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Geochemical implications of production and storage control by coupling a direct-use geothermal system with heat networks

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HIGHLIGHTS

- A model predictive controller is designed to control the geothermal production.
- A case study is presented for a Rotliegend reservoir in Groningen, The Netherlands.
- Demand driven geothermal production has no geochemical effects on the reservoir.
- Anhydrite and Dolomite are the most influential minerals for reservoir performance.
- The lifetime of the reservoir is extended if a time varying production is used.

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ABSTRACT

This paper outlines a method in which the heat production of a geothermal system is controlled in relation to the demand from a district-heating network. A model predictive control strategy is designed, which uses volume measurements in the storage tank, and predictions of the demand, to regulate the production of the geothermal system in real time. The implications of such time-varying production for the reservoir are investigated using a 2D reactive transport reservoir model. As a case study, the Groningen geothermal project is considered. The numerical data generated by the controller, in closed loop with a modelled district-heating network, are used as inputs for the reservoir simulations. The latter make use of discrete parameter analyses to evaluate the effect of pressure depletion, reservoir permeability, flow rate, re-injection temperature and injection pH on the geothermal reservoir, and also mitigate possible risks during development. Using a model predictive control does not create adverse geochemical effects in the reservoir; instead, the controller is able to improve the efficiency of the geothermal heat extraction. The findings pave the way for stronger integration between elements of heat networks and a more sustainable development of geothermal resources.

1. Introduction

Currently heat demand constitutes the largest part (~78%) of household energy consumption in the EU [1]. Renewable heat from geothermal systems can aid the reduction of CO_2 emissions associated with conventional heat production [2–4]. Geothermal district heating systems have been used since the 14th century [5], but were challenged by the wide use of cheap fossil fuels. However, due to global warming and a revived focus on renewable energy sources, district heating and heat energy networks are gaining importance in the provision of renewable energy [6–8]. The spatial topology and integration of a heat network in an urban setting has been recently analyzed in a comprehensive manner [9]. The complexity and challenges related to geothermal heat distribution have been previously outlined [10], while the efficient production and use of geothermal resources has been identified as an important aspect of their sustainable development [11]. Such insights are relevant for all geothermal fields. Nonetheless, the nature and impact of the challenges cannot be fully generalized and should be addressed by means of project-level studies [11].

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In a conventional setup, a geothermal system provides the base-load heat supply, while backup systems cover any excess demand [8,12]. Recently, it has been shown that periods of high and low geothermal heat production can lead to more sustainable utilization of the geothermal resource [13]. Global historical data on direct-use geothermal systems suggest that there is a capacity factor drop over time [14]. This drop could be partly attributed to a better utilization of the geothermal heat produced by means of coupling supply and demand.

It is important to match the heat supply and demand [3] in district heating systems, and daily discrepancies can be bridged with the use of a storage component [8,15], while the geothermal production level can be adjusted to match the seasonal changes. However, applying a seasonally variable production rate to the geothermal system can have several consequences at reservoir level, among which are changes in chemical composition, pressure and possibly also temperature. Moreover, a seasonally variable production rate could also affect the cold front breakthrough time of the reservoir, when compared with a constant production level. Salt dissolution or precipitation can affect reservoir permeability [16] and therefore needs to be addressed with location-specific modelling. Recent experimental studies presented geochemical interactions [17,18] in conduction-dominated geothermal settings [19]. Moreover, chemical implications, in the form of salt precipitation during geothermal production using CO_2 as the energy carrier, have also been recently highlighted [20]. It was demonstrated that a dynamic production rate can lead to clogging of the reservoir due to salt precipitation. To avoid this, the production rate of change should be constrained. Obtaining realistic values for these constraints is often difficult, as they are dependent on the characteristics of the geothermal system and therefore case specific. Furthermore, a geothermal system has upper and lower production constraints determined by reservoir properties and engineering specifications.

In order to satisfy all previously mentioned constraints while supplying a time varying heat demand, a storage device can be used to shift loads in time [15]. To provide the geothermal system with time-varying production rates, a controller should be designed that takes the production and storage capacity constraints into account. In case the demand has a periodic structure, an internal model controller can be used, as is shown in [21]. In [22] several other controller designs are presented that do not require a periodic demand, among which well-tuned propor tional-integral-differential (PID) controllers and model predictive controllers (MPC) are the most promising. The PID controllers are very easy to implement and guarantee stability, but cannot guarantee that the constraints are always met. Conversely, an MPC does have the capacity to guarantee that the constraints are always satisfied but the stability of these controllers is hard to prove. Moreover, these MPC mostly rely on ad-hoc tuning and experimental analysis [23]. Despite these drawbacks, MPC received a lot of attention [23–26] and are also applied to the control of pressure control of geothermal systems [27] and thermal energy storage for buildings [28].

An MPC solves an optimal control problem over a finite discrete time horizon, returning a sequence of control inputs of which only the first one is implemented. After this implementation, the process is reiterated using a new finite horizon that is shifted one step forward. Since the future demand is often unknown, a prediction can be made to solve the optimization problem. These predictions can be based on, for example, historical data and weather predictions. Also, a dynamic model of the system that is to be controlled is required to implement an MPC. Such a model relates flow rates and storage level [29], and is well suited to modelling a district-heating network.

The importance of direct-use, deep geothermal systems for renewable heat supply is recently highlighted [2,4]. However, for the simulation of such geothermal reservoirs, the implications and complexity of the geothermal system are usually simplified [2] or not discussed [4]. Moreover, demand pattern changes are either not taken into consideration [30], or only described by a maximum [31,32] or annual demand level [3,9]. Additionally, direct use geothermal systems often exhibit risks that are difficult to estimate, particularly at the early phases of development [12]. The effect of a variable geothermal production resulting from the coupling between demand and supply to the reservoir geochemistry has not been studied before, possibly impeding the application of such systems.

In this work, the heat demand is delivered using a district heating system that includes a storage device. An MPC is designed that regulates the production of the geothermal system. Although the design of MPC is not new, such a design has not been applied before to a geothermal system. The controller uses a storage level measurement and demand prediction as inputs and takes constraints into account for the production level, change in production level and storage level. A realistic, yearlong demand pattern for an equivalent of 10,000 households is used as input.

The resulting MPC production levels for the geothermal system have a realistic time-varying behavior, which is used as input for geochemical reservoir simulations. In this paper both the implications and complexity of the geothermal system and the changes in demand pattern are taken into account. Moreover, to take uncertainties in reservoir pressure depletion, permeability, flow rate, injection temperature and pH into account, multiple simulations are performed which helps to mitigate possible risks during the development phase.

The reservoir simulations are performed using a 2D model to obtain several insights. Firstly, it is investigated whether the geothermal doublet is able to provide the demanded energy (i.e. feasibility of delivery). Secondly, the long-term effects of a variable, demand driven, seasonal production pattern on the reservoir behavior (i.e. pressure, power, permeability and chemical changes) is compared to constant production rate data. Lastly, the interaction between the chemical and physical parameters of the reservoir is outlined. The analysis makes use of the Groningen geothermal project (NE Netherlands) data and features.

The paper is structured as follows: in Section 2 a controller is designed that regulates the production of the geothermal system, followed by a description of the characteristics of a 2D reservoir located in Groningen. In Section 3 an analysis of the performance of the controller in closed loop with the district heating network is carried out. This is followed by an analysis of the geochemical implications for the reservoir. Finally, a discussion of the findings, and the conclusions that can be drawn are presented in Sections 4 and 5, respectively.

2. Methods and background

The possibility and implications of a time-varying production of a geothermal system that is controlled in real-time are evaluated. To this end, an MPC is designed that regulates the production of the geothermal system. This controller is connected to a modelled storage device in order to analyze its performance. The demand pattern is predicted based on historical demand data. The MPC uses such predictions, in combination with measurements from the storage device, as its inputs. Additionally, the MPC takes into account the predetermined limitations of the reservoir in the form of constraints on the change in production rate. This control structure is depicted in the upper part of Fig. 1.