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CAN ENHANCED GEOTHERMAL SYSTEMS DECREASE THE COST OF A DECARBONISED SECTOR-COUPLED EUROPEAN ENERGY SYSTEM?

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1. ABSTRACT

Enhanced Geothermal Systems (EGS) hold high potential as a generating technology, but cost reduction uncertainties persist. To assess EGS's potential role in the context of this uncertainty, we here address the following question: How much cost reduction is required for EGS to be competitive in a highly decarbonised European energy system and how crucial is heat (co-)generation? To do so, we employ the sector-coupled energy system model PyPSA-Eur and optimise investment and dispatch over a full year, while incorporating EGS at different cost levels and as a generator of *electricity only, low-grade heat and power* or *low-grade heat only*. Our findings indicate that with heat generation, EGS deployment accelerates by approximately 15 years. Assuming cost reductions projected by a recent paper, this yields an installed capacity of ~100 GW borehole capacity by 2030 (equalling approximately 30% cost reduction). However, electricity generation only becomes competitive with cost assumptions for 2035 (50% cost reduction), unlocking a market exceeding 1 TW borehole capacity across Europe.

2. INTRODUCTION

Europe is expected to gradually decrease carbon emissions over the coming decades. While central technologies that contribute to this, mainly wind and solar, have seen substantial cost reductions, it is still expected that consumers will face higher cost of energy in the future [1]. One of the technologies that could undergo substantial cost reductions, thereby reducing electricity cost, are Enhanced Geothermal Systems (EGS), which involve heating brine using an open-loop system penetrating deep rock layers. However, at the current cost of drilling EGS deployment in Europe remains minimal [2].

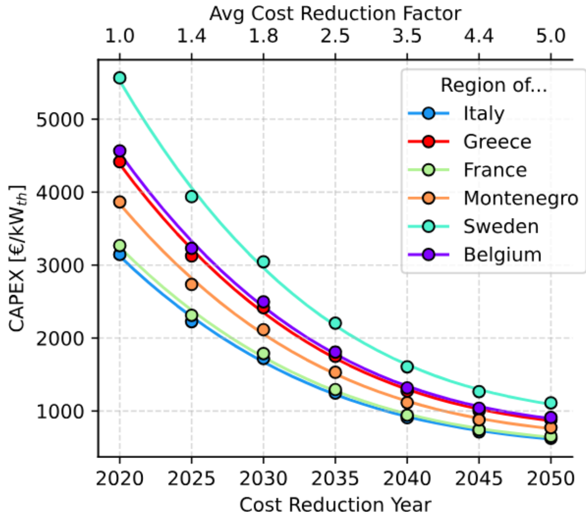

Figure 1: EGS borehole cost reductions expected in Aghahosseini et al.

The low deployment of EGS suggests that given large-scale investment, EGS could yet undergo significant cost reductions [2], leaving modellers and economists uncertain about the conditions under which EGS should be included in future system modelling. Conditions for large-scale feasibility of EGS have been explored in the context of the North American energy system, where a combination of advances in drilling technology paired with flexible well operation could lead to a cost optimal installed EGS capacity of around 100 GW in a carbon neutral system, but even in the present system, EGS makes a substantial contribution to electricity generation due to the extreme geological suitability of regions such as California

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[3]. Meanwhile, in the European context, most installed EGS systems cogenerate heat and power and generally the installed capacity is much lower [4].

Such co-generating EGS plants have in the past not been evaluated within continental scale whole system models, potentially overlooking the role of heat provision in making EGS a viable technology. Sector-coupled energy models have shown that heat, if generated carbon-neutral, is likely to be supplied at a higher marginal price than electricity. Including EGS in such a model provides a realistic context to test under which conditions EGS can contribute to the future energy system. Moreover, analyses of *electricity-only* EGS have so far only been conducted in North America [3], which has a vastly different energy system compared to than Europe.

Here, we begin this analysis by integrating EGS into the European sector-coupled energy system model PyPSA-Eur [5]. This model linearly optimises investment and dispatch over a full year with three-hourly temporal resolution and 72 nodes across Europe covering demands from the power, heat, industry, transport and biomass sectors. The same optimisation is executed with EGS incorporated at varying cost levels and operational modes: *electricity only, combined low-grade heat and power*, and *low-grade heat only*. To respect the heterogeneity of geological suitability for EGS across Europe, we use the findings of Aghahosseini et al. [2] to accurately represent relative cost levels between regions.

3. METHODOLOGY

To enable a continent-scale analysis, the present work models EGS is a linear fashion. The data from Aghahosseini et al. [2] computes the optimal balance for each 1°x1° square across Europe between increasing drilling depth and gaining cost benefits through higher generation efficiencies due to rising temperatures. This results in a pair of capital expenditure and available thermal capacity for each square, which are then inserted into the model. Aghahosseini et al. [2] further assumes cost reductions between the 2020s and 2050 based on the expected increase of installed EGS capacity and resulting technology learning.

The generated heat is integrated into the energy system through three pathways. For the *electricity only* mode, an organic Rankine cycle (ORC) is used for electricity generation at low temperatures, in the *combined low-grade heat and power* mode, the geothermal well connected to district heating networks, and therefore enabled to meet heating demand. The implementation assumes an ORC that can modulate between electricity and heat generation as in Eyerer et al. [6]. Finally, in *low-grade heat only*, the ORC is removed, leaving only a heat exchanger to transfer the cycling fluid to a temperature that is suitable for a district heating network.

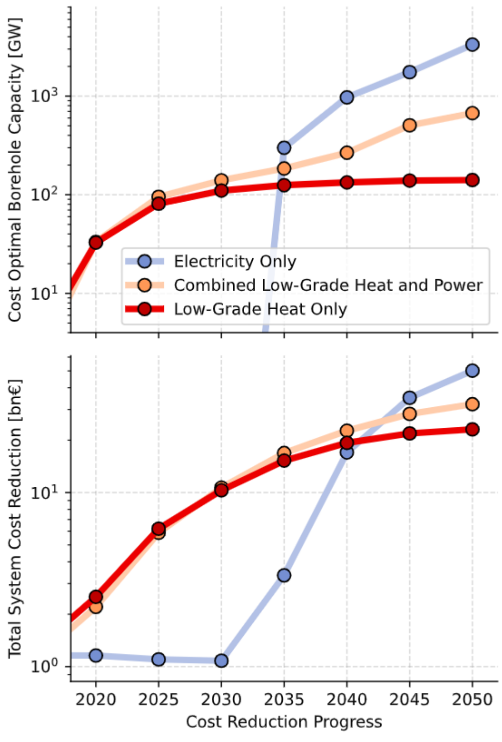

Figure 2: Cost optimal installed EGS capacity for different levels of cost reduction and operational modes.

4. RESULTS

The overall results in Figure 2 show the model to build EGS capacity at substantially higher cost when using EGS to meet heating demand. The upper section of the figure illustrates the cost-optimal borehole capacity for different levels of cost reduction and energy uses, while the lower section shows the induced total system cost reduction. Installed capacity refers to heat before its (potential) conversion to electricity at relatively low efficiency. The results show substantial EGS capacities to be built depending on the energy end use, spanning more than one order of magnitude.

For *electricity only*, the built borehole capacity peaks at around 4,000 GW, at 700 GW for *combined low-grade heat and power* and at 150 GW for *low-grade heat only*. At these capacity expansions, the total system cost is reduced by €50 billion, €35 billion and €22 billion, respectively. These values diverge notably less than the observed built capacities. While all three gradually converge to this value, large-scale adoption occurs at much higher cost for EGS applications that utilise heat directly, while electricity only sees a drop-off at a cost-reduction factor ∼2. Before this cost reduction threshold, *combined low-grade heat and power* and *low-grade heat only* build approximately similar borehole capacities at 100 GW, reducing total system cost by €3-30 billion.

5. DISCUSSION & CONCLUSIONS

This work estimates the conditions under which EGS can contribute to reducing the cost of a fully decarbonised European sector-coupled energy system, considering various levels of cost reduction and the operational modes: *electricity only, combined low-grade heat and power* and *low-grade heat only*.

The bottleneck for EGS deployment, its high cost of drilling, prevents large scale penetration at current cost levels. However, a drilling cost reduction of approximately 30% could create a market opportunity of around 100 GW given that either *heat only* or *power and heat* are generated. A further cost reduction, totalling at ~50% of the current drilling CAPEX, generation of *electricity only* becomes competitive, unlocking a market opportunity of 500-1000 GWth of generation capacity. Thus, a plausible pathway to market for EGS involves achieving cost reductions through heat-generating EGS initially, followed by expansion into the power market once drilling costs has approximately halved.

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