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Towards comprehensive uncertainty quantification in direct-use geothermal systems

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Summary

The energy transition requires a reduction of CO2 emissions from anthropogenic activity. In Europe, heat amounts to 50% of the total gross energy consumption. In conduction-dominated geological settings, geothermal resources can supply renewable, baseload heat for direct uses, in almost all parts of Europe. In these settings, economic viability can be challenging and should be considered as coupled to the development of geothermal fields.

The aim of this paper is to outline the way towards comprehensive uncertainty quantification. A methodology is proposed identifying three main categories of uncertainty sources to be evaluated based on three key performance indicators in a systematic approach. The sources of uncertainty include: a) subsurface characterization, b) development options and c) economics. The performance indicators are : i) cumulative energy generated, ii) system lifetime and iii) economic output. Each of the uncertainty sources and performance indicators are used to demonstrate the importance of a comprehensive approach to uncertainty quantification. Standardization and comprehensive analysis considering the combined uncertainty across the different uncertainty levels and over the key performance indicators is needed to enable more reliable and robust predictions of geothermal developments.

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Introduction

The energy transition requires a reduction of CO2 emissions from anthropogenic activity. In Europe, heat amounts to 50% of the total gross energy consumption (Eurostat, 2023). Geothermal resources can supply renewable, baseload heat for direct uses, in almost all parts of Europe (Limberger et al., 2018). In the absence of tectonic activity, heat conduction is the dominant heat transfer mechanism of the natural system (Moeck, 2014). In conduction-dominated systems, economic viability can be challenging and should be considered as coupled to the development of geothermal fields (Daniilidis et al., 2017).

Recent efforts in Uncertainty Quantification (UQ) for heat production in geothermal systems have made use of layer-cake geometry (Hoteit et al., 2023). Uncertainties related to the the natural temperature at the basin level have also been studied (Degen et al., 2022). For field level developments, the importance of Net-to-Gross (N/G) in predicting the connectivity of sand bodies and their impact on geothermal production related to doublet positioning has been previously studied (Willems et al., 2017). The relevance of spatial correlation of permeability has shown that a reduced well spacing than conventionally used would not have a negative impact on the thermal breakthrough time (Babaei & Nick, 2019). Additionally, interference between adjacent doublets under uncertainty resulted in an increased Heat In Place (HIP) recovery with reduced well spacing (Daniilidis et al., 2021).

Including cells with low permeability as active in the forward simulation highlighted their contribution to thermal recharge and to extending thermal breakthrough time (Wang et al., 2021). Alternative methods for representing heterogeneity in fluvial geothermal systems have shown good agreement in terms of the generated thermal response, albeit for N/G>~70% (Major et al., 2023). Combining subsurface, physical, operational and economic parameters at the field scale level has shown the importance of UQ and how this can be severely underestimated when using homogeneous models (Wang et al., 2023).

The aim of this paper is to describe previous efforts related to uncertainty quantification in geothermal systems and outline the way forward, towards comprehensive uncertainty quantification. Three key performance indicators are proposed: i) cumulative energy generated, ii) system lifetime and iii) economic output in the form of Levelised Cost of Heat (LCOH) or Net Present Value (NPV).

Method outline

The aspects that contribute to uncertainty in geothermal systems and affect the performance indicators need to be made explicit. Broadly speaking, these aspects can be classified in three main categories, namely: a) subsurface characterization, b) development options and c) economics. Each of these aspects can be further elaborated based on data availability and system complexity. A fourth option might be considered in the form of how a geothermal system connects to the broader energy system. However, it can be argued that the energy system would essentially feedback to development options and economic parameters, even if CO_2 emissions are considered as indicators or are monetized, so it does not need to be made explicit.

Subsurface characterization includes the identification of 1) the lithostratigraphic units in space, 2) the presence of faults and their properties and 3) the matrix rock properties, and their related uncertainties. Additional effort is needed to predict the spatial distribution of flow properties, for which often multiple realizations are needed, considering equally probable outcomes. Recent efforts using seismic inversion can potentially sharpen the spatial position of e.g. high permeable channels (Babasafari et al., 2023), but uncertainty within those channels remains.

Development options include aspects such as 1) well number and configuration, 2) operating rates and 3) re-injection temperature. Development options are typically human-controlled, with some degree of freedom and subject to constraints such as balance between total mass injected and produced or maximum injection pressure (e.g. (SodM & TNO-AGE, 2013)).

Economic parameters include 1) costs for both CapEx (e.g. drilling) and OpEx (e.g. pumping costs), 2) discount rates and 3) energy prices for heat and electricity. Additional considerations might include equipment replacement or subsidy schemes available (e.g. (Zaal et al., 2021)).

Uncertainty within each of these categories needs to be studied systematically to identify the impact it can have on the performance indicators. A few examples are given below.

Results and discussion

Flow property distribution in space can have a profound impact on the extent and shape of the cold plume (***Figure 1***). A homogeneous permeability field results in a simplified, symmetrical cold plume (***Figure 1***b). The cold plume shape in highly heterogeneous fluvial settings differs greatly, with complex shapes dictated by the interplay of highly permeable channels and low permeability shales that provide conductive thermal recharge (***Figure 1***d). Assuming homogeneous properties in heterogeneous settings can lead to poor predictions of all performance indicators; characterisation is therefore imperative.

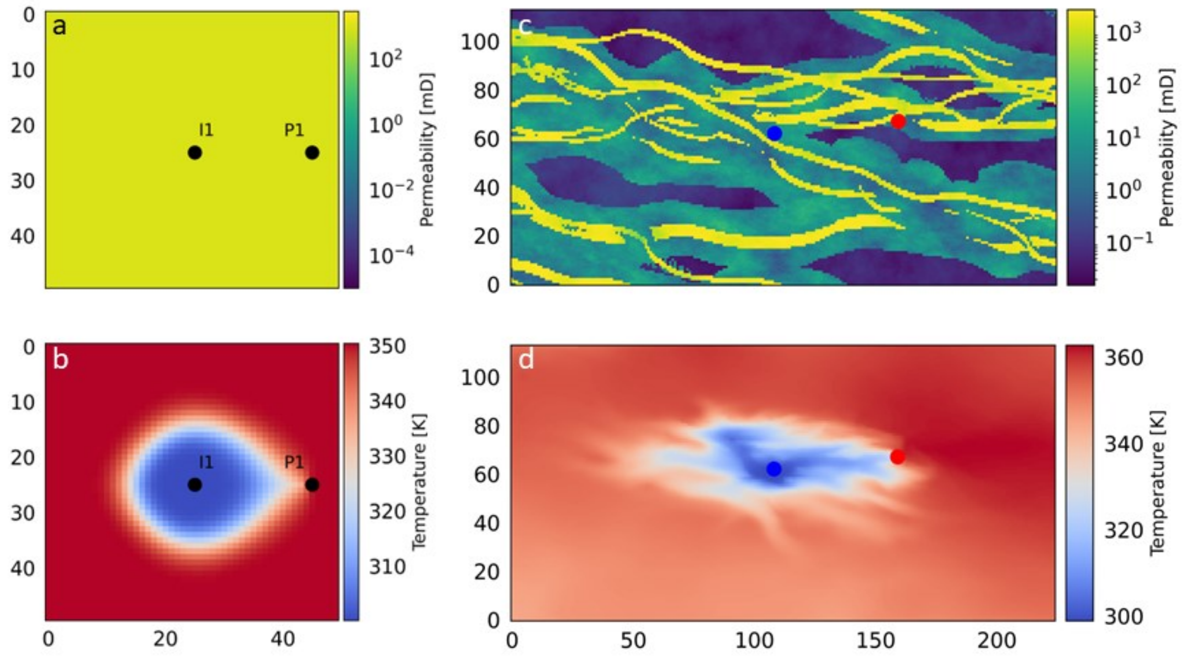

Figure 1. *Impact of spatial permeability on the extent and shape of the cold plume for (a) homogeneous permeability field resulting in a (b) tear-dropped shaped cold plume using injector well I1 and producer well P2, (c) channelized, heterogeneous permeability field resulting in (d) a complex shape and extent of the cold plume. The injector and producer well are denoted with a blue and red dot respectively.*

A rate increase leads to early production temperature drop and thermal breakthrough, even considering homogeneous subsurface properties (***Figure 2***a). Increasing rates can yield more cumulative produced energy, but system lifetime is negatively affected. The impact of higher rates on the economics is complex. Conversely, uncertainty in economic parameters such as the heat price only affect the economic indicators (***Figure 2***b). Nonetheless, changes in economic parameters can dictate different development choices.

Uncertainty related to three classes identified, requires a coupled Thermal-Hydraulic-Economic (TH-E) model to be captured comprehensively. The need for this coupling is substantiated by the fact that unconstrained optimization of energy production does not results an optimized NPV (Daniilidis et al., 2020). Conceptually, comprehensive uncertainty quantification is required prior to optimization efforts. Due to the complexity of the uncertainty parameter space, often simplifications are made in at least one of the uncertainty levels, most often eliminating the economic coupling, or simplifying the geological complexity.

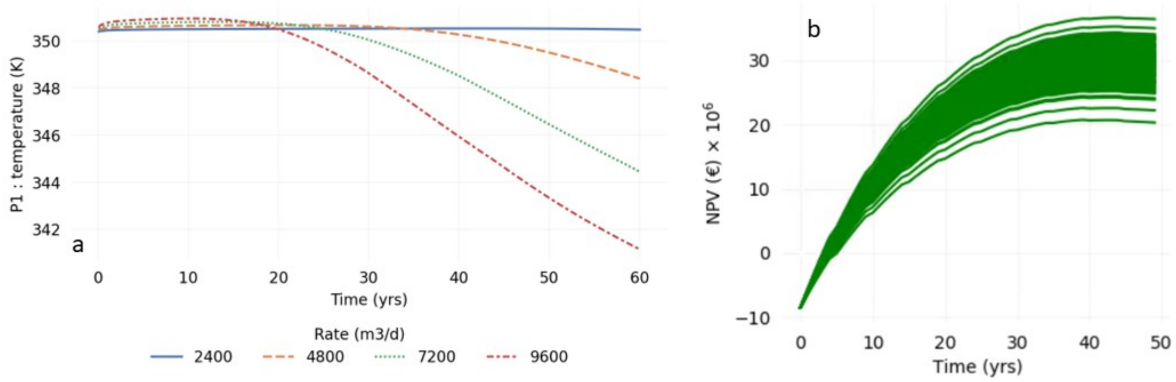

Figure 2. *Impact of (a) rates on production temperature and thermal breakthrough and (b) price variation on the generated NPV*

Highly efficient, full-physics forward simulation capabilities are imperative to accurately predict the performance indexes under uncertainty. Recent advances using GPU enable this possibility (Khait & Voskov, 2021). Standardization and possible expansion of the TH-E scheme is required to ensure better prediction of the key performance indicators. Mechanics and chemistry can also be important to consider depending on the geological setting, further increasing complexity. Comprehensive UQ and understanding the relative impact of each uncertain parameter is important to educate efficient data acquisition in green field developments.

Conclusions

The energy transition requires more robust and reliable predictions for the development of direct-use geothermal systems. Predictions need to include uncertainty across multiple levels, namely a) subsurface characterization, b) development options and c) economics. This paper identifies cumulative energy produced, system lifetime and economic output as key performance indicators. Standardization and comprehensive analysis considering the combined uncertainty across the different uncertainty levels and over the key performance indicators is needed to enable more reliable and robust predictions of geothermal developments .

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