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Mixed integer optimization model for utilizing a geothermal reservoir

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ABSTRACT

Low temperature geothermal resources provide hot water that is commonly used for space heating various or industrial activities. The geothermal resources are in most cases renewable and can be utilized by current and future generations if constraints regarding sustainability are respected. In this work, we propose an innovative model to optimize the present value of profit from utilizing low temperature geothermal resources subject to operational and sustainability constraints. A fundamental part of the model is a sufficiently accurate and efficient reservoir model which simulates pressure changes (drawdown) in the reservoir with respect to utilizing levels. The approach proposed here seamlessly integrates a discretized lumped parameter model of the reservoir with a mixed integer linear program of the utilizing operations. The model is validated with real data from 26 years of utilizing a geothermal reservoir in Iceland and results include different scenarios for illustrating the use of the model. The approach proposed in this paper has the potential to improve current decision-making in this area as it helps studying utilizing strategies in a thorough manner.

1. Introduction

Utilization of renewable and environmentally friendly energy has gained increased attention in recent years. Geothermal energy is a promising source for heat and power that may be harnessed in a sustainable manner by extracting the heat from the earth.

Geothermal systems can be classified according to their temperature and the presence of fluid. Hydrothermal systems are permeable and have geothermal fluid naturally present. This study examines low temperature hydrothermal systems, where geothermal fluid is naturally present and no phase change occurs.

Although many geothermal systems are considered renewable, the regeneration time of a geothermal reservoir may be quite long and it can be challenging to plan the operation strategy to ensure profitable and sustainable production. The size and dynamic characteristics of geothermal reservoirs are often poorly understood when capital investments begin, since thorough exploration is costly and will never completely eliminate uncertainty.

Low temperature geothermal systems are most commonly used for space heating and provision of hot water and in some cases used for generation of electrical power. In particular, the vast geothermal resources in Iceland have been utilized to a considerable extent, mainly for space heating.

A low temperature geothermal field is harnessed by drilling a number of boreholes in the field and pumping geothermal fluid from them. This fluid is used as a heat source, and once heat has been extracted from the fluid it may or may not be re-injected into the field. The production from the field is determined simply by the flow rate and temperature of the fluid extracted. The production capacity of a geothermal field can thus be affected by a drop in the temperature of the fluid or by a decrease in the flow rate. Historical experience indicate that low temperature geothermal fields respond to production by declining pressure (here referred to as *drawdown*) and sometimes declining temperature (Axelsson, 1991; de Paly et al., 2012). This could imply that limiting production might become a necessity after an extended period of operation. Thus, it is important to make a clear distinction between renewability and sustainability. Renewability is a property of a resource where the energy is naturally replaced at a similar time scale as the extraction (Axelsson et al., 2001). Sustainability on the other hand refers to the exploitation of a resource where the production system applied is able to maintain production levels over long periods of time (Rybach and Mongillo, 2006).

From a financial point of view, due to the time value of money, excessive production is beneficial since the annual revenue in the early years has the greatest effect upon the present value of the operation. Lovekin (2000) concluded that a particular aggressive

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Nomenclature

Indices

$t(i)$ discrete time, $t(1) \le t(i) \le t_n$, for all $i \in \{1, 2, \ldots, n\}$, [s]
i discrete time index

Decision variables

$\dot{m}(i)$ extraction from tank 1 at time i, [kg/s]
$y(i)$ number of pumps needed at time i

State variables

$h(i, j)$ drawdown at time i in tank j, for all $j \in \{1, 2, 3\}$ and $i \in \{1, 2, \ldots, n\}$, [m]

Parameters

σ_{12} the conductivity between tanks 1 and 2, [m s]
σ_{23} the conductivity between tanks 2 and 3, [m s]
σ_3 the conductivity between tanks 3 and the external environment of the system, [m s]
S conductivity matrix
h_0 the external drawdown, [m]
$h(1, j)$ drawdown in tank j at time $i = 1$ for all $j \in \{1, 2, 3\}$, [m]
$h_1^{max}(i)$ maximum drawdown of tank 1, sustainability constraint, [m]
$h_e(i)$ historical value of drawdown, at time i, [m]
$\dot{m}_e(i)$ historical value of demand at time i, [kg/s]
$h_z(i)$ appropriate zero point for Taylor approximation, [m]
$\dot{m}_z(i)$ appropriate zero point for Taylor approximation, [kg/s]
κ_1 storage coefficient of tank 1, [m s^2]
κ_2 storage coefficient of tank 2, [m s^2]
κ_3 storage coefficient of tank 3, [m s^2]
K storage coefficient matrix
g gravitational acceleration [m/s^2]
Δt timestep, $\Delta t = t(i+1) - t(i)$, [s]
ρ density of water at 25 °C, [kg/m^3]
C_{Elect} price of electricity, [$/J]
C_{Water} price of water, [$/m^3]
C_{Pump} price of adding another pump, [$]
$P_{Power}(i)$ maximum pump power, [W]
β between 0 and 1, used to scale down the initial values in the iteration process
α step size in the iteration process.

exploitation scenario resulted in a discounted return of investment and present worth almost three times higher than a conservative use of the resource, despite higher costs of make-up wells at later stages in the operation. However, the main drawback of excessive production is that it can lead to resource deterioration or even depletion. It was for example shown in Eugster and Rybach (2000) that the time required for thermal recovery in a specific geothermal system was roughly equal to production time. The increased use of geothermal resources has raised questions regarding their renewability and how the resource is harnessed in an optimal manner. Is it possible to design optimal operation strategies of power plants that ensure profitable and sustainable power production? It is then of considerable interest to be able to predict the dynamic response of the geothermal reservoir to production from it. By doing so it may be possible to manage production so as to maximize revenue, ensure long-term production capability and plan for capital investments such as purchasing and installing borehole pumps and drilling new boreholes. To do so it is necessary to construct a representative model of the underlying reservoir and how it responds to fluid being pumped from it.

Several methods exist for reservoir assessment in geothermal systems. Common ones are, e.g. volumetric methods, detailed mathematical modeling and lumped parameter modeling (LPM). Volumetric methods involve conceptional modeling and are based on estimation of the total heat stored in a volume of rock but do not take into account the dynamic response of the system (Axelsson, 2008). Detailed numerical models include high resolution in three dimension and are eminently suitable for a number of tasks such as selecting borehole locations, etc. The computational cost of these models can however become prohibitive when they are to be used for optimization applications. Also lack of historical data can make it difficult to support such a detailed modeling.

The lumped parameter modeling approach represents the dynamics of the system without information about detailed spatial variation and is thus useful in predicting the production capacity of geothermal fields. A representative lumped model could serve as a useful tool in the decision making process with regards to the exploitation rate, investment cost and sustainability considerations.

A main concern of this work is to look at how to develop a resource in a sustainable manner in light of different constraints and uncertainty of production capacity, reservoir dynamics and market demand. In order to do this it is necessary to include both the dynamics of the reservoir and the markets. This sort of modeling was slightly tested in Sigurdardottir et al. (2010), i.e. for 3 years of production, and synthetic sustainability constraint. The goal in this work is to optimize over 150 years with a validated parameter estimation and a sustainability constraint that can be estimated from the exergy and the temperature in the reservoir

Like in Sigurdardottir et al. (2010), the focus is on low temperature geothermal fields with constant temperature. Historical production data (1985 till end of year 2010) from ten boreholes and drawdown data from one borehole from the Laugarnes geothermal system in South-West Iceland will be used here. The modeling approach will be carried out by first explaining the reservoir model (LPM) and then explaining the operational model, the optimization and the constraints. Results include parameter estimation and validation along with assessment of different operational scenarios.

2. Modeling approach

A lumped parameter modeling (LPM) combined with a mixed integer linear programming (MILP) approach is applied here. These two components are seamlessly integrated into a single mathematical model. The LPM is known for acceptable accuracy in modeling pressure change for isothermal low-temperature systems and requires relatively few commonly available parameters for the physical modeling (Satman et al., 2005). Those advantages do however come at some cost since lumped parameter models usually do not take into account well spacing or well injection locations. They are also unable to match average enthalpy and cannot simulate phase changes or thermal fronts in present state Pruess et al. (1986).

Lumped parameter modeling has been successfully applied to geothermal fields around the world, including Iceland (Axelsson, 1989, 1991; Axelsson et al., 1989; Hjartarson et al., 2002; Thorvaldsson et al., 2010), P.R. of China (Youshi, 2002), Turkey (Satman et al., 2005), Central America (Axelsson et al., 1989) and at various other locations. In order to successfully model a geothermal field using LPM, some production history must be available. The accuracy of the final model depends on the time span and