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# A Hybrid Optimisation Approach to Improve Long-Term Performance of Enhanced Geothermal System (EGS) Reservoirs

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## Abstract

Improving the long-term performance of deep geothermal reservoirs, as an energy source, can lead to a significant increase in efficiency of heat extractions from these assets. This will assist designers, energy firms, managers, and government decision makers to plan and maintain the use of limited available energy resources and hence enhance key sustainable development goals. Enhanced geothermal reservoirs possess a multi-phase behaviour with complex inter-relationship between several parameters that makes the analysis and design of these systems challenging. Often, this challenge is increased when taking into consideration the optimum use of the available resources and induced costs during both creation and exploitation phases. This research presents a novel design approach developed to achieve efficiency and improved long-term performance in doublet enhanced geothermal systems (EGS). The proposed approach is based on an optimisation procedure using a numerical hybrid methodology integrating a multi-objective genetic algorithm with finite element analysis of fully coupled thermal hydraulic processes of reservoirs. The results of the optimisation process are discussed in comparison with data available from a benchmark case study. The results demonstrate a significant improvement in the long-term performance of EGS reservoir, both in terms of thermal power and costs when optimised using the proposed methodology.

**Key words:** Enhanced geothermal system; optimisation; finite element method; thermal drawdown; thermal power production

## 1 Introduction

Geothermal power has been used for many centuries but, mostly extracted from shallow sources and natural hot springs [1]. It is, however, only recently that the technology to exploit hot-dry-rock (HDR) geothermal reservoirs has advanced sufficiently. In 1974, the first HDR deep geothermal reservoir in Los Alamos was developed, where the heat of the subsurface at the depth of between 4 to 5 kilometres was extracted to generate electricity power [2]. This was followed by trials of HDR in the UK at the Rosemanowes Quarry between 1977-1980 [3]. However, the modern process of extracting heat from a

35 deep geothermal reservoir stems from developments in the 1990s where a hot dry rock matrix was  
36 stimulated using hydraulic fracturing at depths over 2.5 kilometres where temperatures of 150-200 °C  
37 exist. This resulted into the development of the so called Enhanced Geothermal System (EGS) [4],  
38 where energy in the form of hot fluid or steam can be produced.

39 In general, geothermal energy, due to its nature, is much more predictable than other renewable sources  
40 of energy; hence it is a popular option in many countries [5]. For example, in China it is predicted that  
41 geothermal reservoirs have the potential to produce enough energy for over 5000 years of China's  
42 annual total energy consumption (i.e.  $95.2 \times 10^{18}$  Joules in 2010), if just 2% of its EGS resources are  
43 recovered [6]. However, due to requirements in advanced technology and economic challenges, as well  
44 as uncertainties that exist at the depths used for EGS [7, 8], EGS is still considered to be at the 'proof  
45 of concept' stage [9]. These challenges have resulted in deserting many geothermal projects, e.g. the  
46 Spa Urach project, Germany, which started in 1977 but was abandoned in 1981 due to financial  
47 problems [10]. Other examples include the Basel Project in Switzerland and Southeast Geysers in the  
48 USA, where they were abandoned because of technical difficulties, see [11] and [12]. Another key  
49 challenge that faces EGS reservoirs is the time taken by the cold fluid front to reach the production well,  
50 known as the thermal breakthrough [13]. This problem was first identified by Gringarten and Sauty [13]  
51 during development of an analytical model for a sedimentary reservoir to optimise the distance between  
52 the injection and production wells in a doublet system with a constant heat for long term production.  
53 The thermal breakthrough of the reservoir has been observed in existing projects such as the geothermal  
54 reservoir in the UK at Rosemanowes Quarry [14] and the Hijiori hot dry reservoir in Japan [15], which  
55 led to abandoning both projects.

56 Due to significant costs involved in field trials of HDR reservoirs [7], computational modelling is  
57 deemed to be an affordable option to enable researchers to investigate possible ways to extend the use  
58 of EGS particularly during the preliminary stages to assess the thermal power and the economic  
59 feasibility of EGS sites [7]. A comprehensive study conducted by [16] on numerical modelling of EGS  
60 reservoirs, indicated that, in general, modelling can be divided into three different categories in terms  
61 of EGS reservoir performance. The first category relates to improving the efficiency of heat extraction  
62 technologies for different rock deposits considering a wide range of contributing temperatures. The  
63 second category aims to evaluate the commercial feasibility of the extracted thermal energy at various  
64 stages of designing prospective resources. The third category estimates the thermal performance of  
65 existing and potential future EGS reservoirs based on the initial thermal energy extraction rate [16]. In  
66 recent decades, different researchers have proposed a variety of numerical modelling strategies to gain  
67 an understanding and explore potential trade-off of the above three key categories [17-20]. These studies  
68 offered some understanding, interpretation and insights into the complex processes taking place in  
69 specific EGS reservoirs. However, they did not probe directly the reservoir design parameters that  
70 influence the long-term performance of EGS reservoirs [16].

71 Recently, several studies have used optimisation approaches in order to achieve efficiency in one or  
72 more aspects of EGS performance. Chen and Jiang [21], used a parametric study to analyse the optimum  
73 design of an EGS multi-wells reservoir. They found that the configuration of production wells in  
74 relation to the injection well affects the reservoir efficiency in terms of heat extraction. However, they  
75 did not consider the change in the distance between the injection and production wells, whilst it has  
76 been shown that this parameter has a significant impact on the reservoir efficiency as stated by [13, 22,  
77 23]. Biagi et al. [24], used a multi-objective genetic algorithm to optimise injection flow rate of Carbon  
78 dioxide (CO<sub>2</sub>) as a working fluid in a geothermal reservoir. The optimisation technique was used to  
79 reduce the impact of CO<sub>2</sub> on the environment in addition to the increase of the power generation for the  
80 long-term performance of EGS reservoirs. Their work can be considered as a management model  
81 assessment tool of the existing sites rather than a way to design EGS reservoirs during the early decision  
82 stages. Chen et al. [23], used a Multivariate Adaptive Regression Spline (MARS) based statistical model  
83 to optimise well positions of a potential geothermal reservoir near Superstition Mountain in Southern  
84 California, USA. They found that the MARS model provides significant improvement when dealing  
85 with the uncertainty of design parameters. Li et al. [25], optimised the design of an EGS based on the  
86 calculation of heat extraction efficiency for long-term performance using finite element analysis and  
87 parametric study of a doublet horizontal wells reservoir. However, they have not considered the impact  
88 of costs over the life of reservoir. Aliyu and Chen [26], conducted a sensitivity analysis on the impact  
89 of artificial and natural design parameters of Soultz reservoir on its long-term performance. They  
90 concluded that the long-term performance of EGS can be enhanced through a strong control of the  
91 investigated parameters, such as temperature and pressure of the injected fluid. However, to make a  
92 decision during the preliminary stage to design a reservoir, there is still a need to develop a new  
93 systematic approach that combines all design parameters in one model. In addition, in previous studies,  
94 inter-relationships of contributing parameters are usually ignored; such oversimplification has been  
95 shown to be insufficient to explain the overall reservoir behaviour [26]. The impact and interaction  
96 between reservoir parameters that influence the overall performance, including the total power and  
97 breakthrough time, are far more complex than simply considering these in isolation.

98 Therefore, it is clear that commercial EGS should combine both design and post-design models in order  
99 to achieve an efficient system. Thus, this has motivated the proposal of the novel approach presented in  
100 this paper to optimise both design and management of EGS reservoirs using a hybrid optimisation  
101 technique. This study integrates finite element (FE) analysis and genetic algorithm (GA) optimisation  
102 technique, to evaluate the influence of design parameters in order to achieve optimal EGS reservoir  
103 design. Via this approach, it will be possible to choose an optimum EGS reservoir design, considering  
104 various key parameters as input variables, with respect to the heat extraction efficiency, commercial  
105 feasibility and reservoir long-term performance. Whilst there are several factors that have impact on the  
106 long-term heat production of an EGS reservoir, it is vital to identify key contributing parameters to

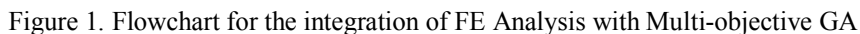
107 ensure suitability of the proposed project. It should be noted that the present study will focus on applying  
108 the proposed technique to the heat extraction process of reservoirs. Results may vary should other  
109 aspects of the system (e.g. energy conversion system on ground) be included in the analyses as reported  
110 by Zhang et al., 2013 [27].

## 111 **2 Methodology and model development**

### 112 **2.1 Integration of the Finite element method with genetic algorithm optimisation**

113 The methodology used in the research presented in this paper is based on a combination of a coupled  
114 heat and mass transfer finite element (FE) procedure with a multi objective genetic algorithm (GA), to  
115 optimise efficiency and performance of enhanced geothermal reservoirs. In this approach, firstly, finite  
116 element models of EGS reservoir are built using randomly selected representative parameters via a  
117 multi-objectives optimisation algorithm. Several scenarios are generated to model an EGS system using  
118 the FE method and each model is evaluated against a set of criteria (i.e. optimisation objectives).  
119 Successful models are taken forward while those models diverging from the optimisation objectives are  
120 abandoned in the next generations. New models are generated using combinations of bioinspired natural  
121 selection functions available in the GA. This process continues until an acceptable tolerance or  
122 maximum number of generations (both defined by the user) have been achieved. The proposed hybrid  
123 approach (i.e. combined FE and GA) allows the exploration of a wide range of FE models to investigate  
124 long-term performance of reservoirs in an efficient and intelligent manner – performing such analysis  
125 using an ordinary FE method alone is unfeasible [28]. Figure 1, shows a flowchart that describes the  
126 process. Further details about the proposed hybrid optimisation approach, and genetic algorithm in  
127 general, can be found in Faramarzi et al. [29].

128

129  Figure 1. Flowchart for the integration of FE Analysis with Multi-objective GA

130 Based on the previous studies and taking into account the long-term performance of EGS reservoirs,  
131 three optimisation objectives are considered in this study; (i) thermal drawdown, (ii) accumulative  
132 thermal power, and (iii) total reservoir cost. These objectives have been selected for optimisation in this  
133 research based on the literature (e.g. [30-32]). Each of these optimisation objectives are briefly  
134 described below:

135 i. Thermal drawdown (*TD*): this parameter is defined as the declination ratio of the production  
136 temperature during heat extraction and it is used to predict the reservoir thermal breakthrough  
137 time [13]. *TD* is calculated using Eq. 1[13]:

$$TD = \frac{T_p - T_o}{T_{inj} - T_o} \quad (1)$$

138 Where,  $T_p$ ,  $T_o$  and  $T_{inj}$  ( $^{\circ}\text{C}$ ) are the production, initial and injected fluid temperature ( $^{\circ}\text{C}$ ),  
 139 respectively. To avoid encountering thermal breakthrough in a reservoir, it has been suggested  
 140 that thermal drawdown must not reach 10% [13, 33, 34]. To account for this important  
 141 performance criterion [30], 10% of  $TD$  is considered as the threshold value during the  
 142 optimisation process used in this study.

143  
 144 ii. The thermal power ( $W_{hp}$ ) is defined as the heat production power of the EGS and is calculated  
 145 based on the first law of Thermodynamics [31], see Eq. 2:

$$W_{hp} = q(h_p - h_{inj}) \quad (2)$$

146 Where  $h_p$  and  $h_{inj}$  (J/kg) are the production and injection specific enthalpies and  $q$  (kg/s) is the  
 147 mass flow rate of the fluid. The accumulative thermal power is calculated up to the end of the  
 148 reservoir service life, which occurs at the breakthrough time, where the thermal power ( $W_{hp}$ ) of  
 149 the reservoir is assumed to be zero at 10% of  $TD$  [33]. The accumulative thermal power is  
 150 ( $\sum W_{hp}$ ) calculated using Eq. 3:

$$\sum W_{hp} = \sum_{t=0}^J W_{hp} \quad (3)$$

151  $J$  (years) is the number of years at the reservoir breakthrough time;  $t$  (years) is the time of  
 152 operation.

153  
 154 iii. The third optimisation objective is the total cost of EGS. The high capital cost of geothermal  
 155 reservoirs and particularly the drilling cost of EGS reservoirs is the main challenge that prevents  
 156 the geothermal power to move from the ‘proof of concept’ stage [9] to become a commercially  
 157 feasible source of energy. The total cost of a reservoir is defined into two parts: the creation  
 158 cost and the operation cost over time. This is explained in details below:

159  
 160 Creation cost: drilling cost has the highest fraction of the total capital cost of the creation stage [32].  
 161 According to Tester and Herzog [35], the drilling cost is ranged anything from 42% to 95% of the power  
 162 plant total creation cost of EGS reservoirs and it is a function of the reservoir depth. Lukawaski *et al.*  
 163 [36], suggested that the drilling cost of each well in the reservoir can be calculated using Eq. 4 [36]:

$$\text{Geothermal well cost } (C_w) = 1.72 * 10^{-7} * D_h^2 + 2.3 * 10^{-3} * D_h - 0.62 \quad (4)$$

164 Where,  $D_h$  (m) is the depth of the reservoir base. Eq. 4 shows that the drilling cost increases non-linearly  
 165 with the increase in the reservoir depth.

166 Operation Cost: The operation cost of heat extraction ( $C_e$ ) of an EGS reservoir is calculated based on  
 167 the following Equation by Kong *et al.* [37].

$$C_e = Q \cdot \sum_{t=0}^J \frac{(\Delta P \cdot pp + \rho_l \cdot c_l \cdot \Delta T \cdot pr \cdot \eta)_t}{(1+r)^t} \quad (5)$$

168 Where  $Q$  (m<sup>3</sup>/s) is the exploited fluid volume;  $\Delta P$  (Pa) is the pressure change at the production well,  $pp$   
 169 (US\$/kWh) is the electrical power price,  $pr$  (US\$/GJ) is the heat price,  $r$  (%) is the discount rate with  
 170 time  $\Delta T$ (K) is the change in production temperature and  $\eta$  is the efficiency of the power plant. The  
 171 values of  $pp$ ,  $pr$  and  $r$  used in this research are reflecting prices in 2012 in Germany. It is worth  
 172 mentioning that the pressure in both injection and production wells are updated as per each finite  
 173 element simulation as well as during the optimisation process.

174 The third optimisation objective, which is the total cost ( $C_t$ ) of the reservoir, can be calculated using  
 175 Eq. 6:

$$C_t = C_w + C_e \quad (6)$$

176 In the present study, the long-term performance of EGS is achieved via maximising thermal power  $W_{hp}$   
 177 and minimising both the thermal drawdown  $TD$  and the total cost  $C_t$  using a bi-objective optimisation  
 178 strategy. This was achieved using an EGS long-term performance criteria proposed by the  
 179 Massachusetts Institute of Technology (MIT) report [38], which considers the reservoir not-productive  
 180 when  $TD$  reaches 10%. In the optimisation algorithm proposed in this study, if the above condition is  
 181 reached in the first ten years of heat extraction process, the design is considered to be redundant. In  
 182 other words, objectives i and ii are combined and will form one objective of the optimisation process  
 183 while the other objective will be the total cost.

184

## 185 **2.2 Governing equations**

186 In general, simulation of heat extraction in an EGS reservoir involves thermal-hydraulic-mechanical  
 187 and chemical (THMC) coupled processes [39, 40]. However, the coupled hydraulic and thermal  
 188 processes, which represent the fluid flow and heat transfer, play the most significant role in the heat  
 189 extraction stage for the long-term performance compared to the other processes [41-43], see further  
 190 discussion in Section 2.3.2.2. Thus, in this paper the mechanical and chemical processes have been  
 191 ignored and only the fully coupled thermal-hydraulic (TH) processes are modelled to assess the long-  
 192 term performance of EGS reservoir. Two energy equations are used to describe both the heat transfer  
 193 in solid rock matrix (conductivity) and the heat transfer between the solid rock matrix and the fracture  
 194 fluid (convection). The time-dependent heat transfer model requires the solution of two sets of



195 differential equations representing the heat transfer in porous media (heat energy conservation) and the  
 196 mass conservation (fluid flow equation).

### 197 2.2.1 Heat transfer:

198 Heat energy conservation and mass balance are the governing equations for the coupled TH processes  
 199 involved in geothermal reservoir. The mathematical model of heat transfer in a porous medium is  
 200 represented by Eqs. 7-10 [3]:

$$(\rho c_p)_{eff} \frac{\partial T}{\partial t} + \rho_w c_{p_f} \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \quad (7)$$

$$\mathbf{q} = -k_{eff} \nabla T \quad (8)$$

$$(\rho c_p)_{eff} = \theta \rho_w c_{p_f} + (1 - \theta) \rho_r c_{p_r} \quad (9)$$

$$k_{eff} = \theta k_f + (1 - \theta) k_r \quad (10)$$

201 Where  $\rho, \rho_f, \rho_r$  are the equivalent, fluid and rock matrix densities ( $\text{kg}/\text{m}^3$ ) respectively;  $c_p, c_{p_f}, c_{p_r}$  are  
 202 the equivalent, fluid and rock matrix heat capacities at constant pressure ( $\text{J}/(\text{kg} \cdot ^\circ\text{C})$ ) respectively;  
 203  $(\rho c_p)_{eff}$  is the equivalent volumetric heat capacity at constant pressure;  $k_{eff}, k_f, k_r$  are the equivalent,  
 204 fluid and rock matrix thermal conductivities ( $\text{W}/(\text{m} \cdot ^\circ\text{C})$ ) respectively;  $\mathbf{u}$  is the Darcy velocity;  $T$  is the  
 205 temperature ( $^\circ\text{C}$ );  $\theta$  is the porosity of the rock matrix;  $Q$  is the heat source/sink term, and  $\mathbf{q}$  is the  
 206 conductivity heat flux of the rock matrix.

### 207 2.2.2 Fluid flow:

208 The mass conservation principle is applied to the hydraulic process. For mass balance, Darcy's Law is  
 209 used assuming a laminar fluid flow. The mathematical model of fluid flow in a porous medium is  
 210 represented by Eqs. 11-12 [3]:

$$\frac{\partial}{\partial t} (\theta \rho_f) + \nabla \cdot (\rho_f \mathbf{u}) = Q_f \quad (11)$$

$$\mathbf{u} = -\frac{k}{\mu} \nabla p \quad (12)$$

211 where  $k$  is the permeability of the porous medium ( $\text{m}^2$ );  $\mu$  the fluid dynamic viscosity ( $\text{Pa} \cdot \text{s}$ );  $Q_f$  the  
 212 fluid sink/source term, and  $p$  is the fluid pressure ( $\text{Pa}$ ).

213 Equations (7) to (12) are solved using the finite element method. Details of the finite element model are  
 214 presented in the next section.

## 215 2.3 The Finite Element Model (FEM)

216 The present research employs a single porosity model in which the geothermal reservoir is described as  
217 a porous medium with single porosity, taking into account both rock natural porosity and the presence  
218 of any fractures. In addition, the work presented in this paper considers an anisotropic equivalent  
219 permeability of the fractured zone.

### 220 2.3.1 Geometry and material properties

221 The Spa Urach geothermal reservoir in Germany is considered as a benchmark scenario for the present  
222 study due to the availability of the necessary data to re-create the finite element models [44]. A three-  
223 dimensional finite element model is developed to simulate the reservoir between 3,850 m and 4,150 m  
224 depth as shown in Figure 2. The temperature gradient is 0.03 °C/m and the reservoir is a doublet well  
225 system which consists of an injection and production wells at a separation distance of 400 m, see Figure  
226 2. The equivalent fracture zone permeability is assumed to be  $1.53e-15$  (m<sup>2</sup>) in the x direction and  $3/8$   
227 of  $k_x$  in the y and z directions [45]. The material properties of the case study are presented in Table 1.

228

229 Figure 2. 3D geometry of the doublet well reservoir used in the FE model [45]

230

231 Table 1. Geometrical parameters and material properties of the FE model (adopted from [45]).

### 232 2.3.2 Initial and Boundary conditions

233 There are two sets of initial and boundary conditions in the present problem. The first set of initial and  
234 boundary values is related to the heat conduction process in the reservoir including the injection well.  
235 The second set of prescribed values consists of the initial and boundary conditions related to the  
236 hydraulic process in the reservoir, including prescribed pressures in the injection and production wells.

237 *2.3.2.1 Initial conditions:* The initial conditions related to both thermal and hydraulic processes are  
238 represented in Figure 3. The initial temperature in the reservoir is assumed to vary linearly with depth  
239 and a temperature gradient ( $T_g$ ) of the Spa Urach site is 0.03 °C/m [45]. The reference temperature  
240 ( $T_{ref}$ ) at a depth of 4445.0 m is 162 °C and the initial distribution of the temperature in the reservoir is  
241 given as a function of depth by Eq. 13 [45]:

$$242 T_o = T_{ref} + T_g(z - 4445) \quad (13)$$

242 Where,  $z$  is depth (m).

243 *2.3.2.2 Boundary conditions:* The fluid in the injection well is assumed to have a constant temperature  
244 of 50 °C as stated by McDermott *et al.* [46]. This corresponds to a Dirichlet boundary condition related  
245 to the heat conduction problem.

246 Fluid pressure in the injection well is assumed to have a prescribed value of 10 MPa at the top surface  
 247 of the reservoir (over-pressurised fluid). This pressure increases linearly with depth as stated by  
 248 McDermott *et al.* [46] according to Eq. 14. The production well is under-pressurised by -10 MPa on the  
 249 top surface and linearly varies according to Eq. 15. On the lateral boundary of the reservoir, which is  
 250 supposed to be at a large distance from the injection and production wells, both isothermal and  
 251 hydrostatic conditions prevail during the whole time period. Hence, no fluid mass or heat flux take place  
 252 through this boundary [47-49], which is enforced by the Neumann boundary conditions Eq. 16 and Eq.  
 253 17.

$$P_{inj} = \rho_f g z + 10 \text{ (MPa)} \quad (14)$$


$$P_{pro} = \rho_f g z - 10 \text{ (MPa)} \quad (15)$$

$$\mathbf{n} \cdot \rho_f \mathbf{u} = 0 \quad (16)$$

$$\mathbf{n} \cdot \mathbf{q} = 0 \quad (17)$$

254 Where,  $P_{inj}$  and  $P_{pro}$  are the injection and production fluid pressures (MPa) respectively, and  $\mathbf{n}$  is the  
 255 outward unit normal vector to the boundary.

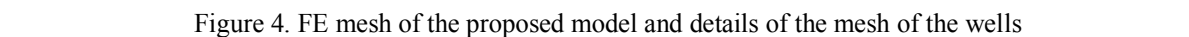
256

257  Figure 3. Initial and boundary conditions for the numerical model [45]

### 258 2.3.3 Meshing

259 The FE mesh is refined around the wells to accommodate the high pressure and thermal gradients, as  
 260 shown in in Figure 4. The mesh size grows outwards to the area surrounding the wells in order to achieve  
 261 a reasonable computational time.

262

263  Figure 4. FE mesh of the proposed model and details of the mesh of the wells

264 Since the hybrid approach can involve millions of runs of FE models, particular attention is paid to the  
 265 meshing to maintain the accuracy of the response while keeping a reasonable computational time. Four  
 266 different mesh sizes were examined: mesh 1 is a coarse mesh which consists of 9709 elements, mesh 2  
 267 is finer than mesh 1, and has 16672 elements, mesh 3 is obtained after further refinement and has 23881  
 268 elements, and mesh 4 is a very fine mesh with 39920 elements. These cases were compared with respect  
 269 to the production mass flow within 50 years of heat extraction, and the results are shown in Figure 5.

270

271 Figure 5. Mesh convergence with response to the production mass flow rate (graph corresponding to mesh 4 is  
272 covering curves 2 and 3)

273 From Figure 5, it is clear that once a certain mesh size is used, there is no further impact on the flow  
274 accuracy. As convergence is achieved with mesh 2, the mesh size corresponding to this mesh has been  
275 selected for the numerical simulations to be presented in the next sections (mesh 2, 3, and 4 are all  
276 providing relatively same curves at the scale presented in Figure 5 and as such it is not possible to  
277 distinguish between them).

## 278 2.4 Validation of the FE model

279 To demonstrate the accuracy of the FE modelling process, COMSOL Multiphysics [50] was used to  
280 replicate the numerical simulation of the Spa Urach geothermal reservoir as a validation problem. The  
281 results obtained with COMSOL Multiphysics (referred to as present work in Figure 6) are compared  
282 with those of [45] where GeoSys/RockFlow code [51] has been used in terms of a production  
283 temperature for a production period of 15 years. The three-dimensional transient FE analysis  
284 corresponding to this benchmark problem, is a fully THM coupled process. The fluid in the injection  
285 well has a pressure of 10MPa and a temperature of 50 °C and reservoir temperature gradient of 0.03  
286 K/m is assumed. In general, the present results and those reported in [45] for the same problem are in  
287 close agreement, as can be seen in Figure 6. The small difference between the results can be attributed  
288 to the modelling of the injection and production wells which are discretised with one dimensional  
289 element 1D in Watanabe *et al.* [45] whereas, taking advantage of the problem symmetry, they could be  
290 modelled as two dimensional 2D half cylinder surfaces in the present study, see Figure 4.

291

292 Figure 6. Comparison of the present FE model and [45]

293 In addition to the above, the present FE model is also validated against the FE simulation conducted by  
294 Chen and Jiang [21] for an artificial reservoir to verify the TH coupled processes with a temperature  
295 gradient of 0.04 °C/m; an injection flow rate of 50 kg/s is considered at an injection temperature of 70  
296 °C. The ground surface temperature is 27 °C. The reservoir has an equivalent permeability of  $1e-14 \text{ m}^2$ .  
297 The simulation of the TH coupled process is performed using a combination of the heat transfer in  
298 porous media and Darcy's Law modules in COMSOL Multiphysics. Hence, mechanical effects are  
299 neglected and the rock matrix is assumed to be rigid. Figure 7, indicates that the values of the production  
300 temperature from the FE model in this paper agree very closely with FE study conducted by [21] for 24  
301 years of heat extraction.

302

303 Figure 7. Comparison of present FE modelling against [21]

### 304 3 Parametric study

305 A parametric study was performed to identify the key variables of the fitness function for the multi-  
306 objectives GA optimisation. The parametric study is limited to those variables of EGS reservoirs that  
307 are typically human-controlled (i.e. design parameters); which in this study, include reservoir depth,  
308 distance between injection and production wells, fluid injection pressure and temperature, and the  
309 equivalent permeability of both fracture and rock matrix network. Figure 8, shows the results of the  
310 parametric study. In these graphs, both objectives are normalised according to their maximum and  
311 minimum values; the breakthrough time varies from 0 to 50 years and the accumulative power varies  
312 from 0 to 200 MW, where these values were selected after a complete sensitivity analysis of the  
313 reservoir design parameters. As mentioned in Section 2 earlier, taking into consideration the threshold  
314 value of  $TD$  at 10 years of heat extraction, 0 for both normalised objectives will refer to the failure of  
315 the reservoir design before 10 years and 1 indicates the maximum values of the objectives.

316 The results are plotted for each key parameter while keeping other parameters constant at their reference  
317 values in Spa Urach project. The results show that the accumulative thermal power ( $\sum W_{hp}$ ) is highly  
318 sensitive to the reservoir depth, well spacing, equivalent permeability of the fractured zone and the  
319 injection pressure. However, both objectives are less sensitive to the injection fluid temperature (Figure  
320 8e). In addition, Figure 8a shows that the breakthrough time is less sensitive to the maximum reservoir  
321 depth. It is worth noting that, the maximum depth of the reservoir has significant impact on the drilling  
322 costs.

323 Figure 8. Sensitivity analysis for the EGS design parameters on both normalised thermal breakthrough time  
324 (dash line) and accumulative thermal power production (solid line) (all parameters are normalised with respect  
325 to their maximum values); where (a) reservoir depth, (b) distance between injection and production wells; (c)  
326 fluid injection pressure.; (d) equivalent permeability of the reservoir; (e) fluid injection temperature

327 Based on the sensitivity analysis, the maximum reservoir depth ( $D_h$ ), distance between the injection and  
328 production wells ( $d$ ), fractured zone permeability ( $k_x$ ) and fluid injection pressure ( $P_{inj}$ ) are selected to  
329 be the optimisation variables. The constraints for these variables are presented in Table 2.

330 Table 2. Constraints of the variables in GA multi-objectives

331 The following points were considered during selection of these constraints:

- 332 • The depth of the reservoir is estimated between 4000-6000 m. This range is assumed as it is  
333 more practical for drilling process [52].
- 334 • The distance between the injection and the production wells in rectangular reservoirs (which is  
335 the case in this research) depends on the industry considerations where the production and the  
336 injection wells should be at the centre of two adjacent circles, which have the same radius,  
337 equal to a half of the reservoir width [53], see Figure 9.

338

339 Figure 9. Industrial consideration for reservoir area based on the Influence zone of each well, after  
340 Wees *et al.* [53]

341 Therefore, based on the industrial consideration, the minimum boundaries of the injection and  
342 production wells are chosen to be at 150m distance from the reservoir edge.

- 343 • The permeability of the fractured zone has values within the range  $10^{-13} \text{ m}^2 - 10^{-16} \text{ m}^2$  [54].
- 344 • The injection pressure is varied between 1MPa to 20 MPa. The value of 20 MPa was determined  
345 after several initial trial and error simulations.

#### 347 4 Results and discussions

348 An algorithm was developed to integrate FE analysis with a GA to find optimum values of the bi-  
349 objective fitness function. The first objective is to minimise the total reservoir cost and the second  
350 objective is to maximise the accumulative thermal power production ( $\sum W_{hp}$ ) of the reservoir at the  
351 breakthrough time. As explained earlier in section 2.1, the thermal drawdown of the reservoir is  
352 implicitly considered in the latter by applying the threshold value of 10%TD during the optimisation  
353 process. The parameters of the Multi-objectives GA optimisation are summarised in Table 3. These  
354 values are chosen based on the number of variables, domain sizes and after a number of trial and errors  
355 simulations.

356 Table 3. Parameters used for the Multi-objective GA in the present research

357 Two scenarios are considered for the optimisation process. In the first scenario, all the design parameters  
358 (i.e.  $D_h$ ,  $d$ ,  $k$  and  $P_{inj}$ ) are included during the optimisation of EGS design. The second scenario is carried  
359 out in order to determine the optimum solutions in the absence of any changes to the reservoir fracture  
360 configuration (i.e. without changing the equivalent permeability of the reservoir). For both scenarios,  
361 the GA-FE optimisation algorithm was run several times using different randomised initial points to  
362 ensure global optimum solutions are achieved. The following sections present the results of the two  
363 optimisation scenarios. The Pareto fronts of both scenarios are illustrated in Figure 10. Figures 10 (a,  
364 b) have been normalised to the minimum and maximum values of each scenario while Figure 10c is  
365 normalised with respect to the combined extreme values.

366 Figure 10. Pareto front of the optimum solutions of both scenarios (with and without changing the equivalent  
367 permeability of the reservoir), (a) 1<sup>st</sup> scenario, (b) 2<sup>nd</sup> scenario and (c) both case scenarios; where S11, S12 and  
368 S13 are the selected best designs in the 1<sup>st</sup> scenario and S21, S22 and S23 are the selected best designs in the 2<sup>nd</sup>  
369 scenario

370 Figure 10, show significant reduction in the value of the first objective (i.e. total cost) particularly in  
371 the first scenario. However, for the second objective (i.e. accumulative thermal power) there is no  
372 significant difference between the two scenarios, values of the second objective are restricted between

373 105-154 MW. In the first scenario, high accumulative thermal power designs have a cost between 75 to  
374 88 Million \$USA, as can be seen in Figure 10a. However, in the second scenario, to achieve a productive  
375 reservoir with high accumulative thermal power, a significantly higher investment is needed (about 110  
376 to 185 Million \$USA), see Figure 10b. Figure 10c presents the optimal trade-off curves of both case  
377 scenarios considered in the present study. The results show the considerable impact of permeability on  
378 the reservoir total cost. It is important to emphasize that this analysis has overlooked the cost of  
379 fracturing the reservoir and is only considering the two scenarios together to highlight the influence of  
380 permeability. The impact of the permeability on the other variables during the optimisation process, is  
381 presented in Figure 11, where the values of the optimised parameters are normalised to the selected  
382 constraints for the GA.

383

384 Figure 11. Maximum values of the normalised variables for both scenarios (with and without changing the  
385 equivalent permeability)

386 The results show that in the first scenario, when all the sensitive parameters vary within the given  
387 ranges, the reservoir extended to a moderate depth. This resulted into a lower drilling cost compared to  
388 the 2<sup>nd</sup> scenario, where the reservoir depth was much higher and corresponded to over 90% of the  
389 normalised depth. This depth was necessary to achieve a higher production temperature, which resulted  
390 into a higher drilling cost. In addition, both scenarios intend to reach about 0.9 of the normalised  
391 distance between the injection and production wells in order to sufficiently reduce the thermal  
392 breakthrough time. Furthermore, the maximum injection pressure in the second scenario is more than  
393 twice of that in the first scenario. The high injection pressure in the second scenario is due to the low  
394 permeability of the reservoir (about half of the maximum permeability of the first scenario) – this has a  
395 significant impact on increasing the operation cost.

396 The process of choosing the best solution from the Pareto front is something open for debate, to some  
397 extent subjective and most importantly depends on the design requirements for specific cases. In this  
398 paper, the minimum distance selection method (TMDSM), also known as Knee point, was used to find  
399 the best optimum solution that satisfies both objectives [55]. All the solutions on Pareto front in Figure  
400 10 can be considered an optimum design for both scenarios, considering the circumstances and the  
401 design requirements. Should both objectives carry equal weights of importance, the minimum distance  
402 to a preferred point, which is (0, 0) in this study, is considered to select the best solution in the Pareto  
403 front. For the first and second scenarios these solutions are shown in Figures 10a and 10b (S11, S12,  
404 S13 and S21, S22, S23). For comparison, these solutions are presented in Figure 12. In this graph,  
405 normalised values of cost and power are both shown for all the cases and are compared with those of  
406 the benchmark case study of the Spa Urach geothermal reservoir. The optimum solutions are sorted  
407 with respect to the total costs.

408

409 Figure 12. Normalised power and cost of the selected best designs (S11, S12 and S13 from 1<sup>st</sup> scenario on  
410 Figure 10(a); S21, S22 and S23 from 2<sup>nd</sup> scenario on Figure 10(b) and the case study

411 In addition, the thermal evolution of two of the best solutions (S11 and S21) are compared to the case  
412 study in this research. It can be seen in Figure 13 that the cold water front in S11 and S21 did not reach  
413 the production well. However, the case study has reached the breakthrough time in early stages which  
414 means that the methodology presented in this paper is proven to be an efficient tool to obtain optimum  
415 designs for EGS reservoirs.

416

417 Figure 13. Thermal evolution of S11, S21 and the case study models

## 418 **5 Conclusions**

419 The purpose of the present study was to develop an advanced systematic approach to enhance long-  
420 term performance of EGS reservoirs. Given that the above is a complex problem that involves several  
421 factors, with inter-relationship between the factors and non-linear, nontrivial behaviour, it was not  
422 possible to use conventional approaches to achieve an optimum design. Therefore, in this research, an  
423 integration of FE analysis and GA optimisation technique was used to develop a methodology to find  
424 optimum designs of EGS reservoirs. This hybrid optimisation approach gives an insightful  
425 understanding of EGS long-term performance regarding the reservoir extraction efficiency, commercial  
426 feasibility and its service life. The research achieved the above objectives by combining both design  
427 and post-design models together.

428 From the results of the sensitivity analysis, it was shown that higher permeability of the fractured zone,  
429 higher fluid injection pressure and shorter distance between the injection and production wells can all  
430 produce higher thermal power at early stages. However, these parameters also have significant  
431 influences on the thermal drawdown and thus lead to the acceleration of the breakthrough time of EGS  
432 reservoirs. Therefore, there is a peak point for the accumulative thermal power when studying each of  
433 the above parameters. On the other hand, higher depth of EGS reservoir enhances the accumulative  
434 thermal power production, while it also results in high creation cost.

435 Taking into account the results of the sensitivity analysis, two scenarios (with and without changing the  
436 equivalent permeability of the reservoir) were considered during the optimisation process to find  
437 potential optimum design of EGS reservoirs. It was observed that the permeability of the reservoir has  
438 a significant influence on the required capital costs for EGS designs. The research also shows that there  
439 is a complex interaction between the reservoir design parameters, which might create challenges for  
440 decision makers regarding both design and post design stages. The proposed methodology, in this paper,  
441 can be used to transform the way EGS reservoirs are currently exploited leading to a sustainable use of



442 these assets. Moreover, it has the flexibility and potential to be adapted during the operation of the EGS  
443 reservoir and/or as further information becomes available.

444

## 445 **References**

- 446 1. Grant, M., Geothermal reservoir engineering. 2013: Elsevier.
- 447 2. Olasolo, P., M. Juárez, M. Morales, and I. Liarte, Enhanced geothermal systems (EGS): A  
448 review. *Renewable and Sustainable Energy Reviews*, 2016. 56: p. 133-144.
- 449 3. Kolditz, O. and C. Clauser, Numerical simulation of flow and heat transfer in fractured  
450 crystalline rocks: application to the hot dry rock site in Rosemanowes (UK). *Geothermics*, 1998. 27(1):  
451 p. 1-23.
- 452 4. Duchane, D. and D. Brown, Hot dry rock geothermal energy development in the USA. Los  
453 Alamos National Laboratory, Los Alamos, NM, 2000.
- 454 5. BP, British Petroleum ,2015, online accessed 27th October 2016  
455 [http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-](http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy/geothermal-power.html)  
456 [energy/renewable-energy/geothermal-power.html](http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy/geothermal-power.html) 2015.
- 457 6. Wang, G., K. Li, D. Wen, W. Lin, L. Lin, Z. Liu, W. Zhang, F. Ma, and W. Wang. Assessment of  
458 geothermal resources in China. in *Proceedings, Thirty–Eighth Workshop on Geothermal Reservoir*  
459 *Engineering*, Stanford University, Stanford, California, February. 2013.
- 460 7. DECC, Deep Geothermal Review Study. 2013, Department of Energy and Climate Change.
- 461 8. GEA, Geothermal Energy Association (GEA). 2013, Geothermal.
- 462 9. Rybach, L. Legal and regulatory environment favourable for geothermal development  
463 investors. in *Proceedings World Geothermal Congress 2010*. 2010.
- 464 10. DiPippo, R., *Geothermal power plants: principles, applications, case studies and*  
465 *environmental impact*. 2012: Butterworth-Heinemann.
- 466 11. Giardini, D., Geothermal quake risks must be faced. *Nature*, 2009. 462(7275): p. 848-849.
- 467 12. Breede, K., K. Dzebisashvili, X. Liu, and G. Falcone, A systematic review of enhanced (or  
468 engineered) geothermal systems: past, present and future. *Geothermal Energy*, 2013. 1(1): p. 1-27.
- 469 13. Gringarten, A. and J. Sauty. The effect of reinjection on the temperature of a geothermal  
470 reservoir used for urban heating. in *Proc. Second UN Symposium on the Development and Use of*  
471 *Geothermal Resources*, San Francisco. 1975.
- 472 14. MacDonald, P., A. Stedman, and G. Symons. The UK geothermal hot dry rock R&D programme.  
473 in *Seventeenth Workshop on Geothermal Reservoir Engineering*. 1992.
- 474 15. Tenma, N., T. Yamaguchi, and G. Zvoloski, The Hijiori hot dry rock test site, Japan: evaluation  
475 and optimization of heat extraction from a two-layered reservoir. *Geothermics*, 2008. 37(1): p. 19-52.
- 476 16. Mudunuru, M., S. Kelkar, S. Karra, D. Harp, G. Guthrie, and H. Viswanathan, *Reduced-Order*  
477 *Models to Predict Thermal Output for Enhanced Geothermal Systems*. 2016.

478 17. He, J., J. Sætrom, and L.J. Durlofsky, Enhanced linearized reduced-order models for subsurface  
479 flow simulation. *Journal of Computational Physics*, 2011. 230(23): p. 8313-8341.

480 18. Kruger, P. and B. Robinson. Heat extracted from the long term flow test in the Fenton Hill HDR  
481 reservoir. in *NINETEENTH WORKSHOP GEOTHERMAL RESERVOIR ENGINEERING*. 1994.

482 19. McClure, M.W. and R.N. Horne, An investigation of stimulation mechanisms in Enhanced  
483 Geothermal Systems. *International Journal of Rock Mechanics and Mining Sciences*, 2014. 72: p. 242-  
484 260.

485 20. Robinson, B.A. and J.W. Tester, Dispersed fluid flow in fractured reservoirs: An analysis of  
486 tracer-determined residence time distributions. *Journal of Geophysical Research: Solid Earth*, 1984.  
487 89(B12): p. 10374-10384.

488 21. Chen, J. and F. Jiang, Designing multi-well layout for enhanced geothermal system to better  
489 exploit hot dry rock geothermal energy. *Renewable Energy*, 2015. 74: p. 37-48.

490 22. Bedre, M.G. and B.J. Anderson, Sensitivity analysis of low-temperature geothermal reservoirs:  
491 effect of reservoir parameters on the direct use of geothermal energy: *Geothermal Resources Council*  
492 *Transactions*. *Geothermal Resources Council Transactions*, 2012. 36: p. 1255-1261.

493 23. Chen, M., A.F. Tompson, R.J. Mellors, and O. Abdalla, An efficient optimization of well  
494 placement and control for a geothermal prospect under geological uncertainty. *Applied Energy*, 2015.  
495 137: p. 352-363.

496 24. Biagi, J., R. Agarwal, and Z. Zhang, Simulation and optimization of enhanced geothermal  
497 systems using CO<sub>2</sub> as a working fluid. *Energy*, 2015. 86: p. 627-637.

498 25. Li, T., S. Shiozawa, and M.W. McClure, Thermal breakthrough calculations to optimize design  
499 of a multiple-stage Enhanced Geothermal System. *Geothermics*, 2016. 64: p. 455-465.

500 26. Aliyu, M.D. and H.-P. Chen, Sensitivity analysis of deep geothermal reservoir: Effect of  
501 reservoir parameters on production temperature. *Energy*, 2017. 129: p. 101-113.

502 27. Zhang, F.Z., Jiang, P.X. and Xu, R.N., 2013. System thermodynamic performance comparison  
503 of CO<sub>2</sub>-EGS and water-EGS systems. *Applied Thermal Engineering*, 61(2), pp.236-244.

504 28. Javadi, A.A., A. Faramarzi, and R. Farmani, Design and optimization of microstructure of  
505 auxetic materials. *Engineering Computations*, 2012. 29(3): p. 260-276.

506 29. Faramarzi, A., A.M. Alani, and O. Harireche, A hybrid approach to design materials with  
507 negative linear compressibility. *Computational Materials Science*, 2013. 79: p. 971-976.

508 30. Bødvarsson, G.S. and C.F. Tsang, Injection and thermal breakthrough in fractured geothermal  
509 reservoirs. *Journal of Geophysical Research: Solid Earth*, 1982. 87(B2): p. 1031-1048.

510 31. Pruess, K., Enhanced geothermal systems (EGS) using CO<sub>2</sub> as working fluid—a novel approach  
511 for generating renewable energy with simultaneous sequestration of carbon. *Geothermics*, 2006.  
512 35(4): p. 351-367.

513 32. Tester, J., H. Herzog, Z. Chen, R. Potter, and M. Frank, Prospects for universal geothermal  
514 energy from heat mining. *Science & Global Security*, 1994. 5(1): p. 99-121.

515 33. Renner, J., *The Future of Geothermal Energy*. 2006, Idaho National Laboratory (INL).

- 516 34. Richards, H., R. Parker, A. Green, R. Jones, J. Nicholls, D. Nicol, M. Randall, S. Richards, R.  
517 Stewart, and J. Willis-Richards, The performance and characteristics of the experimental hot dry rock  
518 geothermal reservoir at Rosemanowes, Cornwall (1985–1988). *Geothermics*, 1994. 23(2): p. 73-109.
- 519 35. Tester, J.W. and H.J. Herzog, The economics of heat mining: An analysis of design options and  
520 performance requirements of hot dry rock (HDR) geothermal power systems. *Energy Syst. Policy*,  
521 1991. 25: p. 33-63.
- 522 36. Lukawski, M.Z., B.J. Anderson, C. Augustine, L.E. Capuano, K.F. Beckers, B. Livesay, and J.W.  
523 Tester, Cost analysis of oil, gas, and geothermal well drilling. *Journal of Petroleum Science and*  
524 *Engineering*, 2014. 118: p. 1-14.
- 525 37. Kong, Y., Z. Pang, H. Shao, and O. Kolditz, Optimization of well-doublet placement in  
526 geothermal reservoirs using numerical simulation and economic analysis. *Environmental Earth*  
527 *Sciences*, 2017. 3(76): p. 1-7.
- 528 38. Tester, J.W., B. Anderson, A. Batchelor, D. Blackwell, R. DiPippo, E. Drake, J. Garnish, B. Livesay,  
529 M.C. Moore, and K. Nichols, The future of geothermal energy: Impact of enhanced geothermal  
530 systems (EGS) on the United States in the 21st century. Massachusetts Institute of Technology, 2006.  
531 209.
- 532 39. Karrech, A., Non-equilibrium thermodynamics for fully coupled thermal hydraulic mechanical  
533 chemical processes. *Journal of the Mechanics and Physics of Solids*, 2013. 61(3): p. 819-837.
- 534 40. Taron, J. and D. Elsworth, Thermal–hydrologic–mechanical–chemical processes in the  
535 evolution of engineered geothermal reservoirs. *International Journal of Rock Mechanics and Mining*  
536 *Sciences*, 2009. 46(5): p. 855-864.
- 537 41. Bataillé, A., P. Genthon, M. Rabinowicz, and B. Fritz, Modeling the coupling between free and  
538 forced convection in a vertical permeable slot: Implications for the heat production of an Enhanced  
539 Geothermal System. *Geothermics*, 2006. 35(5): p. 654-682.
- 540 42. Finsterle, S., Y. Zhang, L. Pan, P. Dobson, and K. Oglesby, Microhole arrays for improved heat  
541 mining from enhanced geothermal systems. *Geothermics*, 2013. 47: p. 104-115.
- 542 43. Neuville, A., R. Toussaint, and J. Schmittbuhl, Fracture roughness and thermal exchange: A  
543 case study at Soultz-sous-Forêts. *Comptes Rendus Geoscience*, 2010. 342(7): p. 616-625.
- 544 44. Tenzer, H., U. Schanz, and G. Homeier. HDR research programme and results of drill hole Urach  
545 3 to depth of 4440 m—the key for realisation of a hdr programme in southern Germany and northern  
546 Switzerland. in *Proceedings World Geothermal Congress 2000*. 2000.
- 547 45. Watanabe, N., W. Wang, C.I. McDermott, T. Taniguchi, and O. Kolditz, Uncertainty analysis of  
548 thermo-hydro-mechanical coupled processes in heterogeneous porous media. *Computational*  
549 *Mechanics*, 2010. 45(4): p. 263-280.
- 550 46. McDermott, C.I., A.R. Randriamanjatoa, H. Tenzer, and O. Kolditz, Simulation of heat  
551 extraction from crystalline rocks: The influence of coupled processes on differential reservoir cooling.  
552 *Geothermics*, 2006. 35(3): p. 321-344.
- 553 47. Pashkevich, R.I. and V.V. Taskin. Numerical simulation of exploitation of supercritical  
554 enhanced geothermal system. in *Proceedings of thirty-fourth workshop on geothermal reservoir*  
555 *engineering*. Stanford (California): Stanford University. 2009.

556 48. Sanyal, S.K. and S.J. Butler, An analysis of power generation prospects from enhanced  
557 geothermal systems. Geothermal Resources Council Transactions, 2005. 29.

558 49. Vörös, R., R. Weidler, L. de Graaf, and D. Wyborn. THERMAL MODELLING OF LONG TERM  
559 CIRCULATION OF MULTI-WELL DEVELOPMENT AT THE COOPER BASIN HOT FRACTURED ROCK (HFR)  
560 PROJECT AND CURRENT PROPOSED SCALE-UP PROGRAM. in Proceedings of the Thirty-Second  
561 Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA. 2007.

562 50. COMSOL-Multiphysics, INTRODUCTION TO COMSOL Multiphysics: Version 5.2a. Stockholm,  
563 Sweden: COMSOL AB. 2016.

564 51. Kolditz, O. and H. Shao, Developer Benchmark Book on THMC Components of Numerical  
565 Codes GeoSys/Rockflow V. 4.9. Helmholtz Centre for Environmental Research (UFZ), Leipzig, 2009.

566 52. Heidinger, P., Integral modeling and financial impact of the geothermal situation and power  
567 plant at Soultz-sous-Forêts. Comptes Rendus Geoscience, 2010. 342(7): p. 626-635.

568 53. van Wees, J., L. Kramers, R. Kronimus, M. Pluymaekers, H. Mijnlieff, and G. Vis, ThermoGIS  
569 TM V1. 0 Part II: Methodology. 2010.

570 54. Kosack, C., C. Vogt, V. Rath, and G. Marquart. Stochastic estimates of the permeability field of  
571 the Soultz-sous-Forêts geothermal reservoir-comparison of Bayesian inversion, MC geostatistics, and  
572 EnKF assimilation. in EGU General Assembly Conference Abstracts. 2010.

573 55. Hussain, M.S., Numerical Simulation and Effective Management of Saltwater Intrusion in Coastal  
574 Aquifers, PhD Thesis, University of Exeter, 2015.

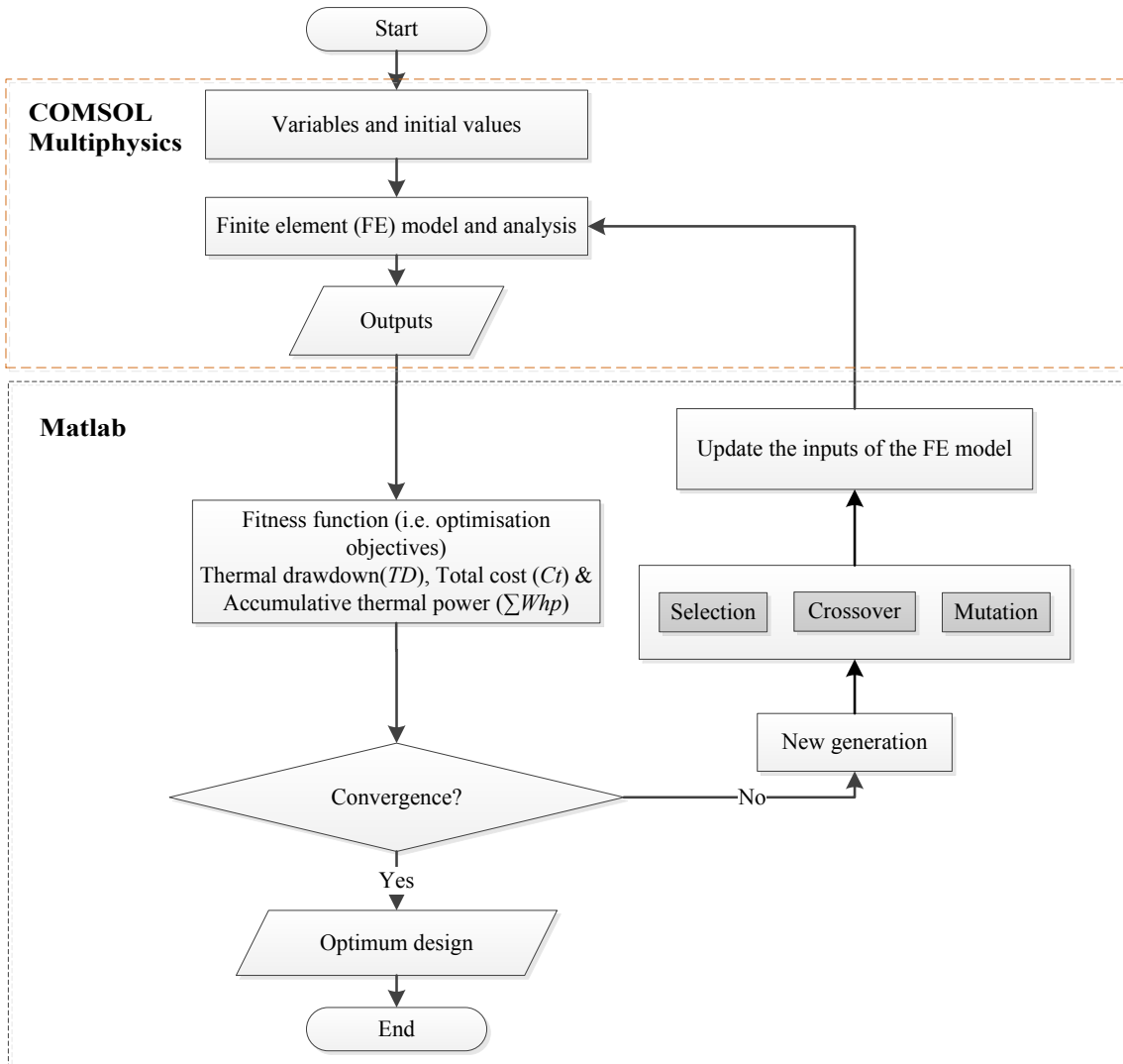


Figure 1. Flowchart for the integration of FE Analysis with Multi-objective GA

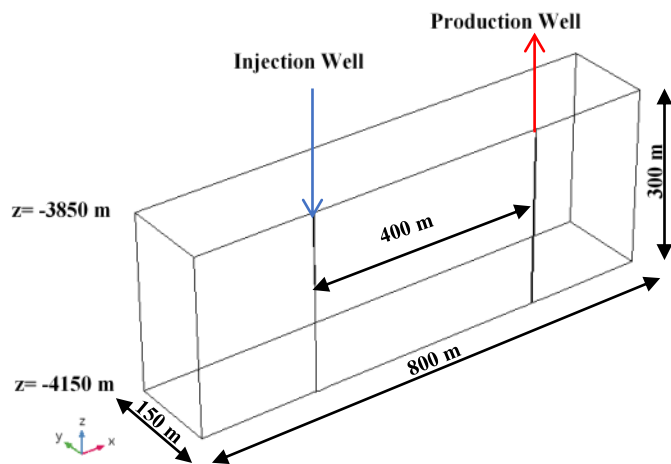


Figure 2. 3D geometry of the doublet well reservoir used in the FE model [44]



Figure 4. FE mesh of the proposed model and details of the mesh of the wells

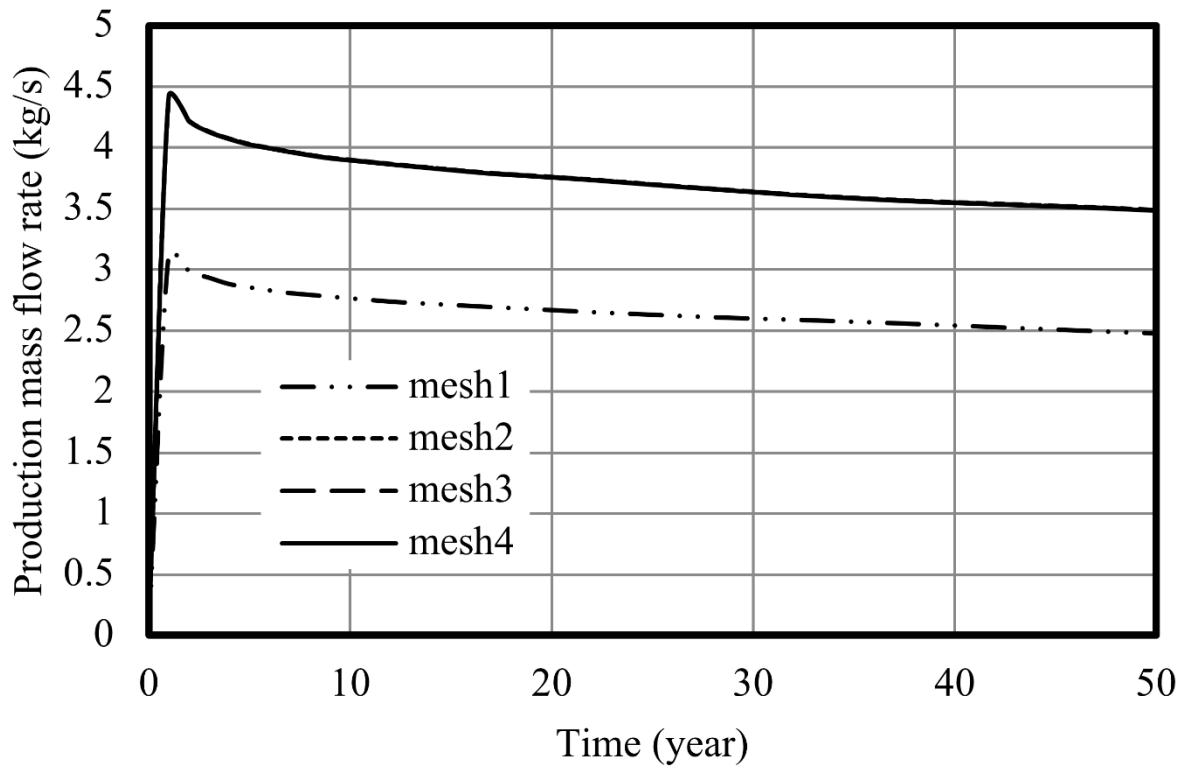


Figure 5. Mesh convergence with response to the production mass flow rate (graph corresponding to mesh 4 is covering curves 2 and 3)

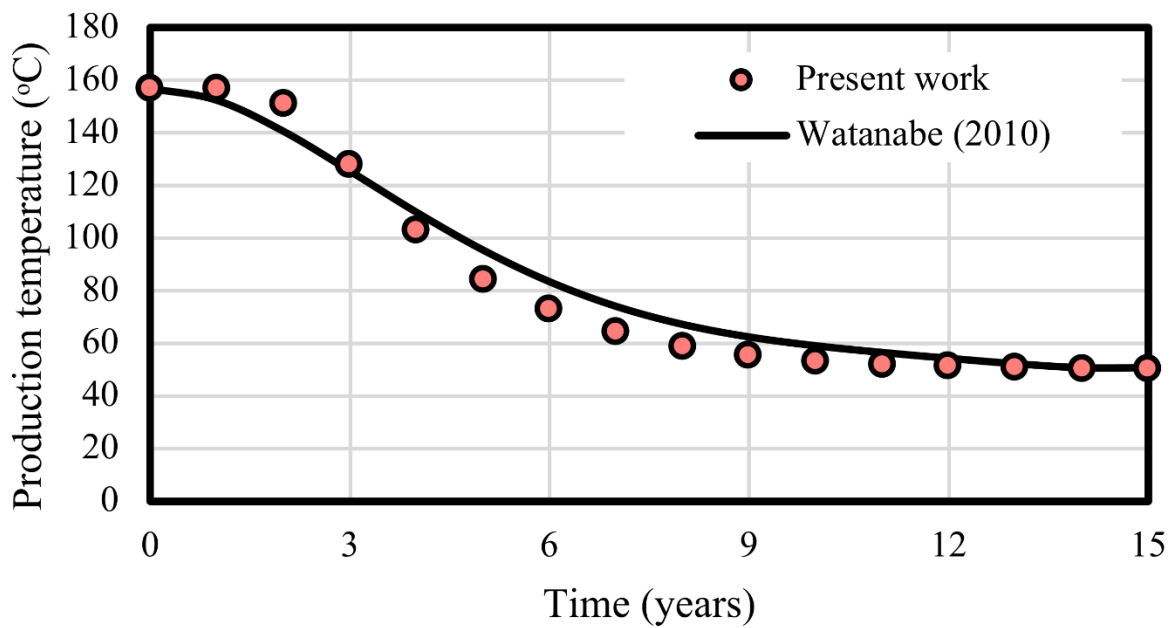


Figure 6. Comparison of the present FE model and [44]

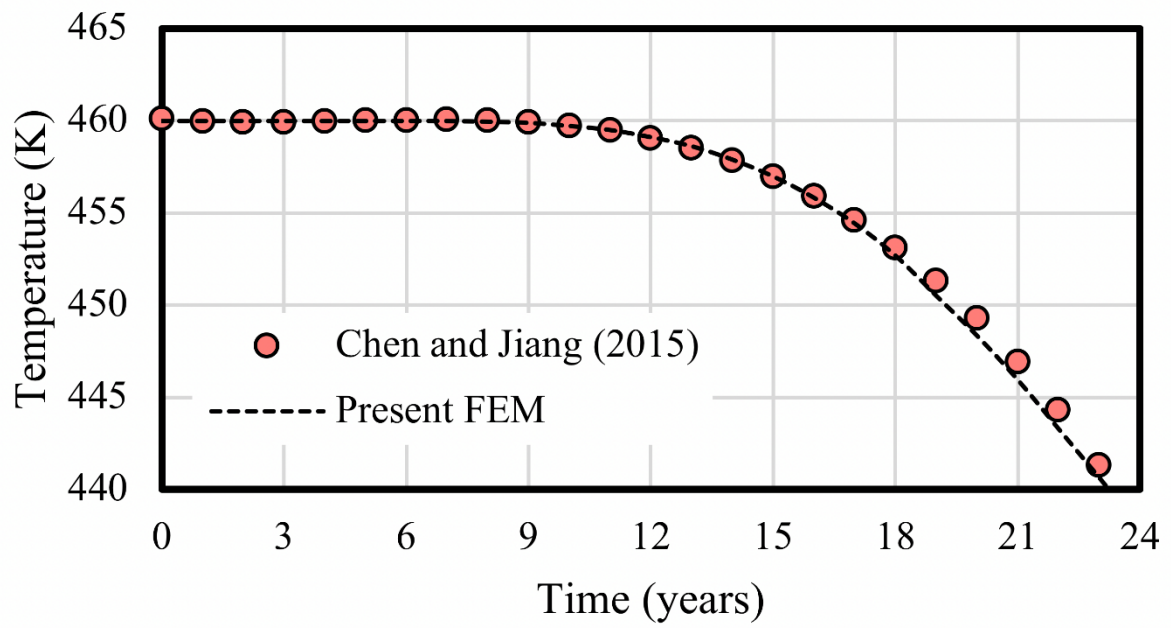


Figure 7. Comparison of present FE modelling against [21]



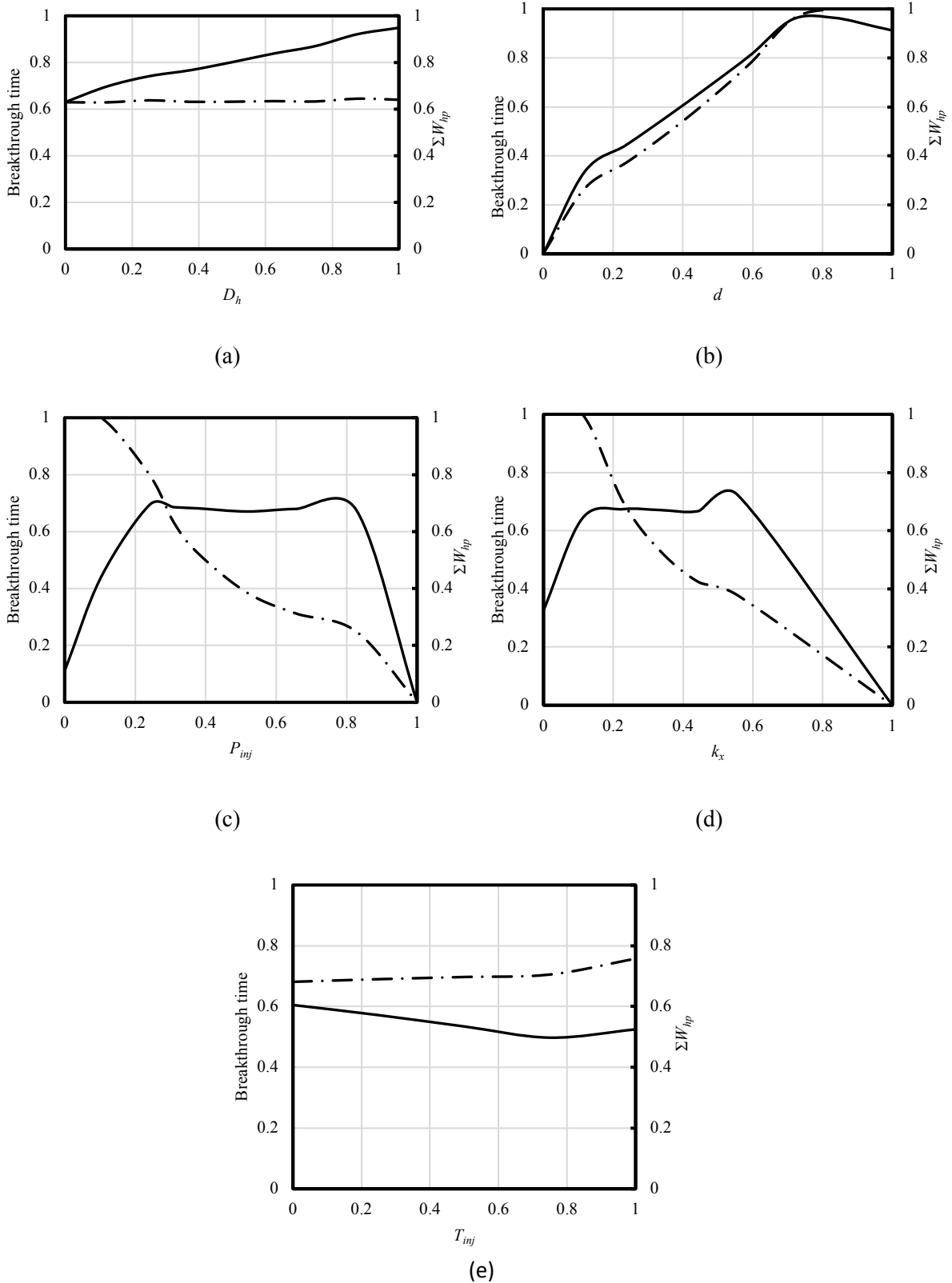


Figure 8. Sensitivity analysis for the EGS design parameters on both normalised thermal breakthrough time (dash line) and accumulative thermal power production (solid line) (all parameters are normalised with respect to their maximum values); where (a) reservoir depth, (b) distance between injection and production wells; (c) fluid injection pressure.; (d) equivalent permeability of the reservoir; (e) fluid injection temperature

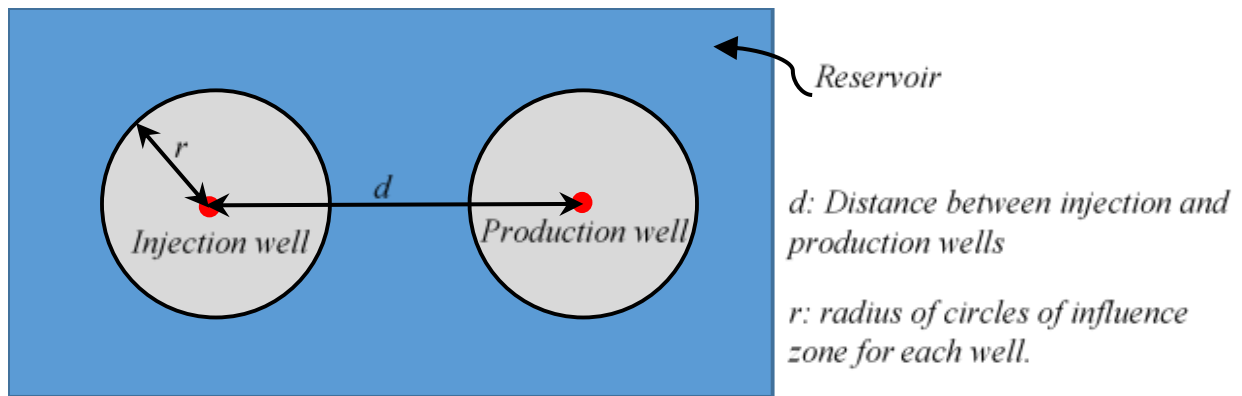
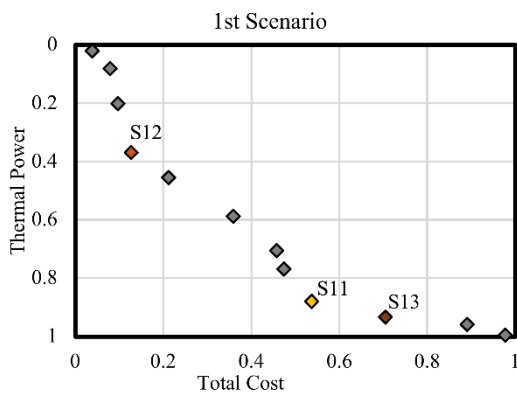
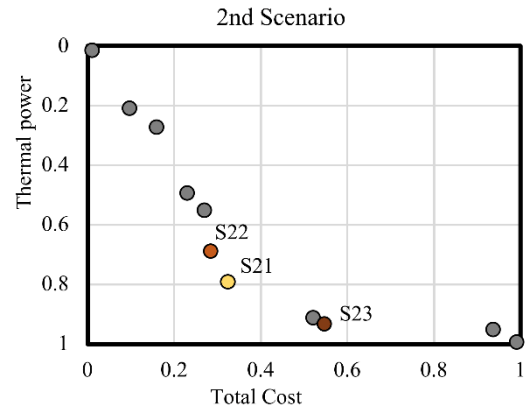


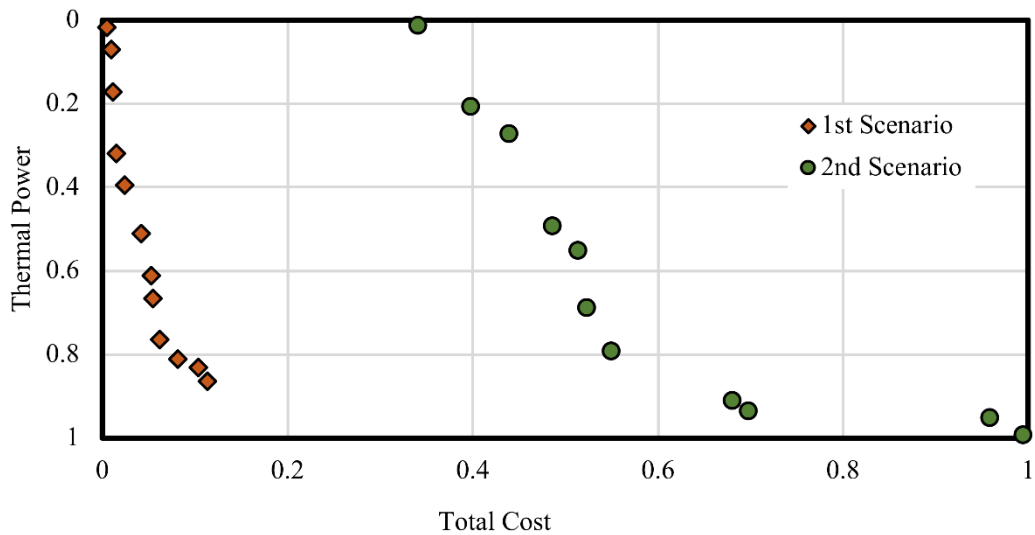
Figure 9. Industrial consideration for reservoir area based on the Influence zone of each well, after Wees *et al.* [52]



(a)



(b)



(c)

Figure 10. Pareto front of the optimum solutions of both scenarios (with and without changing the equivalent permeability of the reservoir), (a) 1<sup>st</sup> scenario, (b) 2<sup>nd</sup> scenario and (c) both case scenarios; where S11, S12 and S13 are the selected best designs in the 1<sup>st</sup> scenario and S21, S22 and S23 are the selected best designs in the 2<sup>nd</sup> scenario

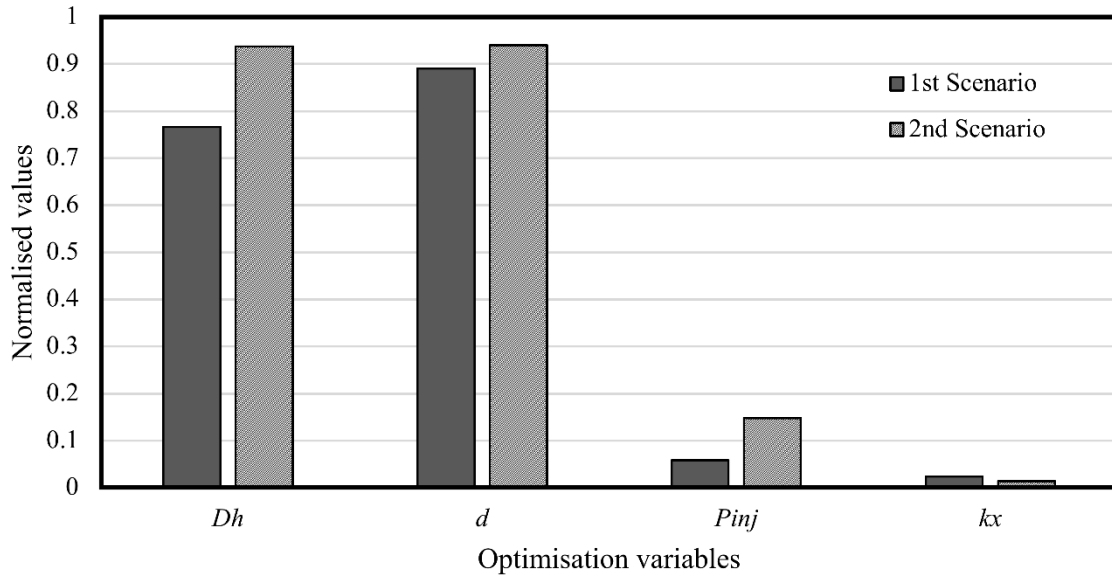


Figure 11. Maximum values of the normalised variables for both scenarios (with and without changing the equivalent permeability)

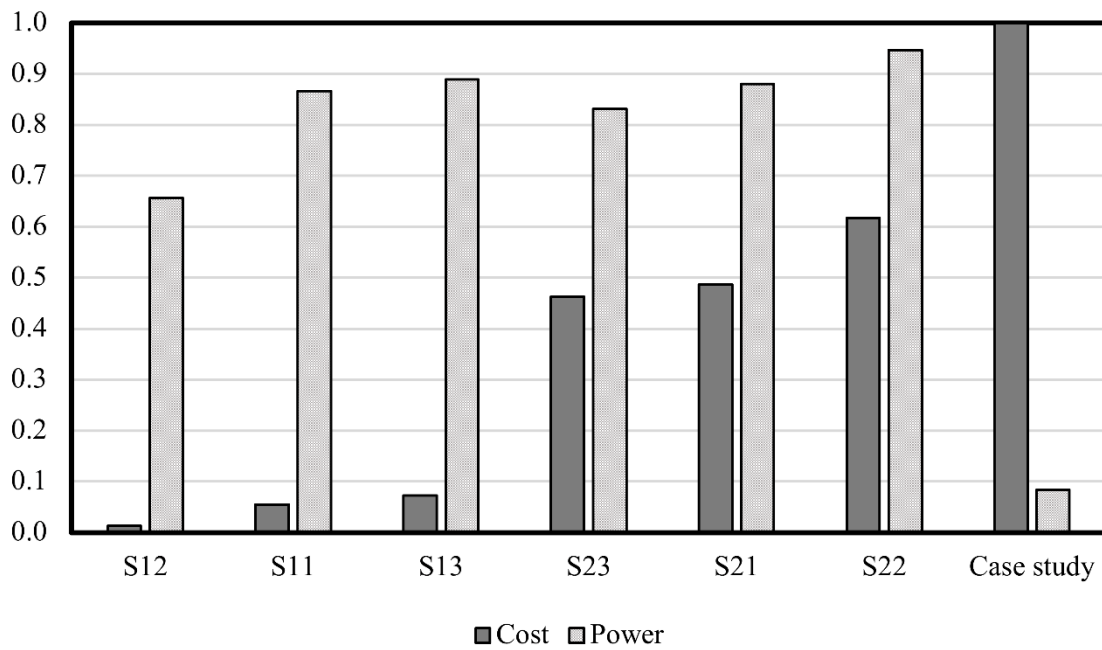


Figure 12. Normalised power and cost of the selected best designs (S11, S12 and S13 from 1<sup>st</sup> scenario on Figure 10(a); S21, S22 and S23 from 2<sup>nd</sup> scenario on Figure 10(b) and the case study)

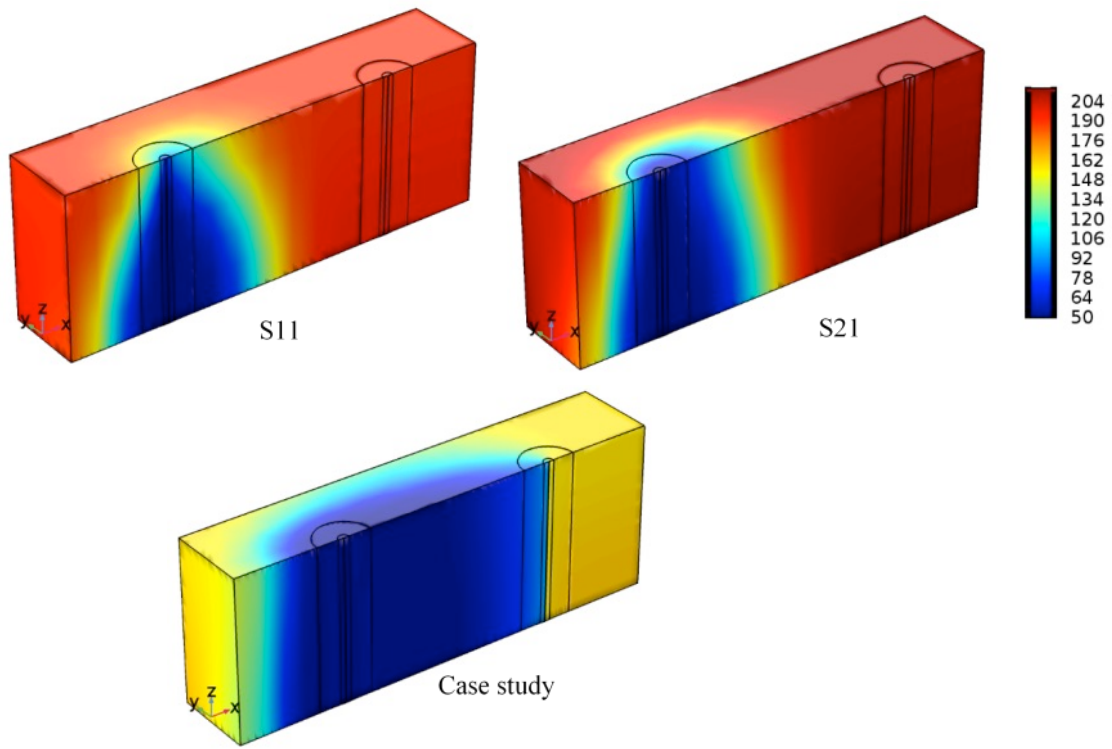


Figure 13. Thermal evolution of S11, S21 and the case study models

Table 1. Geometrical parameters and material properties of the FE model (adopted from [44]).

Parameters		Symbols	Value	Unit
Rock matrix	Domain length	$L_r$	800	m
	Domain width	$W_r$	300	m
	Domain height	$H_r$	300	m
	Reservoir surface depth	$D_s$	3850	m
	Reservoir base depth	$D_h$	4150	m
	Density	$\rho_r$	2750	kg/m <sup>3</sup>
	Permeability	$k$	$k_x=1.53e-15, k_y=k_z=3/8*k_x$	m <sup>2</sup>
	Porosity	$\phi$	0.005	
	Specific heat capacity	$c_{pr}$	850	J/(kg.°C)
	Thermal conductivity	$k_r$	3	W/(m.°C)
Injection fluid	Density	$\rho_f$	1000	kg/m <sup>3</sup>
	Specific heat capacity	$c_{pf}$	4210	J/(kg.°C)
	Thermal conductivity	$k_f$	0.6	W/(m.°C)
	Dynamic viscosity	$\mu$	2e-4	Pa.s
Others	Well length	$L_w$	300	m
	Well diameter	$d_w$	1	m
	Well separation distance	$d$	400	m
	Reference temperature at 4445.0 m	$T_{ref}$	162	°C
	Temperature gradient	$T_g$	0.03	°C/m

Table 2. Constraints of the variables in GA multi-objectives

Constraints	Variables			
	Maximum reservoir depth $(D_h)^a$	Well positions $(d)^b$	Fracture zone permeability $(k_x)^c$	Injection fluid pressure $(P_{inj})^d$
	m	m	m <sup>2</sup>	MPa
Lower bound	4000	300	1e-13	1
Upper bound	6000	500	1e-16	20

Note: values cited are based on a) [51], b) [52], c) [53] and d) trial and errors.

Table 3. Parameters used for the Multi-objective GA in the present research

Number of Populations	50
Maximum generation number	400
Selection	Tournament size 2
Crossover	0.7
Mutation	Constraint dependent