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Performance of low-enthalpy geothermal systems: Interplay of spatially correlated heterogeneity and well-doublet spacings

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HIGHLIGHTS

• 2600 computationally intensive simulations for geothermal doublet systems conducted.
• Discharge, well/doublet spacing, poro-perm correlation lengths and variance varied.
• A doublet spacing equal to well spacing produced consistently best performance.
• Anisotropic heterogeneity led to shorter/longer lifetime for short/long spacing.
• Sufficient lifetime for shorter well spacing than the ones conventionally designed.

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ABSTRACT

The low-enthalpy geothermal systems are commonly deployed in sedimentary geological settings that feature significant levels of deposition-induced heterogeneity. In this paper, realistic levels of heterogeneity in the form of varying porosity variance and spatial correlation lengths are considered for a 3D geothermal system. Using 2600 computationally intensive numerical simulations of two doublets placed in a checkboard pattern, the influence of well and doublet spacings on performance metrics of low-enthalpy geothermal systems are investigated. The simulations strongly support that in varyingly heterogeneous systems, the lifetimes of operation are shorter, and depending on isotropicity or anisotropicity of correlated heterogeneity, the lifetimes vary. Most notably the anisotropically correlated heterogeneity can lead to either positive impact (by diverting the cold water plume) or negative impact (by facilitating an early breakthrough of cold water plume) on the lifetime of the operation compared to isotropically correlated heterogeneity. We also calculate the boundary of the region around the wells designated as the “license area” (where the cold water front reaches to or where a threshold temperature drop of 1 °C occurs). By doing so, it is found that the operator can assume larger extents (of up to 50%) for the license areas of the aquifer than the ones conventionally assumed. To minimize the impact of heterogeneity on operation, the best practice was found to place the doublets in the same spacings as of the wells. Moreover, it is found that the well distance can be significantly shorter than what is commonly realised for heterogeneous geothermal aquifers.

1. Introduction

Many of the low-enthalpy deep geothermal systems are deployed in sedimentary reservoirs at depths between 2 and 2.5 km with a temperature between 70 and 90°C [1]. The most common method of geothermal energy recovery from low-enthalpy aquifers are doublet systems that utilize two wells, one for hot water production and another for cold water injection. The lifetime of the doublet (how long the doublet can produce economically), energy sweep (produced energy compared to the total amount of available energy) and energy production rate of doublets determine the performance of doublet systems. The accuracy of predictive simulation tools is essential for the successful design of doublet systems.

The sedimentary reservoirs are characterised by their lithographical, geological, structural and thermal properties. These characteristics govern the geothermal performance indicators. Various
studies have focused on influence of some of the above-mentioned characteristics on doublet performances. For example, Poulsen et al. [2] investigated the impact of thermal conductivity. Several authors focused on brine viscosity and density dependence on temperature, e.g., Ma & Zheng [3] found that mean discrepancy between the simulated temperature distributions with and without considering the effects of variable density and viscosity is approximately 2.5%. Using a numerical study on density and viscosity variations with temperature, Saeid et al. [4] found that ignoring the variations leads to overestimation of the geothermal system lifetime in hot injection scenarios, and underestimation of the system lifetime in cold injection scenarios. Mottaghy et al. [5] showed that thermal and hydrogeological data are crucial to planning geothermal resource development, and numerical codes should take temperature dependence of thermal properties into account. Vogt et al. [6] demonstrated the importance of accounting for heterogeneity of rock parameters resulting in significant variations of production temperature and well pressure with time.

Several authors including [7–10] studied impacts of well spacing. Saeid et al. [7] showed that the lifetime increases linearly with the well spacing for homogeneous aquifers with no geological complexity or barriers. Willems et al. [8], also for homogeneous aquifers only, optimized well spacing so that the interference between the aquifers are minimized. Pandy & Vishal [9] showed that, for homogeneous aquifers again, at higher well spacing, the flow length/volume increased and so did the pumping power, leading to improved overall performance in heat extraction. Willems et al. [10], for homogeneous aquifers, evaluated both the possible financial advantage of well spacing reduction and its impact on doublet life time.

A recent review of Pandey et al. [11] on geothermal reservoirs coupled thermo-hydro-mechanical-chemical approaches shows that the impact of aquifer heterogeneity on performance of doublets is less studied. The presence of spatial heterogeneity inside a reservoir may induce flow channeling and reduce the volume of reservoir participating in flow fields [11]. Most of the studies on performance of low enthalpy systems, as referred above, have considered homogeneous systems or simple lithographical variations. There are only few existing research works that specifically deal with heterogeneity for geothermal doublet systems [12,6,13–16]. Watanabe et al. [12] found that the most significant factors in the analysis of thermo-hydro-mechanical coupled processes in heterogeneous porous media are permeability and heat capacity. Vogt et al. [6] studied the transient temperature and pressure at the production well for 400 sets of heterogeneous realizations of the fault zone in a doublet system. The authors concluded that the distribution of porosity/permeability and thermal conductivity inside the fault zone significantly impact heat extraction rate from the reservoir. Crooijmans et al. [13] studied the impact of heterogeneity in a fluvial system for a single doublet and they have suggested a correlation for the lifetime as a function of production rate and net-to-gross values. The authors showed that at lower net-to-gross ratio the temperature drop at the production well was slower than the higher net-to-gross ratio for all sets of the heterogeneous reservoirs. Willems et al. [14] studied the impact of heterogeneity on the connectivity in geothermal systems. The authors found that the impact of heterogeneity is significant on heat production and pumping loss was less if the wells were placed parallel to the paleo flow direction. Niederau et al. [15] studied the effect of spatially heterogeneous permeability on the formation and shape of hydrothermal porous flow in the Yarragadee aquifer, Australia. Their results showed the spatially heterogeneous permeability can affect the local convection patterns. Very recently, Liu et al. [16], showed that for a doublet system with increasing correlation length, the possibility of flow channels appearing in well pair system increases, causing a short average thermal breakthrough time and a lower surface settlement around the injection well.

For heterogeneous aquifers, attention has been also mostly paid to geothermal doublet systems with fracture networks. Performance of deep geothermal doublets in fractured reservoirs have been studied either for a single fracture [17], parallel fractures [18] or complex fracture networks [19–21]. Salimzadeh et al. [20] showed that both heat production and required pump energy is very sensitive to fracture spacing, density and connectivity. Pandey & Chaudhuri [22] studied the impact of fracture aperture heterogeneity on geothermal heat recovery in fractured aquifers and found that small correlation lengths in fracture sets do not create much variation in temperature at production well while [23] illustrated the aperture variation induced by thermal or chemical stresses can significantly influence the performance of the geothermal system. Vasilyeva et al. [19] developed multiscale model of heat and flow transport in EGS systems with varying degree of fracturisation. No systematic works, however, have been carried out on geothermal doublet systems to delineate the impact of heterogeneity on well or doublet spacing.

An important design factor for geothermal doublets is the required distance between wells in a doublet system as well as the distance between the multiple doublets. There are research studies dealing with the optimisation of low-enthalpy doublets [24,25]. Chen et al. [24] coupled a complex hydrothermal simulation model and a multivariate adaptive regression spline-based surrogate model to investigate the

Fig. 1. The doublets configuration and the license-boundary control region of the subsurface system used in this study.
effects of geological uncertainties (fault size and geological unit permeability) on optimal well placement and control (re-injection well location, production rate) in a geothermal prospect near Superstition Mountain in Southern California, USA. The model used was homogeneous, so that in each case a constant permeability was chosen in the range of \(-13.8 < \log(\text{perm}) [\text{m}^2] < -13.3\). The authors found the optimal production rate is 30.7 kg/s and distance between production and injection well is 473 m in order to maximize the net profit after 50 years of potential geothermal extraction. Kong et al. [25] used numerical modelling, economic analysis and a homogeneous domain of a synthetic aquifer and obtained an optimal well placement of 400 m.

There are no existing work specifically focusing on well/doublet spacing for heterogeneous geothermal systems. The area of research is important because administering a sub-optimal well/doublet spacing can potentially lead to negative interferences that, in turn, may influence the utilisation efficiency of wells and doublet systems. An accurate modelling-based design that provides optimal solutions will prevent such interferences. Currently, thermal breakthrough which is the moment when the extent of re-injected cold water plume reaches the production wells is the basis to determine production lifetimes as an indicator for the temperature drop at the license boundary. However, the license areas temperature may not immediately drop to non-economic values when thermal breakthrough occurs at production wells. As a result, thermal energy is still available in economic levels and heat production could continue after thermal breakthrough as long as the average temperature at the license boundary has not experienced notable temperature drop (i.e. >1 °C). The temperature drop over the license area’s boundary can instead be used to determine the lifetime of the geothermal doublet systems. This can obtained utilising accurate and realistic production simulations. The temperature distribution and shape of cold water front are strongly controlled by underlying heterogeneities in the geological properties of geothermal aquifers.

To address above-mentioned knowledge gap in the design of geothermal system, in this study, we address the following questions.

1. How does well spacing or doublet spacing under different levels of heterogeneity impact performance of the geothermal system? The performance criteria include lifetime of the operation, energy or

Fig. 2. The porosity fields (mD) fields for four correlation lengths times two variances. The first four fields are for \(\sigma^2 = 0.02\) (C1, C2, C3 and C4) and the second four fields are for \(\sigma^2 = 0.04\) (C1, C2, C3 and C4).
thermal sweep efficiency, energy production, and coefficients of performance.

2. What is the correlation between temperature drop in the production wells and that of license boundary?

3. How significant is the impact of heterogeneity on well spacing design?

To address these questions, we use a numerical simulation tool described in Section 2 alongside the geological properties, heterogeneous property generation, heat recovery scenarios as functions of well or doublet spacing and definition of performance metrics. The results and discussions are presented in Section 3 and the paper is concluded in Section 4.

By answering the above-mentioned research questions, we provide a novel unprecedented understanding of interplay between “realistically-represented fluvial aquifer heterogeneity and geothermal doublet

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Table 1
A summary of simulation varying parameters considered for heterogeneous simulations (total number of simulations are $2 \times 2 \times 4 \times 5 \times 4 \times 8 = 2,560$).

| Parameter                  | Variance of porosity fields ($\sigma^2$) | Injection rate ($Q$) | Well spacing ($L$) | doublet spacing ($dx/L$) | Correlation lengths ($c_x$ and $c_y$) | Realizations ($r$) |
|----------------------------|------------------------------------------|----------------------|--------------------|--------------------------|---------------------------------------|-------------------|
| Magnitudes                 | 0.02 and 0.04                            | 150 m$^3$/h and 250 m$^3$/h | 500 m, 700 m, 900 m, and 1100 m | 0.7, 0.85, 1, 1.15 and 1.3 | 100 m and 500 m varied directionally | C1, C2, C3 and C4 |
| Notations                  | v1 and v2                                | Q1 and Q2            |                    |                          |                                      |                   |
| Number of cases            | 2                                        | 2                    | 4                  | 5                        | 4                                     | 8                 |
design”. This is of direct relevance to subsurface energy application and geothermal heat recovery.

2. Methodology

The numerical simulations are carried out by ECLIPSE E300 simulator [26]. Previously for geothermal heat recovery simulations (including low-enthalpy doublets or deep enhanced geothermal systems), the simulator have been successfully employed [27]. Here, a multi-parametric analysis is carried out on the simulation results to delineate the interplay of heterogeneity and well or doublet spacing. In the following, first we describe the methodology including a brief description of the governing equations for coupled heat transfer and flow in porous media, the geological model considered with heterogeneities of porosity and permeability fields, the simulation scenarios and the performance metrics.

2.1. Coupled heat transfer and flow in porous media

To simulate coupled heat transfer and flow in porous media, a fully implicit finite volume method utilising a two-point flux approximation scheme is employed. The flow and heat transfer solves a coupled problem integrating (i) the conservation equation for each fluid component (water) in each gridblock at each timestep (leading to the non-linear residual $r_f$), and (ii) the energy conservation equation in each gridblock at each timestep (leading to the non-linear residual $r_e$):

$$r_f = \frac{d}{dt} (V_p m) + F + Q = 0 \quad (1)$$

$$r_e = \frac{d}{dt} (V_p e) + F + C_e + Q_{in} + Q_{out} = 0 \quad (2)$$

where $m$ is the moles of fluid component (water) in each gridblock, $V_p$ is the pore volume, $F$ is the net flow rate into neighbouring grid blocks, $Q$ is the net heat rate into the gridblock, $C_e$ is the change in energy due to generation or consumption, $Q_{in}$ is the heat input, and $Q_{out}$ is the heat output.
is the net flow rate into wells during the timestep, $V_b$ is the bulk volume, $e$ is the energy in gridblock that is $e = (\rho C)_w(T - T_{ref})$, where $(\rho C)_w = \phi (\rho C)_m + (1 - \phi)(\rho C)$, in which $\phi$ is the porosity of gridblock, $\rho$ is density of water/rock and $C$ is the specific heat capacity of water/rock. In Eq. (2), $F_e$ is the convective enthalpy flow rate into neighbouring gridblocks, $C_e$ is the conductive energy flow rate into neighbouring gridblocks, $Q_{HL}$ is the conductive energy flow rate to the surrounding rocks (heat loss), $Q_e$ is the net enthalpy flow rate into wells during the timestep [26]. The net flow of water from cell $i$ into neighbouring cells is obtained by

$$F_{ei} = \sum_n \Gamma_i \frac{b_w}{\mu_w} d\Phi_{ni}$$

where $\Gamma_i$ is the transmissibility between cells $n$ and $i$ which is constructed using the harmonic mean of absolute permeability ($K$) of cells $n$ and $i$, $b_w$ is the molar density of water, $\mu_w$ is the viscosity of water, and $d\Phi_{ni}$ is the potential difference of water phase between cells $n$ and $i$. The net flow rate of energy (convection) from cell $i$ into neighbouring cells is obtained in a similar manner:

$$F_{ei} = \sum_n \Gamma_i (\rho C)_w T_{ni} \frac{\mu_w}{\mu_w} d\Phi_{ni}$$

The heat conduction term for cell $i$ is given by summing conduction between all neighbouring cells $n$ as [26]:

$$C_{ei} = -\sum_n \Gamma_i (T_i - T_n)$$
where $\Gamma_{hi}$ is the thermal conduction transmissibility between cells $n$ and $i$ constructed using the harmonic mean of the equivalent conductivity of cells $n$ and $i$. The equivalent conductivity is $\lambda_{eq} = \phi \lambda_w + (1 - \phi) \lambda_r$, where $\lambda_w$ is the water conductivity and $\lambda_r$ is the rock conductivity.

In this study we have not included the heat transfer in the production and injection wells. This has been studied in detail by Saeid et al. [7] for two tubing materials for a discharge rate of 150 m$^3$/h. They concluded that the heat gain and loss in the injection and production wells, respectively, after five days of operation are negligible.

### 2.2. Geological model and fluid properties

We assume a structurally simple, synthetic, 3D rectangle for the geological system under study with 3 km × 3 km × 500 m lengths in x, y and z directions (Fig. 1). The system comprises of an overburden (200 m thick), an aquifer (100 m thick) and an underburden (200 m thick). The system is discretized into laterally uniform 120 × 120 mesh (25 m × 25 m gridblocks). However, vertical discretization is non-uniform. The overburden and underburden are each discretized into one layer only with 200 m thickness. Whereas the aquifer is discretized into 10 layers (each layer 10 m thick). Therefore overall we have 12 layers and 172,800 gridblocks. The top face of the structure is 2250 m deep.\(^1\)

The initial conditions are set as $p_{init}$ (initial pressure) equals to 200 bar at the reference depth of 2500 m, and $T_{init}$ (initial temperature) equals 67.5 °C at 2250 m, 75 °C at 2500 and 82.5 °C at 2750 m. The boundary conditions are fully close to flow in x- and z-directions and fully open to flow in y-direction (the direction of anisotropic heterogeneity). In order to implement open boundaries, the pore volumes of the boundary blocks in y-direction are multiplied by 1,000. This method has been previously used to emulate open flow boundary conditions or infinite domains [28–30].

**Rock properties**

Thermal conductivity of rock is 0.91 W/m/K, rock density is 2650 kg/m$^3$, rock specific heat capacity is 2,000 J/kg/K and rock compressibility is $4.93 \times 10^{-5}$ bar$^{-1}$ at 250 bar. In this study, we neglect the dependence of rock density and heat capacity on porosity as considered by Liu et al. [16]. Porosity of the overburden and underburden is set to 0.01, and permeability of the overburden and underburden is set to 0.001 mD. To generate porosity of the aquifer, a code available online [31] is used to generate correlated fields. The method utilizes the Fourier-transform of the covariance function as the power spectral density function of all realizations. Random autocorrelated fields are generated by creating random phase spectra meeting the conditions of real numbers in the physical domain. The realizations are then converted by back-transformation of the power- and phase-spectrum into the physical domain.

**Correlated porosity fields**

Correlated porosity fields are generated all with a mean of 0.17 and a variance of $\sigma^2 = 0.02$ and 0.04, hereafter referred to as v1 and v2 for simplicity. The covariance matrices of porosity fields are generated by creating random phase spectra meeting the conditions of real numbers in the physical domain. The realizations are then converted by back-transformation of the power- and phase-spectrum into the physical domain.

\(^1\)Our preliminary modelling practices refining the mesh did not yield significant change in the results of a homogeneous and several heterogeneous examples we considered for mesh sensitivity analyses.
where \( c_x = 100 \text{ m} \) means 4 gridblocks are correlated in \( x \)-direction. As such we generate eight fields (2 variances multiplied by 4 different correlation lengths). Eight realizations are generated for each field, totalling 64 porosity fields. Next, the permeability fields are derived from porosities through the following relationship for the fluvial Delft Sandstone aquifers in the Netherlands [32]:

\[
K = -2.03 \times 10^{-7} \phi^4 + 2.55 \times 10^{-3} \phi^4 - 1.04 \times 10^{-3} \phi^3 \\
+ 8.91 \times 10^{-2} \phi^3 + 3.58 \times 10^{-1} \phi - 3.21 \times \phi^2 
\]

(6)

\[ \rho_w(T) = \frac{\rho_w(T_{ref})}{(1 - c_w(T - T_{ref}))(1 + c_{T1}(T - T_{ref}) + c_{T2}(T - T_{ref})^2)} \]

(7)

where \( T_{ref} \) is the reference temperature which is 293.15 K, \( \rho_{wref} \) is the reference pressure which is 200 bar, \( c_{T1} \) is a coefficient which is set to \( 3.0 \times 10^{-4} \text{ K}^{-1} \), \( c_{T2} \) is a coefficient which is set to \( 3.0 \times 10^{-6} \text{ K}^{-1} \), \( \rho_w(T_{ref}) \) is the water density at reference pressure and is set to 1000 kg/m\(^3\), and \( c_w \) is water compressibility and is set to \( 4.0 \times 10^{-4} \text{ bar}^{-1} \).

### 2.3. Heat recovery scenarios

The geothermal heat recovery operation is carried out by two doublets using a checkboard pattern [8]. The injection wells are hereafter referred to as I1 and I2, and the production wells are referred to as P1 and P2 (see Fig. 1). The distance between the injection and production wells in each doublet is \( L \), and the distance between the two doublets is \( dx \). The position of I1 is fixed for all of the heat recovery scenarios and it is at \( x = 750 \text{ m} \) and \( y = 750 \text{ m} \). However, the positions of I2, P1 and P2 change with different \( L \) and \( dx \) values. We assign four values for well spacing, \( L = 500 \text{ m}, 700 \text{ m}, 900 \text{ m}, \) and \( 1100 \text{ m} \). For each \( L \), five doublet spacing, \( dx \), are considered: \( dx = 0.7L, 0.85L, 1.15L, \) and \( 1.3L \).

Cold water is injected using two well injection rates of \( Q = 150 \text{ m}^3/\text{h} \) and \( 250 \text{ m}^3/\text{h} \), hereafter referred to as Q1 and Q2 for simplicity. The injection rates are selected based on the actual production rates applied for the deep geothermal doublets in sedimentary aquifers [34]. The maximum allowable pressure at each well is 260 bar to avoid inducing hydraulic fractures. Above this threshold, the injection rate is decreased and as a result the production rate is also decreased to equate with the total injection rate. However, assuming that for each well stimulation operations have been carried out, porosity and permeability of connection blocks at perforation depths are increased so that they are equal to the average of porosity and permeability of the perforation column. By means of this, the injection and production rates are maintained...
throughout the simulation time for all the simulations in this study.

The temperature of injected water is 30 °C. The operation is continued for 50 years. A robust set of timestepping criteria is employed by the simulator to ensure convergence. The detailed presentation of the timestepping strategy in thermal mode of the simulator is prohibitive to describe here and can be found in ECLIPSE Technical Description manual \[26\] under Thermal Features/Timestepping Criteria. Using this strategy and checking the production profiles for highest injection rate and most heterogeneous porosity/permeability, we checked that there are no significant convergence issues in our simulations.

Using 64 models of porosity and permeability fields, overall we conduct 2,560 simulations: 2 variances multiplied by 4 correlation lengths multiplied by 8 realizations for each pair of variance-correlation length multiplied by 4 \(L\) values multiplied by 5 \(dx\) values, multiplied by 2 injection rates. These parameters are summarised in Table 1. Each simulation in average takes 3,800 s to complete using a Windows Server 2012-operated HP ProLiant server with two Intel Xeon E5-2690 12-core 2.60 GHz CPU processors. A parallel code is developed in MATLAB to call 8 simulations at the same time. This parallelisation saves run time significantly. In order to make comparisons of heterogeneous systems with homogeneous systems, additional simulations are carried out with constant aquifer porosity and permeability of \(\phi = 0.17\) and \(K = 360.2045\) mD (from Eq. 6). Using these homogeneous values, \(Q1\) and \(Q2\), \(L = 500\) m, \(700\) m, \(900\) m, and \(L = dx = 900\) m. In all subfigures, white, cyan and yellow dashed lines represent the \(2L \times 2dx\) extent, \(L'\) extent and \(L''\) extent, respectively.

![Fig. 8. Positions of \(L'\) and \(L''\) for selected examples of \(L = dx\) for the realization 1 and for (a) C1, LTPS, (b) C2, LTPS, (c) C1, LTPn and (d) C2, LTPn, where \(n\) is 10 °C if within 50 years (\(T_1\)) experiences 10 °C drop, otherwise \(n\) is the temperature drop of (\(T_1\)) at the end of simulation (50 years). From left column to right column in all rows: Q1 and \(L = dx = 500\) m, Q2 and \(L = dx = 500\) m, Q2 and \(L = dx = 700\) m, and Q2 and \(L = dx = 900\) m. In all subfigures, white, cyan and yellow dashed lines represent the \(2L \times 2dx\) extent, \(L'\) extent and \(L''\) extent, respectively.](image)
2.4. Definition of performance metrics

In order to investigate the interplay of well or doublet spacing and heterogeneity of the system, first the following parameters are defined:

1. Licensed regions boundary: this is the shell-like lateral inner boundary blocks of the license area. The license area is taken as the $L \times 2x \times 10$-layer rectangle around the wells as shown in Fig. 1.

2. Average temperature of production wells defined by

$$
\langle T_{W} \rangle = \frac{\sum_{j=1}^{n} q_{W,j}^{\text{prod}} T_{W,j}^{\text{prod}}}{\sum_{j=1}^{n} q_{W,j}^{\text{prod}}}
$$

where $q_{W,j}^{\text{prod}}$ is the water production rate at connection (layer) $k$ of well $W$, at time $t$, and $T_{W,j}^{\text{prod}}$ is the block $ijk$ temperature at time $t$. For each production well, obviously $i$ and $j$ are fixed and only $k$ changes from 1 to 10 (uppermost layer of the aquifer to lowermost layer). The denominator of above equation is equal to $Q_{\text{prod},W}$ which is a constant.

3. Converged solution for a variable $\alpha$ over $\ell$ realizations is defined as $\alpha_{\ell} = \left(\frac{\sum_{i=1}^{\ell} \alpha_{i}}{\ell}\right) / \ell$. By looking into the plot of $\alpha_{\ell}$ vs. $\ell$, the convergence of realizations can be assessed, that is, $\alpha_{\ell}$ should converge for a particular $\ell$ so that for $\ell > \ell$, $\alpha_{\ell}$ remains constant. Based on our simulations, the converged solution for $\langle T_{W} \rangle$ is obtained through 6 realizations, proving that 8 realizations are sufficient for convergence.

4. Life time based on production wells: $LT_{W_{1}}$ and $LT_{W_{2}}$ of geothermal heat recovery operation defined as the time (in years) when average...
temperature of production wells has dropped 1 °C with respect to initial condition.

5. Life time based on (average) production: LTP of geothermal heat recovery operation defined as the time (in years) when $\langle T_W \rangle_{T_{w1}^{w2}}$ has dropped 1 °C with respect to initial condition.

6. Life time based on (average) production: LTPn of geothermal heat recovery operation defined as the time (in years) when $\langle T_W \rangle_{T_{w1}^{w2}}$ has dropped n °C with respect to initial condition.

7. Life time based on boundary of license area: LTB of geothermal heat recovery operation defined as the time (in years) when average temperature over the license area boundary has dropped 1 °C with respect to the initial average temperature. This property is calculated based on the converged solution of the average temperature in license region $\langle T_{b} \rangle_{T_{w1}^{w2}}$.

8. Coefficient of Performance defined as:

$$\text{CoP} = \frac{E_{\text{prod}}}{E_{\text{pump}}}$$  \hspace{1cm} (9a)

$$E_{\text{prod}} = \langle \rho C_p \rangle Q \int_{t=0}^{T_{\text{LTP}}} ((T_{w}^*) - T_{w0}) dt,$$  \hspace{1cm} (9b)

$$E_{\text{pump}} = \varepsilon Q \int_{t=0}^{T_{\text{LTP}}} ((p_{\text{inj}} - p_{\text{prod}})) dt$$  \hspace{1cm} (9c)

where $E_{\text{prod}}$ is the energy produced from production wells and $E_{\text{pump}}$ is an estimation of pump energy losses [10], in which $\varepsilon$ is the pump efficiency of %60, and $\langle p_{\text{inj}} - p_{\text{prod}} \rangle$ is calculated by using the converged solution for well bottom-hole pressures of two doublets.

9. Energy Sweep is an indicator of how efficiently heat in the control volume is extracted. This is defined as:

$$S = \frac{E_{\text{prod}}}{E_{\text{R}}}$$  \hspace{1cm} (10a)

$$E_{\text{R}} = \int_{i=1}^{N_{b}} (\rho \beta C_{w} \phi_{i} + \rho \beta C_{l}(1 - \phi_{i}))(T_{\text{init}} - T_{W}) dV_{i},$$  \hspace{1cm} (10b)

where $E_{\text{R}}$ is the available reservoir energy of the license area, $V_{b}$ is the bulk volume of gridblock $i$ in the license area ($2L \times 2dx \times 10$ layers around the doublets), $N_{b}$ is the number of gridblocks in the license area, and $E_{\text{prod}}$ is the geothermal energy recovered by the doublets until the converged solution based-life-time of the operation.
3. Results and discussion

3.1. Lifetime analysis: boundary vs. production wells-based comparison

Fig. 4(a) shows LTP for various correlation lengths (C1, C2, C3 and C4), injection rates (Q1 and Q2) and variances in porosity field (v1 and v2). The profiles are plotted versus L and for dx = L only. As a result there are 16 profiles in this figure. In this figure and the rest of figures in this manuscript, black represents Q1-v1 simulation results, green Q1-v2, red Q2-v1 and blue Q2-v2. Yellow lines represent homogeneous simulations. Some of the profiles are incomplete with respect to L. This is because the average temperature has not dropped 1 °C during 50 years of operation. From Fig. 4(a) it is clear that:

- Increase in injection (Q) and variance of porosity fields (v) lead to decrease in lifetime. This is trivial as cold water front reaches to production wells earlier for higher Q and v.
- Between each fixed pairs of Q-v, there are 4 profiles for each correlation lengths (C). Between them, C1 (c_x = 100 m and c_y = 100 m) leads to largest lifetimes and C2 (c_x = 500 m and c_y = 100 m) leads to...
lowest lifetimes. This point will be further analyzed and discussed in Section 3.3.

- Considering a minimum lifetime of 20 years and an average temperature drop of 1°C at the license boundary as the main indicators of the lifetime, the minimum well distances for Q1 and Q2 (regardless of the heterogeneity variance) are 700 m and 900 m, respectively.

- Considering a minimum lifetime of 30 years and an average temperature drop of 1°C at the license boundary as the main indicators of the lifetime, the minimum well distances for Q1-H, Q1-v1, Q1-v2, Q2-H, Q1-v1, and Q1-v2 (regardless of the correlation lengths) are about 650 m, 750 m, 800 m, 900 m, 950 m, and 1000 m, respectively.

Fig. 4(b) shows LTB for various correlation lengths (C1, C2, C3 and C4), injection rates (Q1 and Q2) and variances in porosity field (v1 and v2), when \( dx = L \). Evidently, LTB is less sensitive towards the correlation lengths and the profiles in each particular group of Q-v are less spread. Similar conclusions can be made for \( dx = 0.7L, dx = 0.85L, dx = 1.15L \) and \( dx = 1.3L \) as shown in Fig. 4(c) and (d).

In order to demonstrate the impact of well or doublet spacing on lifetimes (boundary vs. production wells-based calculations), in Fig. 5 all realizations as well as converged solutions are grouped into fixed \( dx/L \) (varying \( L \)) or fixed \( L \) (varying \( dx \)). Starting from Fig. 5(a), for all realizations, LTB are plotted vs. LTWP. In each plot, injection rate (Q), variance (v) and \( L \) vary. The scattered markers above the 45° line, show that LTB > LTWP. However, there is no dominant pattern in results in order to make a conclusion that LTB is higher than LTWP. Moreover between different \( dx/L \)'s in Fig. 5(a), the extent of lifetimes in x- and y-axes are the same. Therefore, the variation in doublet spacing does not have a clear impact on lifetimes. Conversely, Fig. 5(c) shows that by increasing well spacing (L) the lifetimes increase and scatter markers shift towards right of the plot.

Comparing LTB with LTWP, the scatter markers are mostly above the 45° line, but not all of the realizations produced this trend. For the converged solutions (Fig. 5b and Fig. 5d), there is a general but not a universal trend of LTB > LTP for \( dx/L = 0.7 \) and 0.85, \( L = 900 \) m and \( L = 1100 \) m. Nevertheless, for v2 (green and blue markers), we can deduce that LTB > LTP. This is because for v2 the breakthrough of cold water is happening too early (because of heterogeneity of the system) while the licensed region still has some energy left. We discuss this in details in the next subsection.

### 3.2. Determining the license area’s extent from temperature distribution

If LTB > LTP, the geothermal system has still energy to produce by the time that the production wells signal the temperature drop. This means that the license boundary chosen has not experienced the same level of temperature drop by the time that the production wells have. Here we show that the license boundary can be in fact calculated in a way that the boundaries experience the threshold temperature drop of 1 °C. We show that these boundaries are not necessarily the same as \( 2dx \times 2L \) which were conventionally assumed.

We calculate the distribution of the actual boundaries of license area around operating wells based on a simple search algorithm. To this end, for the case of \( L = dx \) (which was shown to consistently result in optimal well/doublet spacing solutions), and \( L = 500, 700 \) m and 900 m, Q1 and Q2, fixed v2 (with a general trend of LTB > LTP), and C1, C2 and C4, first we calculate LTP1, LTP5 and LTP10, where LTPn represents production lifetimes when the converged solution for production wells (\( \langle T_d \rangle \)) experiences n °C temperature drop. Then, for each realization and at LTPn, we search for a square license area around the wells so that for its boundary blocks, the average temperature drop is 1 °C. The length of this square is denoted by \( L' (= dx) \). Also similarly we find a boundary where the cold plume has farthest spread. That is we search for a farthest boundary away from the wells where the difference between the minimum temperature of that boundary and the initial temperature of that boundary is 1 °C. This boundary represents the extent of cold front. We denote this boundary with \( L'' (= dx') \).

Fig. 6 shows the results of this analysis. For each LTPn (LTP1, LTP5 and LTP10), we show \( L'/L \) and \( L''/L \) for C1 (averaged over all realizations of C1), for C2 (averaged over all realizations of C2), and for C4 (averaged over all realizations of C4). In each subfigure there are four lines for Q1-v2 (for \( L'/L \)), Q1-v2 (for \( L''/L \)), Q2-v2 (for \( L'/L \)) and Q2-v2 (for \( L''/L \)). The following observations can be made from this figure:

1. For \( L > 1000 \) m and the well temperature drop of <10 °C, both \( L'/L \) and \( L''/L \) can be as large as 1.25 and 1.5, respectively.
2. Impact of discharge (Q) on the size of the license area is not as important as how the constraint is considered for the temperature drop at the license boundary, i.e., an average 1 °C or a local 1 °C temperature drop. Note that obviously for a given case \( L'' \) is always larger than \( L' \).
3. For C4 cases \( L' \) and \( L'' \) decrease by increasing the well distance (L) implying that for \( L > 1000 \) m the license boundary can be chosen as \( 2L \times 2L (= 2dx \times 2dx) \) or slightly larger. For both C1 and C2 cases \( L' \) and \( L'' \) remain more or less similar for different L values between 500 m and 900 m.
4. In most cases for the systems with a lifetime defined as 10 °C (or
(lower) temperature drop at the production wells, \( L' \) is between 1 and 1.2 suggesting that the license boundary can be designed as 2.4 \( L \times 2.4 \) if the constraint for the lifetime is defined as the average temperature drop of 1 °C at the license boundary.

Since the lifetime resulted for LTP5 and LTP10 considered for the calculation of \( L' \) and \( L'' \) are more than what is usually considered as the geothermal lifetime (e.g., 30 years) the \( L' \) and \( L'' \) for constant lifetimes of 20, 30 and 40 years, and a constraint of \( T_P < 10 °C \) are shown in Fig. 7. For all the cases \( L' \) and \( L'' \) decrease by increasing the well distance (\( L \)). If an average temperature drop of 1 °C is considered for a lifetime of 30 years, \( L' \) is almost equal or smaller than \( L \) for a well distance of 700 m and 900 m for Q1 and Q2, respectively. These increase by 20% for the lifetime of 40 years.

Fig. 8 depicts the temperature field and the license boundaries defined based on different constraints for realization 1 of C1 and C2, and for different Q and L values. Fig. 9 shows similar results for the converged solutions.

The animations for the development of cold front for the examples shown in Fig. 8 and Fig. 9 are provided in Videos 1 to 8. The videos are zoomed in around the license areas for better visualization purposes and the stills are taken at the production time equal to 10 years. The videos represent how the swept area advances in time for different well distances and heterogeneous fields. Comparing the results of geothermal systems with \( L = 500 \) m for different \( Q \) suggests that while a minimum well distance of \( L = 500 \) m might be enough to provide a lifetime of greater than 20 years for a discharge of 150 m\(^3\)/hr, this well distance is not proper for higher discharge values. For a discharge of 250 m\(^3\)/hr the results suggest that a well distance of 700 m provides a lifetime of more than 25 and 35 years for LTP5 and LTP10, respectively.

### 3.3. Effects of correlated heterogeneity

To investigate the impact of correlation lengths on operation lifetimes, Fig. 10 shows the difference in LTP between C4 and C1 in Fig. 10(a), C2 and C1 in Fig. 10(b), C4 and C2 in Fig. 10(c), and C4 and C3 in Fig. 10(d). All profiles are plotted with respect to \( dx/L \) for fixed \( L \). The following observations can be made:

1. By increasing correlation lengths in both directions from 100 m to 500 m, Fig. 10(a) shows that almost universally lifetimes decrease (negative values in y-axis). The difference between lifetimes of C4 and C1 increases as \( L \) increases.
2. By increasing correlation lengths in only y-direction from 100 m to 500 m, Fig. 10(b) shows that lifetime decreases further (larger negative values in y-axis) for small doublet spacings (\( dx = 0.7L \) and...
dx = 0.85L). However the trend reverses around dx = 0.85L so that for high dx values, lifetimes of C2 is actually higher than C1. This positive difference increases for larger L’s, and specially for Q2-v2 (blue lines).

3. Figs. 10(c) and (d) show that the trend for above points are reversed when we compare C4 with C2 and C4 with C3. That is, for low dx/L values, the higher correlation length in both directions, the larger lifetimes are observed, while for large dx/L values, the higher correlation length in both directions, the lower lifetimes are observed. Again the differences between lifetimes increases with higher L, Q and v.

4. An anisotropic large correlation lengths in a geothermal reservoir reduces production wells-based lifetimes for small doublet spacings, while increases production wells-based lifetimes for large doublet spacings compared to isotropically correlated heterogeneous reservoir systems.

In order to investigate the impact of directional (anisotropic) correlated heterogeneity on lifetime of operation, here, we review the results of six simulation samples between different correlation lengths, namely, C1, C2 and C4, and different doublet spacings, namely, dx/L = 0.85 and dx/L = 1.3:

- Sample 1: \( \ell = 1, Q2, v2, C1, L = 900 \text{ m}, \ dx/L = 0.85 \) (low dx),
- Sample 2: \( \ell = 1, Q2, v2, C1, L = 900 \text{ m}, \ dx/L = 1.3 \) (high dx),
- Sample 3: \( \ell = 1, Q2, v2, C2, L = 900 \text{ m}, \ dx/L = 0.85 \) (low dx),
- Sample 4: \( \ell = 1, Q2, v2, C2, L = 900 \text{ m}, \ dx/L = 1.3 \) (high dx),
- Sample 5: \( \ell = 1, Q2, v2, C4, L = 900 \text{ m}, \ dx/L = 0.85 \) (low dx),
- Sample 6: \( \ell = 1, Q2, v2, C4, L = 900 \text{ m}, \ dx/L = 1.3 \) (high dx).

Fig. 11 shows the permeability distribution (first column) and temperature distributions (second, third and fourth columns) of the reservoir top layer. The temperature distributions are plotted at LTP (second column), LTB (third column) and at the end of simulation (fourth column) for the six samples defined above. The locations of wells are also superimposed on the permeability distribution profiles. Corresponding to these distribution profiles, Fig. 12, shows the flow-rate-weighted average temperature of the two production wells \( \langle T_{W} \rangle \) of P1 and P2 for these samples.

We first concentrate on \( \langle T_{W} \rangle \) of Sample 1 and Sample 3 (low dx but
varying correlation lengths of C1 and C2, respectively corresponding to Fig. 11row a) and Fig. 11row c), and black and red lines in Fig. 12(a)). The early temperature drop of Sample 3 wells (both P1 and P2) compared to Sample 1 can be directly attributed to the correlated heterogeneity in y-direction (along doublet spacing: \(dx\)) that has transported cold water quickly to P2. As a result of these complications, LTP of Sample 1 is higher than Sample 3, and this corroborates results shown in Fig. 10(b) for \(L = 900\) m, Q2-v2 (blue line) at \(\frac{dx}{L} = 0.85\) where \(\text{LTP}_{\text{C2}} - \text{LTP}_{\text{C1}} \approx -10\) years. Such effects of correlated heterogeneity (or channelised heterogeneity) has also been studied in details in a recent publication by Lie et al. [16].

Next, we focus on \((T_{0P})\) of Sample 2 and Sample 4 (high \(dx\) but varying correlation lengths of C1 and C2, respectively corresponding to Fig. 11row b) and Fig. 11row d), and green and blue lines in Fig. 12(a)). In this instance, P2 is experiencing similar temperature drops between two cases. This is because P2 is sufficiently away from I1, so that correlated heterogeneity along I1-P2 corridor cannot lead to quick advection of cold water to P2. Nonetheless, the difference in lifetime between Sample 2 and Sample 4 is made by P1. For Sample 4, the directional correlated heterogeneity is distorting the cold water fronts of both I1 and I2 to the benefit of P1. That is, large parts of cold water fronts of I1 and I2 move alongside y-direction but in the opposite direction towards P1, so that breakthrough at P1 takes place later for Sample 4 compared to Sample 2. As a result of these complications, LTP of Sample 4 is higher than Sample 2, and this corroborates results shown in Fig. 10(b) for \(L = 900\) m, Q2-v2 (blue line) at \(\frac{dx}{L} = 1.3\) where \(\text{LTP}_{\text{C2}} - \text{LTP}_{\text{C1}} \approx 5\) years.

Next, we focus on \((T_{0P})\) of Sample 3 and Sample 5 (low \(dx\) but varying correlation lengths of C2 and C4, respectively corresponding to Fig. 11row c) and Fig. 11row e), and red and orange lines in Fig. 12(b)). The comparison is the same as comparison made between Sample 1 and Sample 3, with Sample 5 behaving similar to Sample 1 when compared to Sample 3. Due to isotropic correlated heterogeneity and proximity of doublets, the rather circular cold front did not lead to an early breakthrough of cold water front as of Sample 3. Consequently, LTP of Sample 5 is higher than Sample 3, and this corroborates results shown.

Fig. 15. (a) \(E_{\text{prod}}\) vs. \(dx/L\) for fixed \(L's\), (b) \(E_{\text{prod}}\) vs. \(L\) for fixed \(dx/L = 1\), (c) \(E_{\text{pump}}\) vs. \(dx/L\) for fixed \(L's\) calculated at LTP, (d) \(E_{\text{pump}}\) vs. \(L\) for fixed \(dx/L = 1\), (e) an illustration of how flow rate increase impacts CoP based on \(E_{\text{prod}}\) and \(E_{\text{pump}}\) dependency on \(Q\), and (f) an illustration of how flow rate increase impacts \(S\) based on \(E_{\text{prod}}\) and \(E_{\text{pump}}\) dependency on \(Q\). These are all calculated at LTP.
in Fig. 10(c) for $L = 900$ m, Q2-v2 (blue line) at $dx/L = 0.85$ where LTP$_{C4} - LTP_{C2} \approx 5$ years.

Finally, we focus on $\langle T_{P} \rangle$ of Sample 4 and Sample 6 (high dx but varying correlation lengths of C2 and C4, respectively corresponding to Fig. 11 row d) and Fig. 11 row f), and blue and cyan lines in Fig. 12b). In contrast to comparison between Sample 4 and Sample 2, (and not P1) makes the difference in determining lifetime. Anisotropic correlated heterogeneity of Sample 4 accounts for preventing the cold water front of I2 to reach P2. Consequently, LTP of Sample 4 is higher than Sample 6, and this corroborates results shown in Fig. 10(c) for $L = 900$ m, Q2-v2 (blue line) at $dx/L = 1.3$ where $LTP_{C4} - LTP_{C2} \approx -10$ years.

The fact that either P1 Sample 2 or P2 in Sample 6 experience earlier breakthroughs than P1 or P2 in Sample 4 is random, however, it is due to isotropy of correlated heterogeneity of Sample 2 and Sample 6 compared to Sample 4. Further to above-mentioned comparisons between different correlation length samples, the comparison of C4 with C1, and C4 with C3 is evident from discussions above and supported by Fig. 10(a) and Fig. 10(d). That is, $LTP_{C4} - LTP_{C1} < 0$ due to impact of isotropic heterogeneity, and $LTP_{C4} - LTP_{C3} > 0$ for small $dx$ and $LTP_{C4} - LTP_{C3} < 0$ for large $dx$ values. While the six samples above were taken from one realization only, it is evident that the converged solution has produced the same ranking between different correlation length cases with respect to production wells-based lifetimes (LTP).

In contrast to all variations in the production wells-based lifetimes observed as a result of change in correlation lengths, Fig. 13 shows that license boundary-based lifetimes (LTB) are significantly less sensitive towards this parameter and as such can be used to reduce uncertainty. This finding is corroborated by examining LT of six samples investigated above and shown in Fig. 11 (third column). The magnitude of difference between LTB of less are the magnitude of difference between LTP’s, for most of the comparisons. For example, $(LTP_{Sample 3} - LTP_{Sample 1}) = -16$ y vs. $(LTP_{Sample 3} - LTP_{Sample 1}) = -8$ y, $(LTP_{Sample 4} - LTP_{Sample 2}) = 9$ y vs. $(LTP_{Sample 4} - LTP_{Sample 2}) = 5$ y, and $(LTP_{Sample 5} - LTP_{Sample 3}) = 15$ y vs. $(LTP_{Sample 5} - LTP_{Sample 3}) = 5$ y. Only for comparison between Sample 6 and Sample 4, the magnitude of differences are equal: $(LTP_{Sample 6} - LTP_{Sample 4}) = 8$ y vs. $(LTP_{Sample 6} - LTP_{Sample 4}) = 8$ y. Therefore the selected examples, clearly demonstrate that LTB is significantly less sensitive towards correlation lengths and heterogeneity of geothermal system. It is evident in Fig. 13 that the impact of the correlation length on the LTB is less than 5 years.

3.4. Coefficient of performance and energy sweep

Figs. 14(a) and 14(b) show the profiles of Coefficient of Performance (CoP) and Energy Sweep (S) calculated from Eq. (9) and (10) as functions of well and doublet spacing for the converged solution at LTP. To avoid crowded figures, only C1 and C2 correlation-length cases are shown. Fig. 14(a and b) shows that

1. For each fixed well spacing, while for heterogenous cases the optimal doublet spacing is at $dx/L = 1$ (in the middle), for homogeneous cases the doublet spacing has negligible impact on CoP.
2. The highest CoP’s are obtained for Q1-v2 at $dx/L = 1$, however, considering the profiles for other $dx/L$, values, Q1-v1 has consistently led to the best CoP’s.
3. One clear observation is the dramatic reduction of CoP due to increase in injection rate (Q). This has also happened for homogeneous cases (compare Q1-H with Q2-H).
4. Similar to the homogeneous reservoirs, for most heterogeneous cases CoP decreases as $L$ increases for $dx/L = 1$.
5. The increase in correlation length mostly decreases CoP.

From Fig. 14(c and d) for S, the following observations can be made:

1. Heterogeneity in general reduces S especially for lower $L$ values.
2. Except for the highest $L = 1100$ m, increasing the variance of porosity fields (v) reduces S (green and blue lines compared to black and red lines).
3. Increasing the injection rate (Q) increases S.
4. It is evident that $dx/L = 1$ is consistently producing the maximum values for S.
5. The increase in correlation length mostly decreases S.
6. Similar to the homogeneous reservoirs, for most heterogeneous cases S decreases as $L$ increases for $dx/L = 1$.

In summary, the increase in correlation length in y-direction (C2 compared to C1) will largely lead to decrease in both CoP and S, with few exceptions when $dx/L > 1$. The increase in variance of the porosity fields (green lines compared to black lines, and blue lines compared to red lines), largely decreases S, but the impact on CoP varies for each $dx/L$. These results suggest that the shorter well distance may provide higher S and CoP. While higher injection rate increases S, it has a negative impact on the CoP.

Fig. 15(a-d) show the profiles of $E_{prod}$ and $E_{pump}$ as functions of well and doublet spacing for the converged solution and the homogeneous simulations. The results show that both of these properties increase with increase in well and doublet spacings due to increasing the lifetime. However, just at $dx/L = 1$, the ratio of $E_{prod}$ over $E_{pump}$ produces a maximum for heterogeneous models. Also with increase in injection rate, $E_{prod}$ and $E_{pump}$ increase. However, increase in $E_{pump}$ is larger than increase in $E_{prod}$, so that CoP decreases by increase in Q, while since $E_{pump}$ is independent of Q, S increases with Q. The changes in CoP and S as a function of Q is illustrated in Figs. 15(e) and 15(f).

4. Conclusions and future works

A comprehensive set of numerical simulations were carried out on synthetic homogeneous and heterogeneous low-enthalpy aquifer system, with a range of operational and physical parameters of the subsurface system. Using multiple performance metrics, the following conclusions were made:

1. Heterogeneity undermines performance of geothermal systems in terms of Life Time of the operation.
2. Spatially highly correlated heterogeneity undermines performance of geothermal systems compared to low correlated systems or randomly distributed heterogeneity.
3. An anisotropically correlated heterogeneous system performs worse than isotropically correlated heterogeneous systems for large well and doublet spacings.
4. Increase in operational flow rate can increase Energy Sweep while decrease Coefficient of Performance.
5. A doublet spacing equal to well spacing robustly leads to best performance of the operation.
6. Use of license area’s boundary showed less uncertainty with respect to various operational and physical parameters, suggesting a better control criterion for the operation design.
7. The difference between lifetimes based on production wells and license area’s boundary is minimum for when well and doublet spacings are equal.
8. Sufficient lifetime (>20 years) could be achieved for the well spacing of less than 900 m for a discharge of 250 m$^3$/hr. The lifetime can be increased significantly or the well spacing can be further reduced if larger temperature drop (>1°C) at the producers are permitted. This would however require a larger license area than the $2dx \times 2L$ in order to minimise the negative interference with the neighbouring geothermal projects.

Future directions include use of robust optimisation algorithms to obtain optimal well or doublet spacing for heterogeneous geothermal systems. While previously, Kong et al. [25] conducted optimization of
geothermal systems using homogeneous models, the heterogeneity will have non-trivial effects on positions of wells and doublets, and consequently it will also impact optimal solutions. The well spacings can be optimised further with including the economics of the project.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2019.113569.

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