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Numerical modeling of high-enthalpy reservoirs: an opportunity to accelerate the geothermal industry growth in Colombia

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ABSTRACT:
A global analysis of the most recent trends in the use of geothermal reservoir simulators identified research and development (R&D) opportunities that can contribute to the growth of this industry in the LATAM region [1]. The widespread availability of open-source software offers an interesting and timely alternative for the training of young researchers and industry professionals. To assist Colombia, and taking into account the updated regulatory framework, a bibliometric analysis spanning the last decade has been undertaken. Academic programs, data availability, government funding of R&D projects, and existing professional associations were also considered. This paper provides a general overview of geothermal modeling in Colombia. The results highlight current gaps, and solutions are proposed from the perspective of reservoir simulation. This can facilitate improved decision-making for project implementation and thus accelerate the local energy transition.

1. Introduction

With 1.1 GWe of untapped geothermal potential for electricity generation [2], Colombia is yet to harness this source, hindering the third-most populous country in Latin America's efforts to meet its climate change commitments. The International Geothermal Association (IGA) deems strong geothermal policies, and strong renewable energy targets to be essential to achieving national targets to reduce carbon dioxide (CO_2) emissions [3]. Colombia's Decree 1598 of 2024, strives to introduce a competitive process for permit allocation, and calls for developers to confirm geothermal resources through detailed feasibility studies. Appropriate financial incentives and risk mitigation mechanisms are also required, especially for the drilling exploratory phase. Numerical modeling can help as it is one of the tools available to characterize, understand, and predict the behaviour of reservoirs. Additionally, the trend toward coupling Machine Learning (ML) algorithms with

traditional numerical models reduces computational costs. To identify opportunities to implement this technology through the use of open-source codes and ML, we have analysed publications dating from 2016. This paper describes the status of geothermal reservoir modeling in Colombia and proposes how projects could benefit from currently available data. Making the most of this information would boost industry and academia by enabling better-informed decision-making, promoting R&D, enhancing efficiency and contributing to the overall progress of the country.

2. Methodology

A literature review was conducted using a combination of electronic sources (bulletins, theses and social media) and two databases. Articles stored by the IGA were filtered by year and restricted to those that mentioned Colombia in the abstract. Consulting Elsevier's Scopus involved a two-term Boolean search: "Colombia" AND "geothermal". The chosen timeframe acknowledges the first National Geothermal Meeting (RENAG for its acronym in Spanish). From the 130 database-hits, 108 were selected and added to the 259 other-sourced documents. Thus 367 publications were included for the analysis presented here. To make best use of the most recent ML applications in subsurface geothermal technology [4], 84 articles were classified into 7 categories: exploration, reservoir characterization, reservoir engineering, production and injection well engineering, petrophysics, drilling, and seismicity. 20 publications addressing country update; regulations; environment; socioeconomic; and associations, were grouped separately. *Biblioshiny* was used for the bibliometric analysis.

3. Results

New since the latest country update [5] are the following: Decree 1598; a subject to commence in 2026 at the National University's Faculty of Mines; funding for R&D including modeling through grant 951 by the Ministry of Science, Technology, and Innovation and the National Hydrocarbons Agency; and a cluster [6]. Our analysis also shows that no publication was reported on drilling but, since 2023, the first two training courses on the matter have been delivered. Conversely, exploration seems to be the most addressed topic, followed by reservoir characterization. Only one study was found to use ML, applied for predicting Colombia's geothermal gradient [7]. At least a dozen local and three international universities have conferred under- and postgraduate theses in geothermal. Among the latter, an AUTOUGH2/Waiwera model was developed to perform a resource assessment of the Nevado del Ruiz Volcano (NRV) [8]. Fig1 shows laws and legislation is an emerging theme, and seismology is highly studied; while volcanoes and geochemistry are areas of advanced knowledge. The NRV remains the most studied and as depicted in Fig. 2., interest in the Paipa project is strong.

Figure 1. Scopus Thematic Map

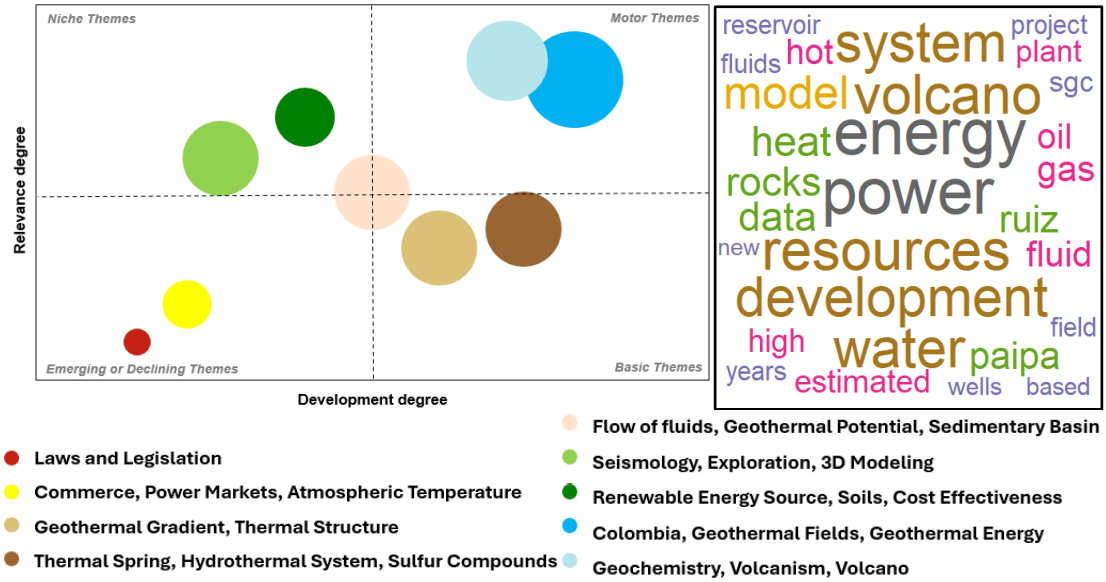

Figure 2. IGA Word Cloud

4. Discussion

As an emerging geothermal market, Colombia must target risk-reduction to attract investors. Our analysis considers tools mapped by the IGA [3] while keeping abreast of innovative modeling solutions from global leaders. Grant 951 is promising. It is designed to deepen understanding of renewable energy sources and CO_2 storage. Similar initiatives are required for modeling of drilling as it is a costly contributor to geothermal development. ML algorithms can help to optimize the prediction of target locations [9]. Geothermal induced seismicity is also a risk forecastable with ML [10]. The NRV model [8] follows a paragon workflow: it was built with Waiwera, an open-source simulator [11], and used a new method based on well-established uncertainty quantification techniques [12]. This roadmap requires an ensemble of models and high computational speed. Being highly parallelized, Waiwera can massively shorten time to deliver results, especially when supercomputers are used, e.g. Colombian BIOS and Apolo [6]. The NRV model could be improved by addressing uncertainties associated with the magnetotelluric surveys and petrophysical data. Shallow neural networks could estimate subsurface temperatures, and combined with a Hidden Markov Model can identify spatial distribution of rock properties and the intrinsic depositional rules [4]. Government-supported training and international cooperation is underway. This is noticeable through RENAG, which has also attracted active participation from the IGA and Ecopetrol, Colombia's largest oil and gas company. Researchers will need to have access to data suitable for ML. We propose a central accessible geothermal repository as cross-domain data gathering to efficiently maximise collective knowledge. Lastly, all work needs to be coordinated with the local authorities to develop a strong regulatory framework.

5. Conclusions

Colombia is at a turning point. The country's transferable knowledge from the hydrocarbon industry is suitable for building on its almost 6-decades of volcano exploration data. Weaknesses include lack of access to simulators and access to skilled professionals. Yet, the opportunity to use avant-garde open-source codes with ML tools awaits. This proposal opens possibilities to collaborate, create new research lines, reinforce academia-industry alliance and nurture socio-economic development. Priorities should be to counter any threat that might arise from a national economic crisis, insufficient programs for financial risk mitigation during the initial stages, unfavorable electricity rates for geothermal generation or losing momentum. By embracing new modeling techniques and attending to these other issues, Colombia will be en route to reducing its greenhouse gas emissions by 51% by 2030 and to achieving net zero by 2050.

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