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Implications of Geothermal Resource Dynamics on Capacity Expansion Planning

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ABSTRACT

Geothermal resources can be temporarily depleted if they are utilized excessively for electricity production and their regeneration can take a long time. While the dynamics of geothermal resources have been considered for individual reservoirs, they have not been studied at a systems level. To study the potential contribution of geothermal resources to sustainable energy system development, it is important to consider the dynamic behavior of resources. Hence, the aim of the paper is to present a System Dynamics model for geothermal power plant expansion considering the dynamics of geothermal resources. The presented model consists of three main modules: resource dynamics, plant construction, and geothermal economics. The geothermal field stock decreases due to utilization for electricity production and increases through natural recharging. Changes in geothermal reservoir stock, and thus in well production capacity, lead to additional well requirement to maintain electricity production levels. Well production capacity not only influences the well construction rate but also influences the unit cost of electricity. Connecting resource dynamics, plant construction and economic aspects on a system's level, enables the analysis of geothermal resource dynamics in the context of energy system modelling. To showcase the presented model structure, it is applied to Iceland's geothermal resources available for electricity production but not Iceland's energy system as a whole. Two main scenarios are simulated and compared based on whether the geothermal resource dynamics are incorporated or not. The simulation results show the implications of incorporating resource dynamics for well construction, generation capacity, and geothermal development cost in long-run. The findings indicate that incorporating the dynamics of geothermal resources into energy system modelling has significant impact on estimated costs. In the cases of incorporated resource dynamics, additional wells are drilled to maintain production levels. This leads to increased total geothermal development cost as well as unit cost. Additionally, when the effects of resource dynamics are incorporated the distribution of resource utilization among different fields is improved, leading to less capacity drawdowns in individual plant areas.

1. INTRODUCTION

Between 2010 and 2016 overall geothermal resource utilization has grown significantly. Geothermal power production grew by 16% between 2010 and 2015 globally (Sigfússon and Uihlein, 2015). Geothermal resources are renewable, have relatively low emission rates, and production is unrelated to weather and climatic conditions making them suitable to provide base-load electricity for a CO_2-neutral future-society. Due to these characteristics, further expansion of geothermal resources is expected (Bruckner *et al.*, 2014; Sigfússon and Uihlein, 2015). However, geothermal resources, unlike other renewable resources, can be almost depleted temporarily, if they are utilized far beyond their regeneration rate (Axelsson and Stefansson, 2003; Dayan and Ambunya, 2015). Once a geothermal resource has been utilized close to depletion, full recovery can take a century or more (Juliusson *et al.*, 2011). The production capacity of a geothermal power plant depends on the available geothermal energy resource in the reservoir, which is influenced by the extraction rate (Rybach, 2007). When a geothermal resource is utilized beyond its recharge rate, the production level of the plant decreases over time. To some extent, geothermal production losses can be compensated by drilling additional wells (Juliusson *et al.*, 2011). To investigate these characteristics, it has been argued that the geothermal resource can be studied as a stock and flow system (Júlíusson and Axelsson, 2018).

So far, those resource dynamics are mainly dealt with from the perspective of the management of individual reservoirs, optimizing the exploitation of the reservoir. For example, a study presented at the World Geothermal Congress in 2005 (Stefansson and Axelsson, 2005) found that despite the fact that larger geothermal plant developments are often viewed as more economical, the Icelandic case showed that stepwise development, in which capacity is added in steps rather than all at once, can be more beneficial. Sustainable geothermal resource management occurs if energy supply can be maintained for a long period of time (i.e. 100-300 years). Often unsustainable resource utilization due to bad management can be caused by lack of knowledge, but good monitoring, reservoir models and reinjection can improve the situation (Axelsson and Stefansson, 2003). A mathematical model that combines the geothermal reservoir's production capacity with economic parameters, such as cost, was introduced in (Juliusson *et al.*, 2011). The goal was to determine the best utilization of the resource to maximise profits of an individual plant.

Previous studies modelled and analysed geothermal resource dynamics for individual reservoirs or plants, focusing on optimizing their utilization in terms of resource capacity and related cost but did not, for example investigate the economic implications of geothermal resource dynamics in the context of the entire energy system (Axelsson and Stefansson, 2003; Juliusson *et al.*, 2011). However, those resource dynamics can influence relevant energy system variables such as production cost or resource availability. Hence, they should also be included when analysing energy systems such as at the national level enabling analysis of economic and resource effects on a larger scale. This allows to reveal the impacts of geothermal dynamics on national price developments and energy security, which is important due to the relationship between reservoir behaviour and economic constraints (Rybach, 2007).

The aim of this paper is to understand geothermal resource dynamics and economics on a system's level. This paper is based on the system dynamics model introduced in (Spittler *et al.*, 2019). The model captures geothermal power plant expansion considering the dynamics of geothermal resources and consists of three main modules: "geothermal resource dynamics", "power plant construction", and "geothermal economics". Although components of each of the modules have been modelled before, no study so far investigated the interplay between them. By connecting the dynamics of the three modules, not only the economic and resource parts of the individual reservoirs are connected, but the relation between the different geothermal resources (i.e. fields) becomes obvious. Natural recharge and the utilization of the geothermal resource for electricity production influence the field stock of individual plants. The changes occurring in the reservoir stock lead to well capacity changes and therefore, additional wells need to be drilled to maintain intended production levels. This not only has an impact on the well construction rate but also influences the unit production cost and level of the geothermal resource. The model is applied to Icelandic geothermal resources.

In section 2 the geothermal resource utilization model is explained in brief. Section 3 presents the assumptions and description of the scenarios. Section 4 presents and discusses the main findings of the scenario runs with regards to resource availability, production and cost. Section 5 provides some concluding remarks.

2. MODEL

The method used for developing the model is system dynamics. Since system dynamics is a stock-flow based modelling approach, it is suitable for modelling geothermal resource dynamics. Due to its differential equation-based modelling method, it allows combining the stock-like behaviour of the geothermal resource with feedbacks from the economic module and vice versa.

The geothermal resource utilization model consists of three main modules: resource dynamics, plant construction, and geothermal economics. A conceptualization of the main connections between those modules is represented in Fig. 1. The stock of well capacity in the geothermal resource dynamics module (green) affects the capacity difference and thereby, original and make-up well construction. The number of wells times well capacity and installed plant capacity determine how much actual electricity production takes place, which effects the field stock that is linked to well capacity. Through the number of wells drilled in the geothermal plant construction module (blue) the cost of original and make-up wells in the geothermal economics module (orange) are affected. This influences actual production cost and more importantly the levelized cost, which directs the production cost signal. The production cost signal controls the choice of plants that are built, which again impacts extraction from the field through electricity production. The colours of the arrows refer to whether the connections are considered in the different scenario runs presented in this paper (see section 4 Scenarios).

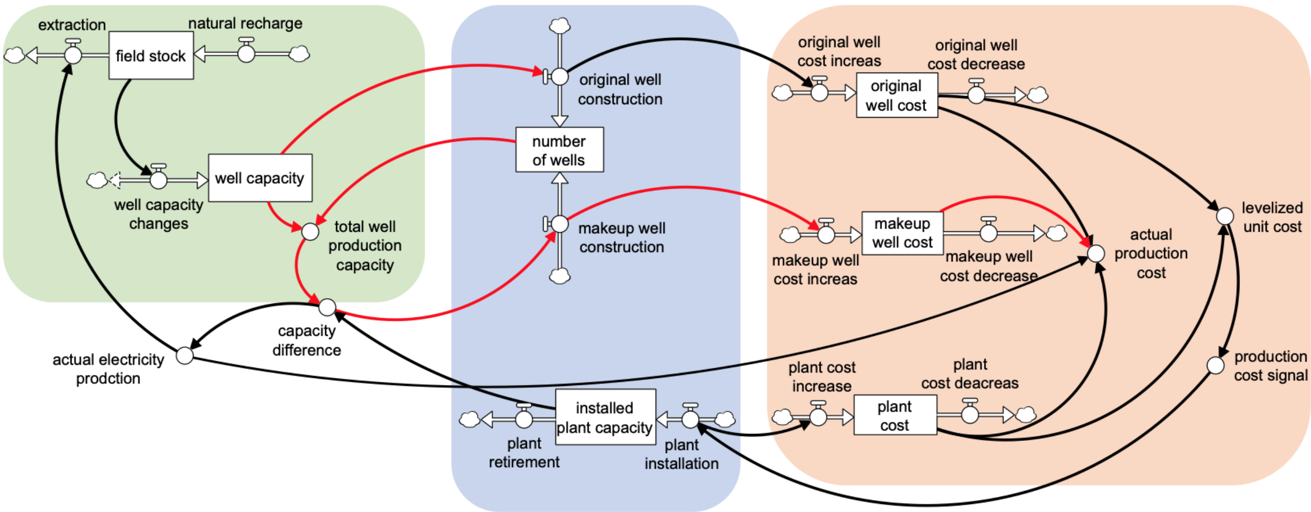

Fig. 1: Conceptualization of connections between resource dynamics, plant construction and economics

3. ASSUMPTIONS AND SCENARIOS

The model is applied to the Icelandic case and following the results of the Icelandic Master plan for Nature Protection and Energy Utilization considers seven fields available for geothermal electricity production (Steering Committee, 2016). Each field can encompass several geothermal plants. In total 15 plants (named A to O), of which five were already were developed at the start of the simulation in 2015, are accounted for. The detailed data and assumptions on resource and cost parameters for each plant can be found in (Spittler *et al.*, 2019).

The scenarios are a subset of the ones defined in (Spittler *et al.*, 2019). Two scenarios are run. They differ in terms of if geothermal resource dynamics are incorporated or not. The feedback between the resources' dynamics and the economics and plant construction can either be fully considered (including red and black arrow connections displayed in Fig. 1) or not considered at all (only black arrow connections displayed in Fig. 1). Resource utilization in both scenarios is considered to be high (4.4% growth per year).This results in the following two scenarios: i) Feedback–High utilization, ii) No feedback–High utilization.

3. RESULTS AND DISCUSSION

In this section results from the simulation of the four scenarios are presented and discussed. Results are presented in two ways: i) the resulting absolute values of one or several scenarios are displayed in one chart, and/or ii) percentage change in selected results due to the consideration of resource "Feedback" or "No feedback" cases.

3.1 Geothermal Electricity Production

Fig. 2 shows the total electricity produced in the case of including resource dynamics. As Fig. 3 demonstrates, including the feedback of geothermal resource dynamics allows us to capture changes in electricity production due to well capacity declines. These changes are rather small (due to the demand-driven nature of the model) and highly variable during the entire simulation period. Make-up well construction cannot fully compensate for the productivity losses, because it happens with a delay. These varying production patterns could also be historically witnessed in already existing power plants in Iceland (Spittler *et al.*, 2019).

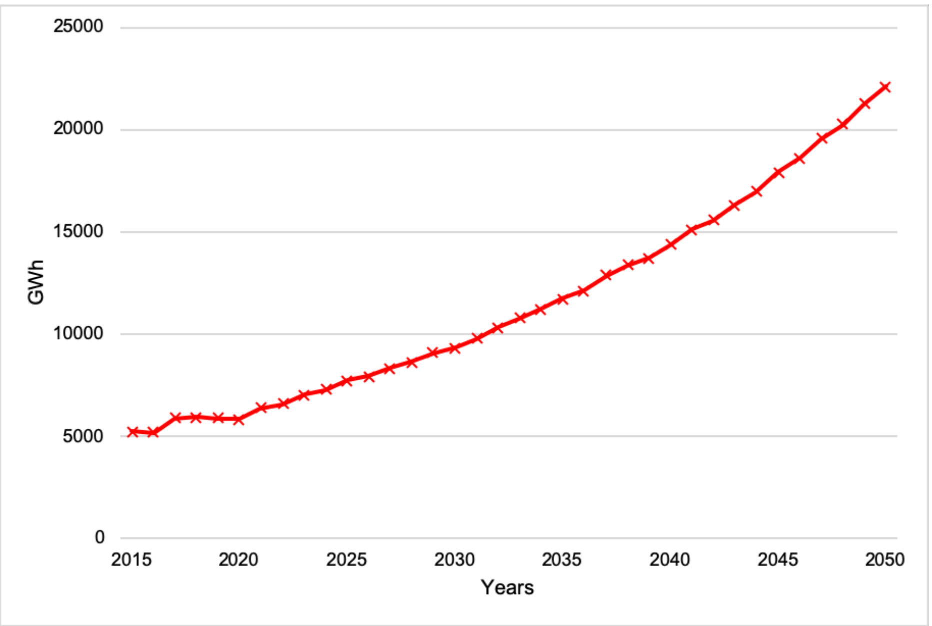

Fig. 2: Total electricity production including feedbacks

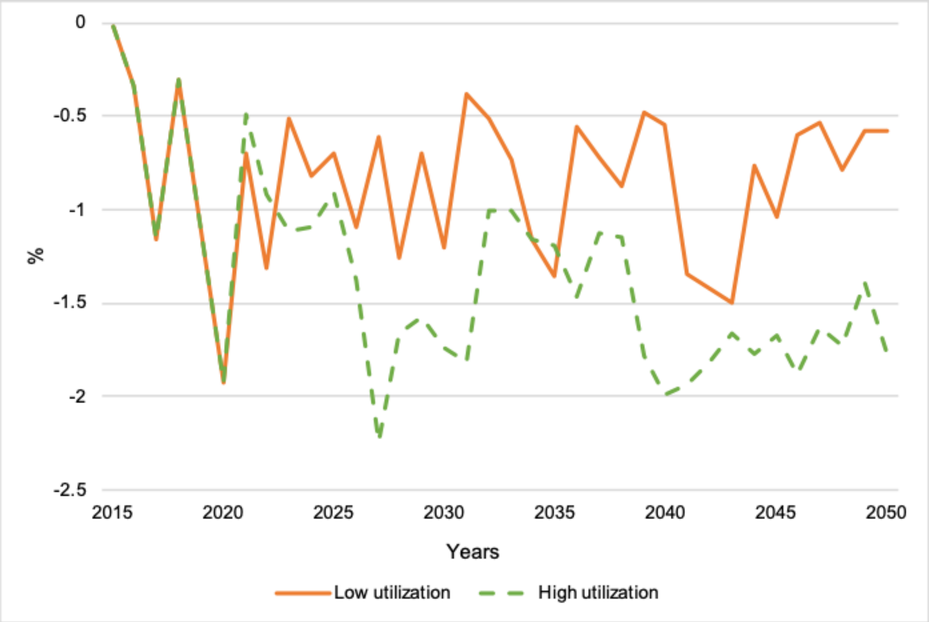

Fig. 3: Total production changes due to the effect of resource dynamics

3.2 Resource Availability

Fig. 4 depicts well capacities by plant. These capacities are average capacities and can be seen as representative values for available geothermal resource stock in the plant area.

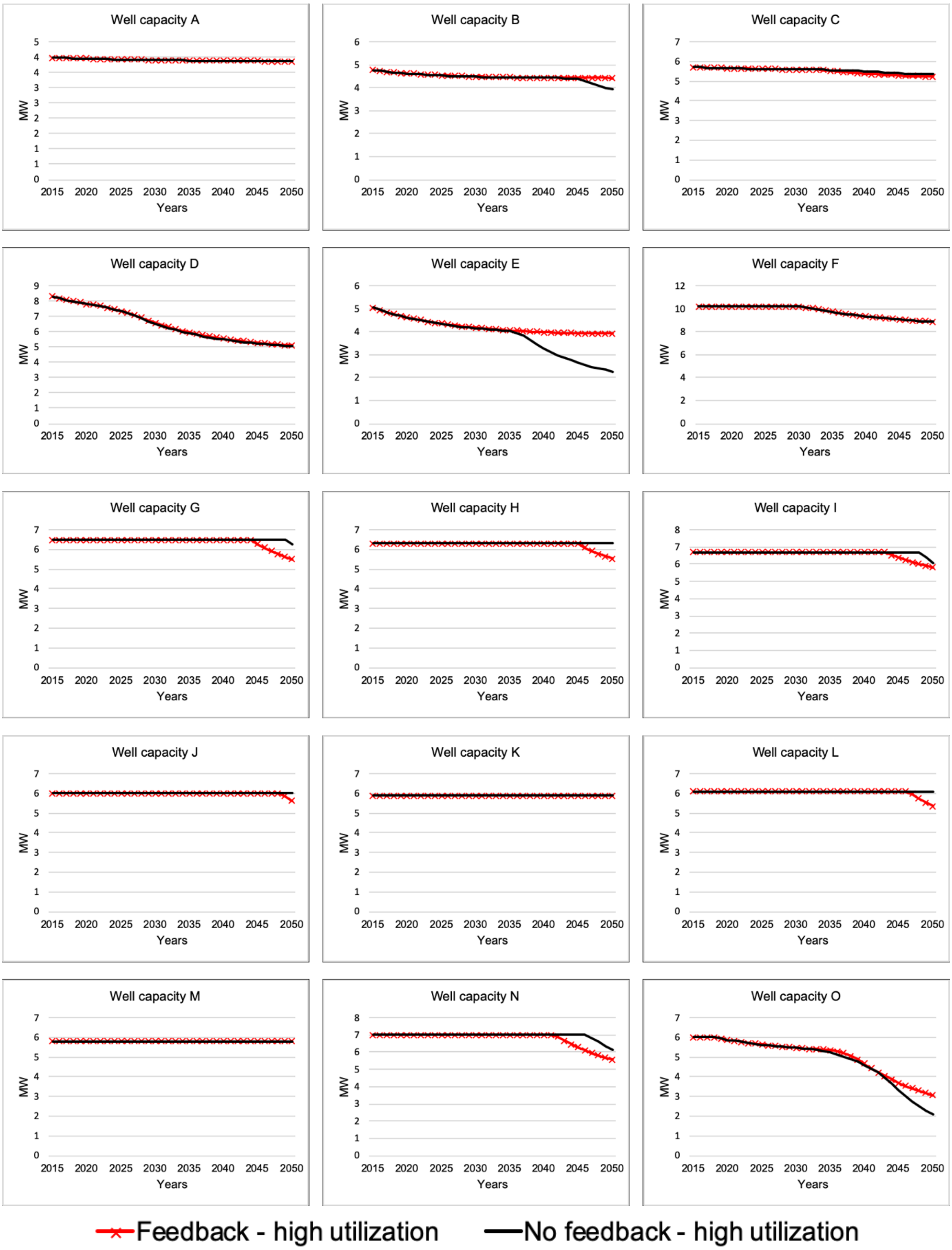

Fig. 4: Well capacity by plant and by scenario

The lowest well capacities can be found for plant D, E, F, N, and O. Plants G, H, I, N, and L only get installed towards the end of the simulation period, but similar patterns seem to emerge. Regarding the effects of resource dynamics, generally in the "No feedback" scenarios well capacities of some (i.e. B, E, O) plants are significantly lower than in the scenarios considering the feedback effect. This is particularly true for plants E and O in which their capacities decline to less than half of the original capacity. Because of higher costs (i.e. cost per MW per well) when feedback is considered, capacity expansion of plant B and E are lower than in the case of "No feedback". The implications of including the feedback thus leads to a redistribution to and earlier exploitation of other fields that are less expensive, namely, G, H, N and I. Hence, their well capacities are lowest in the scenario of "Feedback-High utilization". The well capacity changes for plant A are very small, because the plant is not economically competitive with other plants. This is because of the relatively low well capacity and related higher unit production cost. Therefore, in none of the scenarios additional capacity is added to that field. Hence, its utilization does not lead to a significant reduction in well capacity, despite having been installed before the simulation period.

The reason why resource dynamics are important for estimating well capacities of individual plants is that if resource dynamics are considered, more wells are necessary in already developed fields, which influences the production cost signal. This effect is not present in the case of "No feedback". Ignoring the impact of resource dynamics on wells leads to installation of capacity in a smaller number of fields. Thus, higher levels of exploitation and inaccurate lower unit cost of electricity in those fields occur. Hence, including feedback dynamics leads to better informed economic decisions in terms of cost as well as resources in the long term.

3.3 Costs

Fig. 5 displays the cost differences, between "Feedback" and "No Feedback" scenarios. The estimated difference in total cost due to incorporating the feedback is around 8% by 2050. The changes in estimated cost occur because more make-up wells need to be drilled when the feedback from the resources' dynamics to the economic and plant construction modules is considered. When capacity is added to an already existing plant, lower well capacities in this area leads to higher well requirements. The changes in average unit production cost are higher than in total geothermal development cost. This is because lower production levels occur when resource dynamics are considered than when they are not. Hence the unit cost of electricity production is even higher.

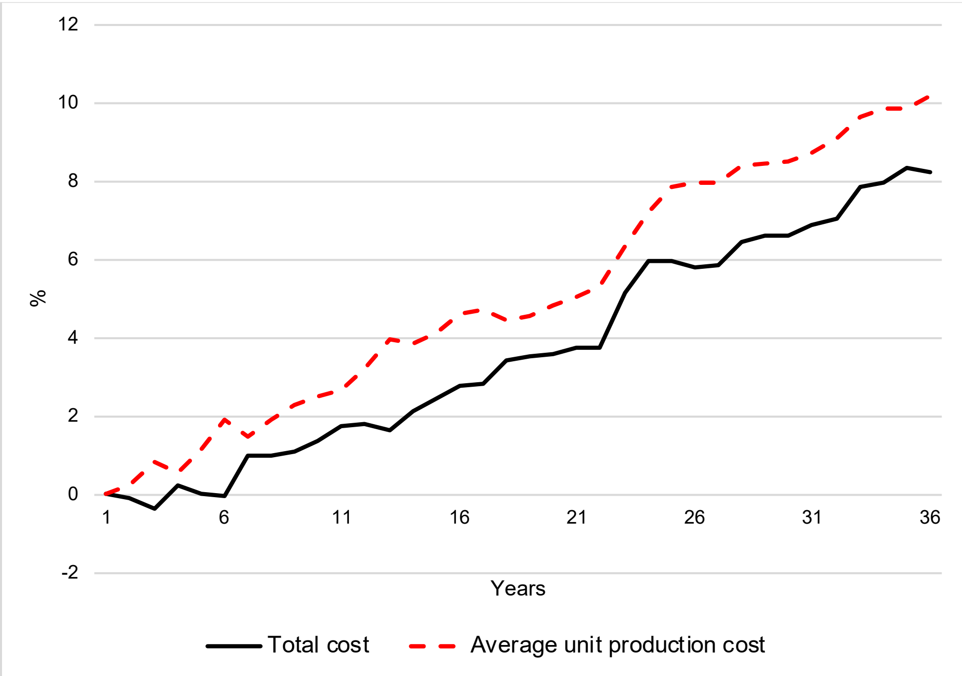

Fig. 5: Impact of resource dynamics modelling on cost estimates

4. CONCLUSION

The simulation results show the implications of incorporating resource dynamics for production, well capacities and related resource availabilities, production cost per kWh, and total geothermal development cost over the time horizon 2015-2050. Estimated production and resource availabilities are influenced by resource dynamics. This means better planning on a system's level is possible when those dynamics are considered. Additionally, the findings indicate that incorporating the dynamics of geothermal resources into energy system modelling has significant impact on estimated costs for the development of the geothermal system.

Future work that incorporates geothermal resources into national energy systems models will allow to explore a wider range of scenarios regarding resource availabilities and their implications for long-term energy system development. This is particularly important for assessing energy production cost and energy security. This can facilitate improved decision making, in countries that have high geothermal potentials and aim at exploiting them.

REFERENCES

Axelsson, G. and Stefansson, V.: Sustainable Management of Geothermal Resources, International Geothermal Conference, *Proceedings*, Reykjavík, Iceland (2003).

Bruckner, T. et al.: Energy Systems, in Edenhofer, O. et al. (eds) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, (2014) , 511–598.

Dayan, G. M. and Ambunya, M.: Geothermal Energy-Making It Renewable and Sustainable, *Proceedings*, Fourtieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, (2015).

Juliusson, E. et al.: Optimal Extraction of Geothermal Resources, Geothermal Resources Council Transactions, 35, (2011), 1457–1466. doi: 10.1002/yd.430.

Júlíusson, E. and Axelsson, G.: Stock models for geothermal resources, Geothermics, 72, (2018), 249–257. doi: 10.1016/j.geothermics.2017.11.006.

Rybach, L.: Geothermal Sustainability Assessment Framework, *Proceedings*, European Geothermal Congress. Unterhaching, Germany (2007).

Sigfússon, B. and Uihlein, A.: JRC Geothermal Energy Status Report, (2015). doi: 10.2790/959587.

Spittler, N. et al.: 'Modelling geothermal resource utilization by incorporating resource dynamics, capacity expansion, and development costs', Renewable Energy, Working paper, (2019).

Steering Committee: Final report of the steering committee of the third phase of the Master plan for Nature Protection and Energy Utilization 2013 – 2017, Reykjavik, Iceland, (2016).

Stefansson, V. and Axelsson, G.: Sustainable Utilization of Geothermal Resources through Stepwise Development, Proceedings, World Geothermal Congress, Antalya, Turkey (2005).