quotient of the electrical output and the total heat supply, decreases if additional heat is introduced to the system since some of the heat supply is at a lower temperature (Second Law of Thermodynamics). An apparent increase in the efficiency can, however, be observed, if the electricity generation is compared only to the fossil fuel-based primary energy supply.

The quotient of the net power output, P_{el} and the primary energy flow, $\dot{W}$ is termed the electrical output ratio β of the primary energy flow. In the determination of this output ratio, the additional heat supply and the heat extraction for district heating are not taken into account. Thus the influence of geothermal heat supply on the fossil fuel based efficiency of the power plant may be read directly from the output ratio β.

The following index "sol" refers to the thermal brine (German: *Sole),* i.e. the effects of the additional heat supply. The following Parameters facilitate a description of the two (idealised) operational concepts, booster operation and fuel saving operation. They were formed through a comparison with the initial fossil only status marked with "o" (no additional heat supply).

In booster mode with a constant supply of primary energy, $\dot{W}$, the additional net electric power output of the power plant, $P_{el,sol}$, in relation to the additional heat input, $\dot{Q}_{sol}$ results in the conversion factor κ:

$$\kappa = \frac{P_{el,sol}}{\dot{Q}_{sol}} = \frac{P_{el} - P_{el}^{\circ}}{\dot{Q}_{sol}} \qquad (1)$$

For the entire facility, (power plant plus thermal water cycle), the geothermal net additional power output, $P_{net,sol}$ is calculated deduction of the power consumed by the thermal water pump, P_{eigen}. From this, the annual electricity yield, $E_{el,a}$ can be calculated using the full load hours t_{vh} of the geothermal facility (**BRUHN** et al. 1999).

The characteristic benefit in fuel-saver mode is the saved primary energy flow, $\Delta\dot{W}_{sol}$, with constant electrical output. A judgement of this mode of operation, as well as a direct comparison of the **results** for fuel saving and for boosting can he made by transforming this to an equivalent electrical output. The transformation is accomplished using the electricity output ratio at the initial status, β^{o}. In analogy to equation (1), this equivalent output yields an equivalent conversion factor, κ':

$$\kappa' = \frac{\beta^{o} \cdot \Delta\dot{W}_{sol}}{Q_{sol}} = \frac{\beta^{o} \cdot (\dot{W}^{o} - \dot{W})}{Q_{sol}} \qquad (2)$$

The specific fluid consumption f of a geothermal power plant is the quotient of the thermal water mass flow, $\dot{m} = \dot{V} * \rho_{sol}$, and the net electrical output, P_{el}. In the case of geothermal feedwater preheating, the net geothermal output $P_{net,sol}$, is taken as a basis.

In addition to geothermal feedwater preheating, a geothermal heat supply for district heating is also possible in combined heat and power plants. Due to the great variety in possible compositions, the more general calculations are usually done for pure water.

Power plant performance with additional geothermal heat supply

The usage of geothermal feedwater preheating in large modem power plants was investigated for the reference power plant using computer simulations of the steam cycle. In addition, a combined heat and power plant in condensing mode (pure electricity generation) was analysed. Important data on the power plants and the simulation inputs are given in table 1. The reference power plant is a modem installation completed in the 1990s and operating in Germany. The combiped heat and power plant was also used by **BRUHN** (1999) as an example for computer simulations. Its basic parameters were **taken** from another modem installation completed in Germany in the late 1980s. Schemes of both plants are given by **BRUHN** et al. (1999).

The results show that a noticeable contribution from geothermal preheating in a large power plant can only be achieved by large volumes of thermal water flow. At a thermal water temperature of 70 °C, there is no net improvement in the electricity output, since the yield is cancelled out by the energy consumed by the thermal water pump under the assumptions made. Preheating with water at temperatures as low as 70 °C can thus only be considered in cases where no additional energy consuming processes are required, for example, in an artesian system.

Table I: Simulation inputs for the reference plant and for the combined heat and power plant. Q_{FW}: heat flow extracted for district heating, $\vartheta_{ZÜ}$: reheat temperature, p_{Kond}: pressure in condenser, ϑ_V/ϑ_R: supply- and return temperature for district heat, η_{net}: net efficiency, η_{DE}: steam generator efficiency, $\beta°$: electricity output ratio at initial status.

Parameter	unit	reference plant	combined plant (condensing mode)
plant data			
Fuel		hard coal	hard coal
P_{el} (design)	MW	550	277
P_{el} (simulation)	MW	520	211
$\dot{Q}_{FW}$ (design)	MW	300	386
$\dot{Q}_{FW}$ (simulation)	MW	100	-
live steam parameters	bar/°C	250/540	190/535
A, .	°C	560	538
number of preheaters		Seven	eight
p_{Kond}	bar	0.038/0.052	0.058
district heat: ϑ_V/ϑ_R	°C	135/60	-
η_{net} (design)		0.43	0.409
η_{DE} (design)		0.943	0.923
$\beta°$ (simulation)		0.424	0.447
turbine internal efficiency		constant	constant
geothermal heat exchanger			
feed water inlet temperature	°C	28	36
min. temperature difference	K	5	5
ratio of mass flows	-	1:1	1:1
Simulation			
program used		Ebsilon	CHP (CHUNG 1990)

Figure 2 shows the equivalent conversion factor for the reference power plant plotted against the thermal water temperature. The combined heat and power plant was investigated for comparison (table 1). In this case, hot water reservoirs at high temperatures were included using a thermal water temperature of 218 "C as an example.

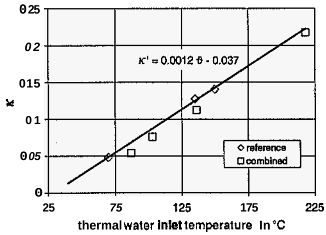

Figure 2: Conversion of additional geothermal heat in modem power plants: equivalent conversion factor for the reference plant and for the combined heat and power plant plotted against the thermal water-inlet temperature. The function indicated gives the correlationfor the referencepower plant.

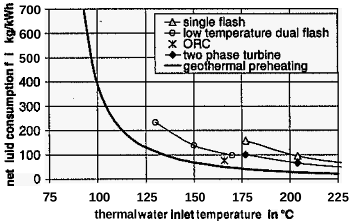

Figure 3: Fluid consumptionf plotted over thermal water temperature (pure water) for geothennal electricity generation at low to medium temperatures (**HUDSON** *1990, SHULMAN 1995, BRONICKI 1998).*

A somewhat lower equivalent conversion factor was attained at the same temperature in the combined heat and power plant as compared to the reference power plant. This corresponds to the lower efficiency at design conditions. There is an approximately linear development of the equivalent conversion factor in relation to the thermal water temperature. A linear approximation was determined for the reference power plant which is given in figure 2. This approximation is used as a basis for the calculations of output and efficiency given below.

Table 2: Plant parameters for a hypothetical reference power plant at Neustadt-Glewe

echnical data			
Thermal water temperature	ϑ	98	°C
Thermal water reinjection temperature	ϑ''	33	°C
Salinity		28.1	% by mass
Equivalent conversion factor	κ'	0.0806	°C
Productivity	v	100	m³/hMPa
Equilibrium thermal water level	H_r	100	M below surface
Pressure loss in above ground installation	Δp_V	1	Mpa
Volume flow rate	$\dot{V}$	110	m³/h
Pump efficiency (hydraulic to electric)	η_{Pu}	0.65	
Pump power consumption	P_{eigen}	0.146	Mw
Annual full load hours (geothermal)	t_{vh}	7 000	h/a
Annual electricity yield	$E_{a,sol}$	3 234	MWh/a
Annual fuel savings	$M_{B,a,sol}$	1054	t/a
conomic data			
Investment cost	I	12	Mio DM
Amortisation period	n	20	a
Interest rate	p	0.06	
Annuity factor	a	0.0872	
Annuity		1.046	Mio DM
tesults			
Electricity cost	k	324	**DM/MWh**
Fuel saving **cost**		993	DM/t

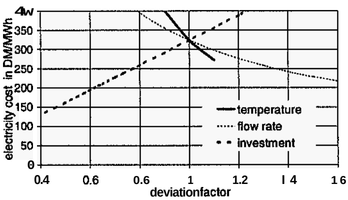

Figure 4: Sensitivity check for the annual electricity production, $E_{a,sol}$ (left) and for the electricity cost (right) for the hypothetical power plant at Neustadt-Glewe. See Table for standard case (i. e. deviation factor 1).

As an alternative to using the conversion factor, the conversion of geothermal heat can be described using the specific fluid consumption *f*. Figure 3 compares geothermal feedwater preheating in steam power plants with common processes for geothermal electricity generation in the lower and middle temperature ranges. The thermodynamic advantages of this concept can be seen in the considerably lower fluid consumption.

Total system: power plant with thermal water cycle

An estimate of the output and the efficiency of geothermal feedwater preheating, as attainable in Germany, can be achieved by combining the conversion factor of a modem power plant with the data of an existing geothermal heating plant. Thus the annual fuel savings and output have been calculated for the thermal water conditions of Neustadt-Glewe geothermal heating plant (cf. KAYSER & KALTSCHMITT 1998) utilising the function portrayed in figure 2 for the conversion factor in the reference power plant (table 2).

The economic efficiency is calculated through the unit cost of the geothermal net additional power output and alternatively through the cost per ton of combustible fuel saving. The combustible fuel saving cost reflects the financial investment required to save a ton of hard coal by means of geothermal feedwater preheating. Annual costs for operation, maintenance etc. are thought to be included in the annuity because a relatively high investment cost was assumed. The attained unit cost of the electricity lies at a little less than three times the unit cost of electricity generated by conventional methods in Germany. The cost per ton of combustible fuel savings, however, lies at more than ten times the current price of imported coal. Thus, geothermal feedwater preheating is only financially viable in modem power plants if an increase in electrical power output is required.

According to BRUHN (1999) (figure 3-10), a higher level of combustible fuel saving can be achieved in power plants with a poorer efficiency than the modern steam power plants considered here. The combustible fuel savings with geothermal feedwater preheating can thus be particularly high in simple facilities (for example, in developing countries or in smaller industrial power plants).

For the above calculation on the reference power plant combined with Neustadt-Glewe data, the sensitivity of the results was checked in individual parameters (figure 5). Each parameter was varied individually over a realistic range, whilst all other parameters were held constant.

Although the site at Neustadt-Glewe heating plant has the best conditions of all the geothermal heating plants operating in north-eastem Germany, higher thermal water temperatures are possible at other places in Central Europe. A location with a thermal water temperature ϑ of 108 °C (deviation factor of 1.1 as opposed to Neustadt-Glewe) and a flow rate of 150 m^3/h (which would be possible in Neustadt-Glewe after the appropriate bore-hole expansion work) would, as an outcome, produce an electricity cost of 205 DM/MWh instead of **324** DM/MWh (figure **4).**

As can be seen from this, all the considerations are extremely dependent on the local conditions, both **on** the characteristics of the individual power plant and on the thermal water availability.

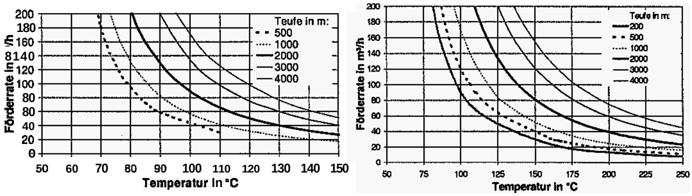

Figure 5: Temperatures ϑ and flow rates $\dot{V}$ required to reach an electricity cost of 300 DM/MWh (left diagram) or 100 DM/MWh (right diagram). Depth is used as a parameter. For further assumptions cf. Table 3.

CO_2 savings

According to BAEHR & **DRAKE** (1995) the energy-related carbon dioxide load of electricity generated from hard coal lies at 0.97 t/MWh. For the above calculation, "Neustadt-Glewe/reference power plant", an annual CO_2 saving of 3137 t/a can be calculated. In the case of lignite fired plants, the savings are around 10% higher. In comparison to other renewable energy sources, the geothermal feedwater preheating method can be seen to be favourable (cf., e.g. **BRUHN** 1999, pp. 159 ff.). This is particularly due to the fact that fuels with a high carbon content can be saved on.

Possible sites

At present fuel prices, the efficiency calculation rules out the possibility **of** a system based on geothermal feedwater preheating in Germany which can compete with conventional facilities. In areas with the appropriate geothermal conditions, it is possible with a subsidy of around 50 % to attain an electricity cost equivalent to the German minimum price paid **for** electricity from renewable energy sources. A decisive advantage, in comparison to wind-generated electricity is the almost 100 % availability **of** the geothermal energy. However, a geothermal installation must make use of this advantage to the maximum in order to achieve the results shown above. All the economic efficiency calculations given above are valid only if a geothermal facility can be run 7000 full load hours per year.

In order to realise the potential of geothermal feedwater preheating. it is necessary to make geological assessments of a large number of power plant locations. For a preliminary pre-selection and **for** a rough estimate **of** the efficiency, figure ***6*** was created.

For example, a sandstone horizon lying at a depth of 2000 m below a power plant facility, with the typical drilling costs in Germany (compare table 2) and with a thermal water temperature of around 90 "C would need to deliver around 130 m^3/h **of** thermal water. With flow rates lower than this, the mark of **300** DM/MWh (which was chosen arbitrarily as a basis for figure ***5)***, shall be exceeded (left figure).

Table 3: Assumptions for calculating economical thermal water parameters for a given depth and a given electricity cost (cf. figure 5). In addition, the relation $\kappa'(\vartheta)$ figure 2) must apply. Calculations done for pure water. For further assumptions see table 2.

Geology:				
Productivity	v	150	m³/hMPa	
Thermal water reinjection temperature	ϑ''	**42**	°C	
Economics				
Electricity cost (assumption)	*K*	**300/100**	**DM/MWh**	
Specific drilling cost (completed well)	f_1	**2 000**	**DM/m**	**2500** m and less
Specific drilling cost (completed well)	f_{1b}	**2 250**	DM/m	**3000** m and more
Investment **for** above ground installation		3 Mio.	DM	

The ideal technical prerequisites for the realisation of geothermal feedwater preheating can be found in coal fired steam power plants which are located in tectonically active regions.

The right hand diagram in figure ***5*** can be utilised for an initial rough estimate for some international locations **of** steam power plants. It shows the geological pre-conditions for electricity generation at 100DM/MWh for German cost structure. When using the figure, the local variations in prices must be taken into account. In addition to the local typical drilling cost (which is often cheaper in places other than Germany), the type of power plant is an important variable in this calculation. Other, for example, geological uncertainties, or, for example, an extremely high or an extremely low mineral content in the water can result in strong deviations from the cost estimates shown here.

Acknowledgements

This research was funded by the **German** Ministry of Education, Science, Research and Technology (BMBF, BEO **0326969).** The authors would like to thank the East German utility company **VEAG AG** Berlin for carrying out the calculations for the reference power plant and for their support in the evaluation of the results.

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