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Stock models for geothermal resources

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ABSTRACT

Stock models are useful for quantifying geothermal resources with a focus on important large-scale reservoir characteristics such as energy content, well deliverability and recharge into geothermal systems. Stock models have the benefit of being dynamic, although they do not require much more input than the volumetric models used commonly in the geothermal industry. Stock models can also be calibrated to production histories from geothermal systems in various settings and at varying stages of development. Due to its simplicity, the stock modelling method lends itself well to statistical methods, strategic optimization and integration with financial models.

1. Introduction

Stock models have a long history of application in analyzing the economics of natural resources. These models date back to the work of Hotelling (1931) on "The Economics of Exhaustible Resources". Since that time stock models have been applied for various natural resources be they expendable (e.g. wind energy, solar radiation), renewable (e.g. forest products, geothermal energy, fish stock) or exhaustible/depletable (e.g. oil and minerals) as discussed by Kneese and Sweeney (2017). Stock models have not been applied much to geothermal problems, although there are a few reports that build on this, or a similar concept (Madlener and Hochwald, 2008; Juliusson et al., 2011; Björnsson, 2016; Golab and Scherer, 1900; Malafeh and Sharp, 2015). It is clear, however, that stock models can be very useful for increased understanding of economic incentives and decision making in the geothermal industry, as in other industries. In particular, they are useful for answering important questions about how to best utilize geothermal resources.

Another reason for promoting the use of stock models is that they can assist in standardizing reports of energy reserves from various energy sources. For example, there is an ongoing effort by the United Nations to create a standardized framework for reporting energy and mineral reserves (UNFC, http://www.unece.org/energy/se/unfc_gen.html). A group titled the Expert Group on Resource Classification (EGRC) has been challenged with the task of coordinating the resource reports from various types of energy resources, which can be very challenging when comparing resources of inherently different nature such an oil field or a wind farm. In this case the stock models provide a nice balance between the simplicity required to be able to convey a clear message to a large group (without expert industry knowledge, e.g. project investors), and the complexity required to deal with the difference between the nature of expendable, renewable and exhaustible resources. It is also important that this method be applicable to both green-field and brown-field projects.

The goal of this work is to present how the stock model approach can be applied to geothermal resources and give the reader insight into the dynamics of the solution. The reader is encouraged to contemplate benefits that this method provides in balancing complexity and practical utility when compared to volumetric models and full-physics reservoir models (e.g. TOUGH2 or TETRAD models). We show how the model can be applied to both to a green-field project (which has reserves previously estimated by a volumetric reservoir model) and a brown-filed project (which has a long production history and reserves estimated by a full-physics reservoir model). Further utilization of stock models as constraints for a production optimization problem are an added benefit that would not be viable with full-physics reservoir models, although that topic will be detailed future work.

2. Basic reservoir model

The basic principle behind the method presented here is to model the reservoir as a container with some stock of electrical energy equivalent (alternatively one could model the stock in terms of thermal energy). This stock is represented by the variable S. The energy stock can be reduced by extraction through wells, and it can be recharged by interaction with a heat source and an aquifer that feed the reservoir.

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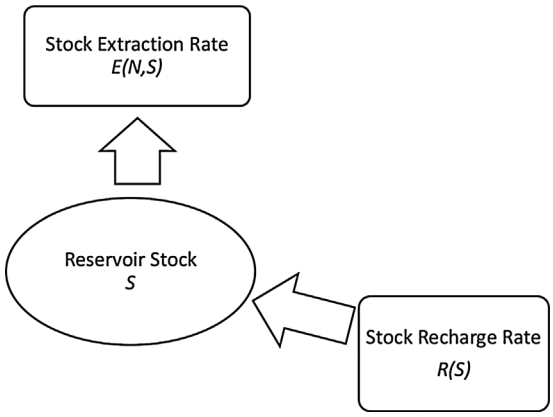

Fig. 1. Conceptual diagram of a simple reservoir model based on energy stock, S, with simple recharge and extraction rate functions, R(S) and E(N,S), respectively.

The extraction rate, E, is governed by a function that depends on the number of wells in the reservoir, N, and the amount of stock in the reservoir, $E(N,S)$. Similarly, the recharge is modelled with the function $R(S)$, which depends on the stock. This way, the governing equation for the stock in the reservoir becomes (Fig. 1):

$$\frac{dS}{dt} = R(S(t), t) - E(N(t), S(t), t) \tag{1}$$

The discrete analog of Eq. (1) is:

$$S_t = S_{t-1} - E_t\Delta t + R_t\Delta t = S_{t-1} - N_t E_w(S_{t-1})\Delta t + R(S_{t-1})\Delta t \tag{2}$$

Here we have introduced the explicit form of the stock balance equation. Note that E_t, R_t and N_t represent average quantities over the period from time $t-1$ to time t. The total extraction depends on the number of wells, N_t, and the production capacity of each well, $E_w(S_{t-1})$, which in turn depends on the amount of stock in the reservoir in the previous period. Various possible assumptions for the characteristics of the recharge and extraction functions are discussed in Sections 2.1 and 2.2.

The keen eye of an expert from the geothermal industry will identify that stock models are in many ways similar to the lumped-parameter models (a.k.a. tank models) commonly used for low temperature geothermal resource estimates. The stock model presented here has one open tank and the balance equation is on electrical energy equivalent stock, whereas the standard lumped parameter model may have more tanks and deals with mass balance in the reservoir. In Appendix A we derive some analytical solutions to the stock equations that yield results that are similar to those that have been derived for lumped parameter models. We also give further explanation of the relationship between extraction from the system, the recharge rate and steady state yield.

2.1. Recharge functions

In general, the recharge function should represent as closely as possible, the natural recharge process of a geothermal system as its energy stock is depleted. It is acknowledged that representing the depletion process by a function of a single variable, the stock S, is in many aspects an over-simplification. However, it should be considered that there will always be some ambiguity in the estimate of the recharge rate, and that modelling recharge is an improvement compared to the formulation of the volumetric method (most commonly used for green field project evaluation), which does not include explicit accounting of recharge.

One would expect the net recharge of the system to be close to zero when the reservoir is fully stocked, because in its natural state the flow of energy into the system is approximately equivalent the flow of energy out of the system. When the reservoir has been depleted the net recharge should become positive because the gradient between the heat source and reservoir has increased, and the same applies for the gradient between the surrounding aquifer and the reservoir. Some complications to this picture arise when one considers that recharge from the aquifer will also introduce marginally colder water to the system, thus the net energy influx need not increase monotonically as energy stock is depleted from the reservoir.

Following are a few suggestions for (net) recharge functions that have zero recharge when the reservoir is fully stocked, i.e. $R(S = S_{\mathrm{MAX}}) = 0$:

A line:

$$R_1(S) = a_R(S_{\mathrm{MAX}} - S) \tag{3}$$

A parabola:

$$R_2(S) = a_R(S_{\mathrm{MAX}} - S) + b_R(S_{\mathrm{MAX}} - S)^2 \tag{4}$$

A rational function:

$$R_3(S) = a_R\frac{S^{b_R} - S_{\mathrm{MAX}}^{b_R}}{c_R S^{b_R} - S_{\mathrm{MAX}}^{b_R}} \tag{5}$$

An exponential function:

$$R_4(S) = a_R\left(e^{b_R(S_{\mathrm{MAX}}-S)} - 1\right) \tag{6}$$

Fig. 2 illustrates recharge functions corresponding to the examples given in Eqs. (3)–(6). Of course the shape of these functions will depend on the choice of a_R, b_R, c_R and S_{MAX}. In Fig. 2 these parameters have been chosen (somewhat randomly) such that the recharge with an

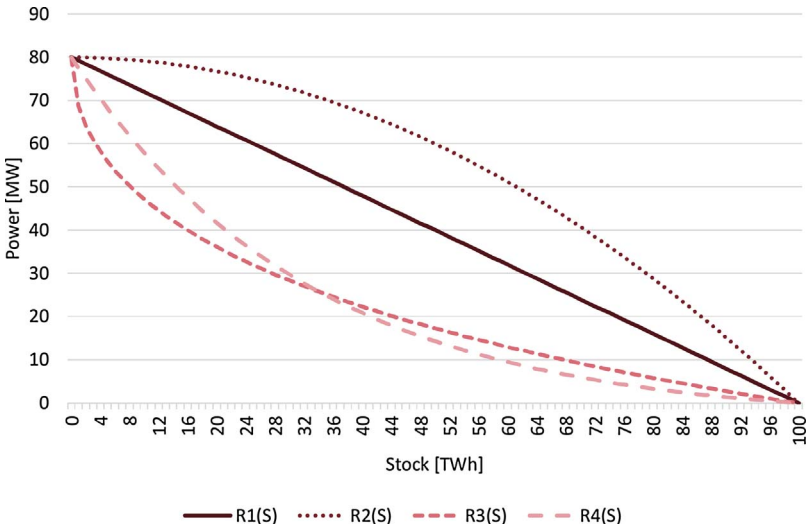

Fig. 2. Examples of recharge functions corresponding to the formulations given in Eqs. (3)–(6).