Numerical Studies of Combined Shallow and Deep Geothermal Systems

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ABSTRACT

Currently, EGS technologies suffer from increased development costs during periods when the financial risk is very high, mostly due to uncertainties regarding thermal and more importantly electrical power revenues. Optimization of the EGS working cycles can improve electrical energy production and thus promote EGS projects. For such optimizations, difficult inverse problems have to be solved to obtain parameter sets for maximum profits. These approaches require fast yet accurate forward models that can properly account for those parameter variations. Here, a 1D model is devised that can be used for quick estimates of the EGS production temperatures. It is designed for fast calculations of the production temperature in highly fractured reservoirs. It allows to compute different solution families and is controlled by few model parameters. When these parameters are calibrated with a 3D EGS model, this 1D model can accurately predict the production phase for a wide range of scenarios; the results proofed to be in good agreement with those obtained from much more expensive 3D simulations. Temporal flow variations are not considered at this point; i.e. chemical, mechanical, and hydrological phenomena are not captured by the suggested 1D model. Together with the 1D model, various validation studies are presented. Then it is used for optimization of combined shallow and deep geothermal reservoirs, and it is shown that the relative cost can significantly be reduced with such systems.

1. INTRODUCTION

Contrary to most renewable resources, geothermal energy can be utilized on a constant basis and thus it can cover a portion of the base load energy needs. Currently, 48 GW of thermal power is exploited globally (Lund et al., 2011) and the electrical power production is expected to rise from 10 GW, to 70 GW, by the year 2050. If EGS technology is successfully developed, then an installed capacity of up to 140 GW, is predicted by the year 2050 (Bertani, 2012). For making EGS technology financially sustainable the cost of electrical power production needs to be reduced and the risks associated with it need to be moderated.

In general, geothermal power production technologies suffer from increased development costs during periods when the financial risk remains high (Gehringer and Loksha, 2012). EGS power plants operate at large depths. However, the drilling cost increases exponentially with the depth due to the diminishing drilling progress (Huenges, 2010). Consequently, drilling cost dominates the overall EGS cost. Its exponential increase with depth is a major factor in modeling the economic potential of EGS projects and the assessment of revenues from possible investments (Heidinger et al., 2006, Gerber and Maréchal, 2012).

To reduce the drilling cost per unit of produced electrical energy, the net electrical energy production \( E_{el} = E_w \eta_{th} \) needs to be maximized, where \( \eta_{th} \) is the net thermal efficiency and \( E_w \) the total thermal energy extracted from an EGS reservoir. An estimation of the thermal efficiency \( \eta_{th} \) of plants that operate at temperatures close to geothermal ones has been given by Tester et al. (2006), and they found that the \( \eta_{th} \) is correlated with the production temperature \( T_{prod} \) of the power plant as

\[
\eta_{th} = \frac{0.0935 \cdot T_{prod} + 2.3266}{100}.
\]

(1)

In Fig. 1a the thermal efficiency according to Eq. (1) is compared with the efficiency of the Carnot cycle for a similar range of temperatures. This efficiency is low and increases linearly with the temperature at which the fluid reaches the surface. Obviously, maintaining high temperatures of the produced fluid has a desirable effect on \( E_w \). However, maintaining high production temperatures for a longer time period is in conflict with commercially interesting rates of extracted energy. The later requires high production flow rates \( F_{prod} \), which can extract heat from the hot rock at higher rates. The total thermal energy \( E_{th} \) extracted from an EGS reservoir is equal to the time integral of the rate at which heat is extracted during the life span of the EGS, i.e.

\[
E_{th} = \int_{t_l} F_{prod} \cdot c_f \cdot (T_{prod} - T_{inj}) \cdot T_{inj} \cdot dt.
\]

(2)

where \( t_l \) is the EGS life time, \( c_f \) the specific heat capacity (here assumed constant) of the working fluid and \( T_{inj} \) the temperature of fluid that gets re-injected.
In general, the life expectancy $t_l$ decreases, if the mass flow rate $F_{inj}$ increases, or if the re-injection temperature $T_{inj}$ decreases. Long life expectancy can be combined with commercially interesting rates, when the EGS reservoir is characterized by low impedance between its wells and if the injected fluid stays long enough inside the reservoir. The creation of a reservoir that serves as such an efficient and large heat exchanger between rock and fluid is the main purpose of the EGS reservoir stimulation process.

However, estimations regarding the fracture network inside a reservoir are still subjected to high uncertainty and thus the desired heat exchange efficiency of an enhanced reservoir is not always achieved. The EGS site of Hijiori in Japan is an example of a stimulated reservoir with low thermal recovery efficiency. There, one of the production wells penetrates the fracture system in such a way that a short circuit of fluid is created between the injection and one of the production wells, which is only 90 m away. Along this circuit the rock temperature decreases rapidly for high (and thus commercial) flow rates. Within 300 days the initial production temperature of 260°C from that well was reduced to less than 140°C, implying the existence of this too short flow path. Tenma et al. (2008) optimized the operation cycle of the Hijiori EGS power plant with the mass flow rate as a variable and even for the optimized scenario, the net thermal output reduces to one third of its initial value within the first year of operation. The opposite was the case for the 3.5 km reservoir at Soultz-sous-Forêts, France. There, the flow paths between injection and production wells occur at least in part within fracture zones and faults that are both highly permeable and of high porosity (Evans, 2005). Consequently, large flow rates can circulate inside the EGS reservoir in Soultz and extract thermal energy from a larger hot area.

An illustrative sketch of these two EGS scenarios is shown in Fig. 1b. On the left side of Fig. 1b, a typical EGS scenario is depicted. The right sketch illustrates the proposed combined operation of the deep and shallow reservoirs. There, the cold working fluid is injected into a shallow reservoir (preheater), where it heats up as it passes through the reservoir, and then it is brought back to the surface at elevated temperature. From the surface, this warm water is then injected, into the deep reservoir, where it is heated to the final production temperature and pumped to the surface. In general, as Baria et al. (1999) noted, the HDR concept progresses towards larger reservoirs, thus, the combined use of shallow and deep reservoirs may be a realistic future approach.

It becomes clear that the production temperature $T_{prod}$, the injection flow rate $F_{inj}$ and the life expectancy $t_l$ of a particular EGS reservoir are strongly related to each other and determine the optimal operation cycle. Each combination of these three parameters results in different thermal revenues and their optimal combination needs to be found for minimizing the cost of the EGS electrical energy production $E_{el}$, even when the exact geometry of the EGS reservoir is not known.

Here, the relationship between the production temperature $T_{prod}$, the injection flow rate $F_{inj}$ and the life expectancy $t_l$ of an EGS reservoir is studied with a 1D model. First, this 1D model is described, then it is verified, and finally it is employed to examine the potential gain from combining shallow and deep geothermal exploitation.
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2. SIMPLIFIED 1D MODELING OF HEAT TRANSPORT IN AN EGS

Here, a 1D model is described that can be used for quick estimates of the production temperature of an EGS power plant, and then comparisons with results from HFR-Sim are made.

1D models have been previously developed for simple HDR calculations and they have been reviewed in the past by Willis-Richard and Wallroth (1995). Bodvarsson (1974) developed a 1D single fracture model that uses the analytical functions derived by Carslaw and Jaeger (1959) for the computation of the outlet water temperature in simple shaped fractures. An intergranular 1D model, which assumes that water temperature equals rock temperature and neglects heat conduction, was also proposed there. A 1D radial model for permeability enhancement studies was used by Elsworth (1989), while Kruger et al. (1991) made use both of the analytical fracture equations and of a simplified 1D model that splits a reservoir into many identical rock segments. Within each segment a 1D heat conduction is solved. The latter model uses dimensionless equations.

We consider an EGS reservoir with an effective porous domain $\Omega$ of length $L_w$, which equals the distance between injection and production wells. Further, its swept mean surface is $A_w$, such that $|\Omega|=A_wL_w$. Porosity $\phi$ is assumed constant everywhere in $\Omega$ and temperature variations only occur along the domain length $L_w$. For that reason, from now on $\Omega$ is treated as a 1D domain of length $L_w$, cross section $A_w$ with injection occurring at $x=0$ and fluid being extracted at $x=L_w$.

Figure 2 illustrates such a 1D domain.

![Figure 2: Sketch of the assumed 1D EGS domain.](image)

2.1 Governing equations and discretized 1D model

Commercial EGS power plants operate within a range of injection rates $F_{inj}$ that result in a slower rate of heat diffusion inside the rock than the heat exchange rate between the hot rock and the fluid. For that reason, heat diffusion inside domain $\Omega$ can be neglected and the flow rate considered constant and equal to $u = (F_{inj}/A_w)$.

Constant heat capacities and densities are considered both for fluid and rock. Energy balance leads to

$$\frac{\partial \rho c_T}{\partial t} + u \frac{\partial T}{\partial x} = \frac{\epsilon_{r}\rho w c_p r}{A_w} \left( T - T_f \right),$$

(3)

and

$$\frac{\partial (\rho w T)}{\partial t} = \frac{\epsilon_{r}\rho w c_p r}{A_w} \left( T - T_f \right),$$

(4)

for $0 \leq x \leq L_w$, where $T_f$, $\rho_f$ and $c_p$ are the rock temperature, density and heat capacity, respectively, and the coefficient $\epsilon_{r}$ is a heat exchange coefficient that indicates the efficiency with which the fluid exchanges heat with the rock, i.e. quantifies the rate of heat transferred per unit length and per unit temperature difference $\left(T - \bar{T}_{r}\right)$. Here, this coefficient $\epsilon_{r}$ is treated as a constant that accounts for the geometry of the fracture network and the rock thermal conductivity.

The non-dimensional form of Eqs. (3) and (4) provides valuable insight for the behavior of the model presented above. In order to non-dimensionalize these Eqs., the reference time $t_0 = (L_w \phi u)$ and the reference length $L_w$ are introduced. The time $t_0$ corresponds to the time needed by a heat perturbation at the injection well (at $x=0$) to get advected to the production well (at $x=L_w$). The difference between the initial production temperature $T_{prod}(t=0)$ and the injection temperature $T_{inj}$ is the reference temperature difference $\Delta T_{inj} = T_{prod}(t=0) - T_{inj}$. The non-dimensional variables $\tau = u t_0$, $\chi = x / L_w$, $\theta = (T - T_{inj}) / \Delta T_{inj}$ and $\theta' = (T' - T_{inj}) / \Delta T_{inj}$ can be defined. In non-dimensional form Eqs. (3) and (4) then become

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial \theta}{\partial \chi} = \frac{\epsilon_{r} \rho w c_p r}{F_{inj}} \left( \theta' - \theta \right),$$

(5)

and
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\[ \frac{3 \theta'}{3 \tau} = \frac{c' \tau - f}{F_{\text{m}j}} \left( \theta - \theta' \right) \frac{c Z}{c_i} \]

for \( 0 \leq \tau \leq 1 \). For each pair of coefficients \( c_1 \) and \( c_2 \), a unique solution of Eqs. (5) and (6) exists. This solution corresponds to an infinite number of problems.

The system (5)-(6) is solved numerically with a finite volume method. The domain is discretized by \( N \) volumes and the mean values of \( \theta'_i \) and \( \theta''_i \) of each volume \( i \) are computed at each time-step \( n+1 \) as

\[ \theta''_i = \theta'_i + \Delta \tau \left( \theta''_{i+1} - \theta''_i \right) + \Delta \tau \eta \left( \theta''_{i+1} - \theta''_i \right) \]

and

\[ \theta'_i = \theta''_i + \Delta \tau \left( \theta'_i - \theta''_i \right) \]

where \( \Delta \tau \) is the time-step size for which the CFL condition is satisfied and the superscripts \( n \) and \( n+1 \) denote old and new time levels respectively.

The thermal efficiency of Tester et al. (2006) given by Eq. (1) becomes

\[ \eta_{th} = \frac{Q_0}{W_{\text{prod}}} = \frac{0.0935 \cdot \Delta T_{\text{prod}}}{100} + \eta_{th} \]

where \( \eta_{th} \) is the efficient of the injection and production process. The total electrical energy can be approximated as

\[ \frac{1}{C_{\text{p}0}} \frac{1}{T_{\text{prod}}} \int_0^{\tau_{1/2}} \left( \eta_{th} F_{\text{m}j} \rho C_p T_{\text{prod}} \right) \frac{1}{C_{\text{p}0}} \frac{1}{T_{\text{prod}}} \int_0^{\tau_{1/2}} \left( \frac{\Delta T_{\text{prod}}}{100} + \eta_{th} \theta_{\text{prod}} \right) d\tau \]

where the non-linear relationship between electrical power and \( T_{\text{prod}} \) can be seen. A decrease in production temperature \( \theta_{\text{prod}} \) reduces the produced electrical power quadratically.

2.2 Verification of simplified 1D model

Following the work presented by Karvounis and Jenny (2012), the 1D model is verified with the simulation results of the EGS scenario that was presented there. Two hydraulically identical 3D models were considered for the deep reservoir and the preheater domain. The major axis of the elliptic cylinder is 270 m long, the length of the minor axis is 210 m, and the permeable region is penetrated at the ends of the major axis by two parallel horizontal wells; each one having an open case length of 400 m. The size of the rock domain \( \Omega \) is 400 m x 400 m x 300 m centered around the permeable region. The assumed geometry is depicted in Fig. 3a.

There, a linear temperature increase with depth is assumed, where the temperature of the hot rock is 125°C at 1 km and increases by 25°C per 1 km. The injection rate is 40 l/s and simulations stop when the temperature of the produced water becomes lower than 100°C. The material of the considered rock has properties similar to granite (i.e. \( \rho' = 2700 \text{ kg/m}^3 \) and \( c' = 920 \text{ J/kg} \)) and fresh water (\( \rho = 1000 \text{ kg/m}^3 \) and \( c = 4183 \text{ J/kg} \)) is used as working fluid. The black curves in Fig. 3b show the evolution of the simulated non-dimensional produced temperatures with and without a preheater. Here, \( \Delta T_0 = (233.75\text{°C}-60\text{°C}) = 173.75\text{°C} \) and \( t_{\text{ro}}=3.10^5 \text{s} \).
Initially, a simplified 1D EGS model is found that returns results in close agreement with the results obtained from the 3D model for the scenario where only a deep reservoir is used (typical EGS scenario). The coefficients $c_1$ and $c_2$ are treated as the matching parameters with $AT_0 = 173.75^\circ C$ and $t_{p}\tau = 3\times10^7 s$. It is found that the set of coefficients $(c_1, c_2) = (2.718, 0.3927)$ leads to a production temperature history, which is in good agreement with the 3D model (typical EGS scenario). The production temperature decline computed by the calibrated 1D model is plotted in Fig. 3b and can be compared with the results obtained from the 3D model.

It is noted that the ratio of $c_1$ over $c_2$ is a function of porosity and of the known material properties. Here, the material properties are known and equal to the values employed by HFR-Sim. Thus, this set of coefficients $(c_1, c_2)$ implies an effective porosity of $\varphi = 0.079$. This effective porosity differs from $\varphi'$, i.e. it corresponds to the ratio of the void volume through which flow occurs over the volume of rock out of which heat is extracted when water is injected at a rate of $F_{w,j} = 0.04 m^3/s$.

The same set of coefficients $(c_1, c_2)$ is then used to simulate the scenario where a preheater with initial non dimensional temperature $\theta_p = 0.5683$ is employed. This non-dimensional temperature $\theta_p$ matches the initial production temperature of the simulated 3D preheater. In agreement with the assumptions made during the HFR-Sim simulation, the 1D preheater is assumed to be a shallower reservoir with the same heat exchange coefficient as the deep one. In Fig. 3b the results from this 1D model are plotted and can be compared with the corresponding results from the 3D model.

The overestimation of the cold water breakthrough time results from the fact that 3D simulations also account for fluid dispersion in all directions and therefore the production curve is smoother. Aside from that, it is evident that the 1D model gives results which are in good agreement with the 3D simulation, also when a deep reservoir is combined with an identical but shallower reservoir.

3. NUMERICAL STUDIES OF COMBINED SHALLOW AND DEEP GEOTHERMAL EXPLOITATION

In this section, the discretized non-dimensional equations of the simplified 1D model are solved for a number of different solution families and the energy revenues are computed and compared.

The simulations can be divided into two sets. The first set consists of simulations of typical EGS operation scenarios that are described by Eqs. (7) and (8). The second set of simulations consists of scenarios where a preheater is involved.

For both sets of simulations the deep reservoir has a constant porosity of $\varphi = 0.05$, the distance between the wells is $L_w = 1000 m$, the effective area is $A_w = 10,000 m^2$ and the injection rate is $F_{w,j} = 0.04 m^3/s$. Here, the material of the considered rock again has properties similar to granite (i.e. $\rho = 2700 kg/m^3$ and $c_p = 920 J/(kg)^\circ C$) and fresh water ($\rho = 1000 kg/m^3$ and $c_p = 4183 J/(kg)^\circ C$) is used as working fluid. The reference time according to our definition is $t_0 = 3\times10^3 \approx 1.6$ years.

For the traditional EGS model it is assumed that the initial (at $\tau < 0$) temperature in the deep reservoir is $T_{prod}$ and thus $\theta' = \theta = 1$, and that the injection temperature (at $\chi = 0$) is $T_{w,j}$ and thus $\theta = 0$.

For the second set of simulations it is assumed that the fluid first circulates through the shallow reservoir (also called `preheater`) and then enters into the same deep reservoir as in the first set of simulations. Here, the deep and the shallow reservoirs are assumed to have the same heat exchange coefficient $\tau$, the same distance between the wells $L_w$ and the same material properties. Therefore, both can be treated as a single 1D non-dimensional domain of length 2. With the non-dimensional initial rock temperature $\theta_p$ of the preheater, initial conditions in the domain are

\[
\theta' = \theta = \begin{cases} 
\theta_p & \text{for } 0 \leq \chi < 1 \\
1 & \text{for } 1 \leq \chi < 2 
\end{cases}
\]  

and the boundary conditions for $\tau \geq 0$ are $\theta(\chi = 0) = 0$. 

5
Simulations were conducted with the preheater temperature $\theta_p$ set to 0.3, 0.4 and 0.5, i.e. such that it potentially can provide 30%, 40% and 50% of the overall temperature gain, respectively.

For each set and for each $\theta_p$ ten different heat exchange coefficients $c_f \rightarrow c_r$ are used and solutions with the corresponding parameters $c_1$ and $c_2$ are computed. Note that here $\frac{c_f}{c_r} = \frac{\varphi \rho c_p}{(1-\varphi) \rho c_p} = 0.008863$, and therefore only the corresponding $c_f$ values are listed in Table 1. The values employed for $c_f \rightarrow c_r$ and $c_f$ scale logarithmically and the first one without preheater corresponds to a scenario where power production beyond time $\tau_0$ is of almost no commercial interest. It is assumed that only $\theta \geq 0.3$ is of commercial interest, which determines the duration of the simulations.

<table>
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In Fig. 4 the non-dimensional temperature production histories for the logarithmically increasing set of $c_f$ coefficients are given for each scenario. Each curve corresponds to a solution family.

For the traditional EGS operation cycle (far left plot), the least efficient models result in a rapid drop of the production temperature, i.e. the injected fluid does not reach temperature equilibrium with the rock. On the other hand, the use of a shallow reservoir as a preheater results in a significant temperature increase at later times. Using a preheater results in an increase of the effective rock volume out of which thermal energy is extracted. This is the reason for the ‘plateau’ of the $\theta$-curves for $0 < \tau < 2$, e.g. in case of $c_f \leq 1.5091$. After a period of two reference times the production temperature declines more rapidly.

The most efficient scenarios with high $c_f \rightarrow c_r$ and high $c_f$ values benefit less from the preheater. As a consequence of the high efficiency, with which heat is extracted from the deep reservoir, the influence of the preheater only shows up later, when the production temperature approaches the temperature of the preheater. The produced energy is then similar to the one produced by the preheater alone. For the scenario with $\theta_p = 0.3$, where the shallow reservoir alone does not have commercial potential, its combination with the deep reservoir increases the lifetime of the system by more than 25% for all the $c_f$ values.

Important quantities for determining the amount of produced electrical energy $E_{el}$ are the integrals $I_1 = \int_0^\tau \varphi d\tau$ and $I_2 = \int_0^\tau \varphi^2 d\tau$ that appear in Eq. (10). The produced electrical energy at each time $\tau$ can be computed as

$$E_{el} = \frac{F_{pre} \rho c \Delta T_{0} \tau}{100} \left[ 0.0035 \Delta T_{0} I_2 + \eta \Delta T_{0} I_1 \right]$$

In general, the use of preheaters not only increases the life expectancy of the least efficient reservoirs, but also leads to higher revenues during the same operation time.
Figure 5: (a) Total electrical energy production for the four scenarios. (b) Total gain in electrical energy produced compared to the typical scenario. (c) Increase in electrical energy production compared to producing electrical energy from the deep and the shallow reservoirs independently.

For the following economic study it is assumed that \( T_{w0} = 55^\circ \text{C} \) and \( T_{prod} = 180^\circ \text{C} \). The electrical revenues for each heat exchange coefficient and each of the four scenarios (without and with preheater of \( \theta_p = 0.3 \), \( \theta_p = 0.4 \), and \( \theta_p = 0.5 \)) are computed. Moreover, for comparison, the revenues for the two warmer preheaters alone, i.e. not in combination with the deep reservoir, are computed. Figure 5a shows the total electrical energy produced for each scenario and for each \( c_i \). Figure 5b shows the additional electrical energy produced due to a preheater in the EGS working cycle. It can be seen that the electrical energy gain for the least efficient models, i.e. for \( c_i < 2 \), is enormous. Apparently, the ratio of drilling costs per produced electrical energy unit is only reduced for \( c_i \) values that correspond to an electrical energy gain larger than the additional drilling cost required; e.g. for \( c_i = 15 \) a preheater with \( \theta_p = 0.3 \) would result in a decrease of relative drilling costs, only if drilling for the preheater is cheaper by more than 19.05% than for the deep reservoir. In Fig. 5c the additional produced electrical energy is quantified for each parameter \( c_i \) and is compared to the scenario of producing electrical energy independent deep and shallow reservoirs. This electrical energy gain can be considered as a reduction in drilling cost per produced electrical energy unit. Here, the curve that corresponds to the scenario with \( \theta_p = 0.3 \) is identical to the one for \( \theta_p = 0.3 \) in Fig. 5b, since the preheater is not considered to have high enough temperature for electrical energy production.

4. CONCLUSION

A simplified 1D model is presented, which can be used for quick estimates of thermal and electrical energy production by an EGS. The model uses non-dimensional equations for the modeling of heat transport and is governed by only 2 parameters. Each parameter pair leads to a solution of a family and represents an infinite number of different scenarios. The model was quantitatively compared to results that were obtained by hydro-thermal 3D simulations of a more complicated EGS model. It was shown that the evolutions of the modeled production temperatures computed by the two models are in close agreement. Thus, for parametric optimization studies the 1D model, which is computationally much more efficient, can be used in place of the more complicated and much more expensive one. An important step, however, is the proper estimation of the two 1D model parameters.

Further, this simplified model was employed to investigate the concept of combined deep and shallow geothermal reservoirs. The model equations were numerically solved and a number of solution families were obtained. Curves that show the time-dependent decline of the produced water temperature were derived for each solution family and for four different EGS working cycles; i.e. three working cycles with a preheater and one without. The electrical energy revenues were computed with the 1D model using realistic. It was found that exploitation from combined deep and shallow reservoirs always produces more electrical energy compared to exploitation from the same reservoirs independently.

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