PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Learning in geothermal power and heat generation – A German case study

Florian Mueller[1], Bjarne Steffen[2] and Tobias Schmidt[1]

[1]Energy and Technology Policy Group, ETH Zurich, Switzerland [2]Climate Finance and Policy Group, ETH Zurich, Switzerland

florian.mueller@gess.ethz.ch

Keywords: Geothermal energy, learning, innovation

ABSTRACT

Geothermal energy, while generally recognized for its potential in climate change mitigation, has featured a much slower global deployment over the last two decades than other renewables like wind and solar PV. The latter has experienced massive cost reductions due to incremental innovation ("learning") and economies of scale. In contrast, geothermal cost data remains inconsistent, with a large cost variation between technologically similar projects and some studies showing strong cost increases over time. This inconsistency in cost data highlights the need for a detailed investigation into the factors influencing geothermal energy cost dynamics, including the differentiation between sub-technologies and regional variations. Here, we focus on the German geothermal sector to detect successful learning and barriers across several channels described in the innovation literature. We reveal how technological progress, characterized by the exploration of higher-temperature resources and enhanced well yields, coexists with significant barriers, particularly in project complexity and market structure. These findings are a first step towards a detailed understanding of geothermal innovation and cost dynamics and offer first insights for policymakers and industry stakeholders to foster innovation, cost reductions, and capacity growth.

1. INTRODUCTION

Deep geothermal energy is considered a key lever for climate change mitigation (Tester et al., 2006). It can generate firm electricity and support the transition to renewable heating, including high-temperature industrial heat applications (Ricks et al., 2024). However, the global build-out of geothermal energy has been substantially slower than for other forms of renewable energy, like wind and solar photovoltaics (PV) (International Renewable Energy Agency, 2022). The build-out dynamics seem to correlate with reductions in the investment and levelized cost of renewable energy technologies (Creutzig et al., 2017). For example, solar PV capacity has increased 25-fold while its levelized costs of electricity decreased by 89% between 2010 and 2022. In contrast, geothermal energy capacity has only increased by 45%, and its LCOE has – according to some sources – increased by 6% within the same period (International Renewable Energy Agency, 2023). However, whether these numbers accurately represent the cost dynamics and which factors could drive cost increases remains unexplored. This knowledge gap is problematic as these numbers inform not only public and private investment decisions but also energy system models, which inform energy and climate policy.

To describe the cost dynamics of (renewable energy) technologies, it is common to rely on experience curves, which describe the empirical situation that specific costs typically decrease by a fixed percentage for every doubling of cumulatively installed capacity (the percentage is described as "experience rate", ER). Experience curves are often used to describe the effect of learning throughout an industry on cost decreases and how they differ between technologies (Junginger et al., 2010; Malhotra & Schmidt, 2020; Rubin et al., 2015). Compared to other renewable energy technologies, geothermal energy has received little attention in experience curve analyses, and the results of the few extant studies are rather inconclusive, reporting ERs of -29% -53% (Yao et al., 2021) – which would be extremely negative values when compared to other technologies, e.g., bioenergy. Furthermore, the variance between the data points in the studies is often very high. For example, according to the International Renewable Energy Agency (2023), the installed cost of geothermal energy varies by a factor of ten within the same year and technology.

The inconclusive data about the cost dynamics of geothermal energy calls for a more nuanced investigation of the actual relationship between deployment and cost and the reasons behind the observed cost variations and identified increases. One potential source of cost variations lies in aggregating different geothermal sub-technologies with distinct cost profiles, such as direct steam plants and binary plants. Furthermore, cost dynamics and technological experience are partly local phenomena, meaning regions may progress differently (Huenteler et al., 2016; Malhotra & Schmidt, 2020). Although there have been studies about the cost dynamics of some parts of the geothermal value chain, most notably the drilling (Lukawski et al., 2014; Sanyal, 2004; Sanyal & Morrow, 2012), the literature lacks holistic insights into developments of the overall technology, including all its components. While here, we do not estimate experience rates; we analyze technological learning and its drivers and barriers in greater detail.

A better understanding of geothermal cost dynamics should be based on the theory explaining cost reductions observed in experience curves, which represents a sub-set of the innovation literature. Following the innovation literature, possible reasons for cost reductions can be attributed to experience within the industry and fall within one of the following categories: Economies of scale, where fixed costs can be distributed over more produced units; learning by doing, where a firm or industry learns by repeated practice; learning by using, where a firm or industry learns from using a product or service; or learning by interacting, where the interaction of firms on different levels of the value chain jointly improve a product or service (Arrow, 1962; Malerba, 1992; Papineau, 2006; Rosenberg, 1982). Importantly, variance in cost reductions between different technologies can be explained by differences in technologies' design complexity and the need to customize (Malhotra & Schmidt, 2020). Another potential factor is the absence of adding capacity, which can lead to the loss of knowledge within an industry over time (Argote, 2013; Argote & Epple, 1990; Grubler, 2010; Sturm, 1993). Finally, cost dynamics can also be driven by general price trends, such as from raw materials, spillovers from advances in other technologies, and changes to regulation and market structure (Stephan et al., 2021).

To address the gap in the existing literature and circumvent the technology lumping and local vs global learning issue, we conduct a case study of the cost dynamics, focusing on one country (Germany) and one sub-technology: binary plants, producing heat and/or power. Germany is among the top 20 countries for geothermal energy production and had a particularly dynamic build-out of geothermal power plants in the last two decades, mainly due to policy incentives. We collect data from (1) multiple public and proprietary databases, complemented by desk research to fill gaps and resolve inconsistencies, focusing on technological parameters of plants, and (2) eleven interviews with project owners and key stakeholders from the geothermal value chain. We focus on the development of the targeted resources, i.e., the depth and temperature of reservoirs and achieved flow rates. Furthermore, we analyze the interviewed experts' statements and link them to the principles of learning theory.

2. METHODS

The scope of this study comprises geothermal projects with a resource temperature of at least 60°C and depths of at least 1,500 meters. Our quantitative data is based on extensive desk research drawing on publicly available and proprietary databases. Missing and suspected uncertain data was also gathered from expert interviews. Interviews were conducted between September 2023 and January 2024. The experts were selected so that the most relevant projects were covered. Also, we selected experts to cover the most crucial parts of the geothermal value chain, including the factors with the highest cost contribution and criticality for project success. The interviews were semi-structured and lasted between 60 and 150 minutes. All interviews were recorded and transcribed.

3. RESULTS

3.1 Quantitative results

The key metric to determine the economic performance of energy generation technologies and projects is usually described as an output quantity per cost. In the case of German geothermal power plants, the output is mostly electricity and heat. Some plants only have electricity or heat generation. A plant's output is primarily determined by the resource temperature times the mass flow from that resource. This section investigates which resources have been targeted over time and what yield project operators achieved. Within the given scope, the first plant to be considered started operations in 1984, the most recent in 2023. The plants are in three regions in Germany: The Northern German Basin, the Upper Rhine Valley, and the Bavarian Molasse. The region has implications on drilling costs, operations, and the geothermal gradient, indicating the temperature increase per depth. It should be noted that in hydrothermal applications described in this study, project operators depend on the presence of water-conducting layers underground. These layers are typically only a few hundred meters in thickness. Therefore, at any given location, the reservoir temperature and depth cannot be chosen freely but is limited within narrow margins. The economic benefit of a given resource disproportionally increases with temperature. In heating, the lower temperature of heating grids is usually around 60°C; therefore, only the temperature above this can be used. For electricity generation, the Carnot efficiency of plants increases with temperature, making high temperatures desirable. So far, all plants with electricity generation have resource temperatures of at least 100°C. Below this level, the generation of electricity is not economically viable.

As observed in Figure 1, the first projects were in shallow resources and, therefore, easier to use. However, as there is a relationship between resource temperature and depth, called the geothermal gradient, more shallow resources also have lower temperatures and power output. With greater reservoir depths, the costs for drilling increase. The cost increase emerges from longer drilling times and the need for larger drilling rigs with higher hook loads as drill and casing strings become heavier. Furthermore, higher temperatures are challenging for the tools used in drilling and lead to cost increases. The data shows that hotter and deeper resources have only been exploited gradually, which can be seen as a technological progress and positive experience effect as project owners accepted the higher financial risk for deeper wells. Notably, projects in the Upper Rhein Plain have a higher geothermal gradient and were the first ones with temperatures exceeding 140°C. So far, the targeted temperatures have not exceeded 160°C, and the depths have been below 6,000 meters. Temperatures of around 160°C have already been used from as early as 2007, however, the well depths have increased more steadily over time. In other words, the same high temperatures have only been found in deeper reservoirs. As the drilled depths increased, it can be argued that improved drilling technology made it possible to find high temperatures in more places. Notably, not all wells target very deep reservoirs. The fact that there are still new projects in shallow depths can be attributed to the fact that heat, other than electricity, cannot be transported over long distances. The projects with lower target temperatures were all built for heat demand.

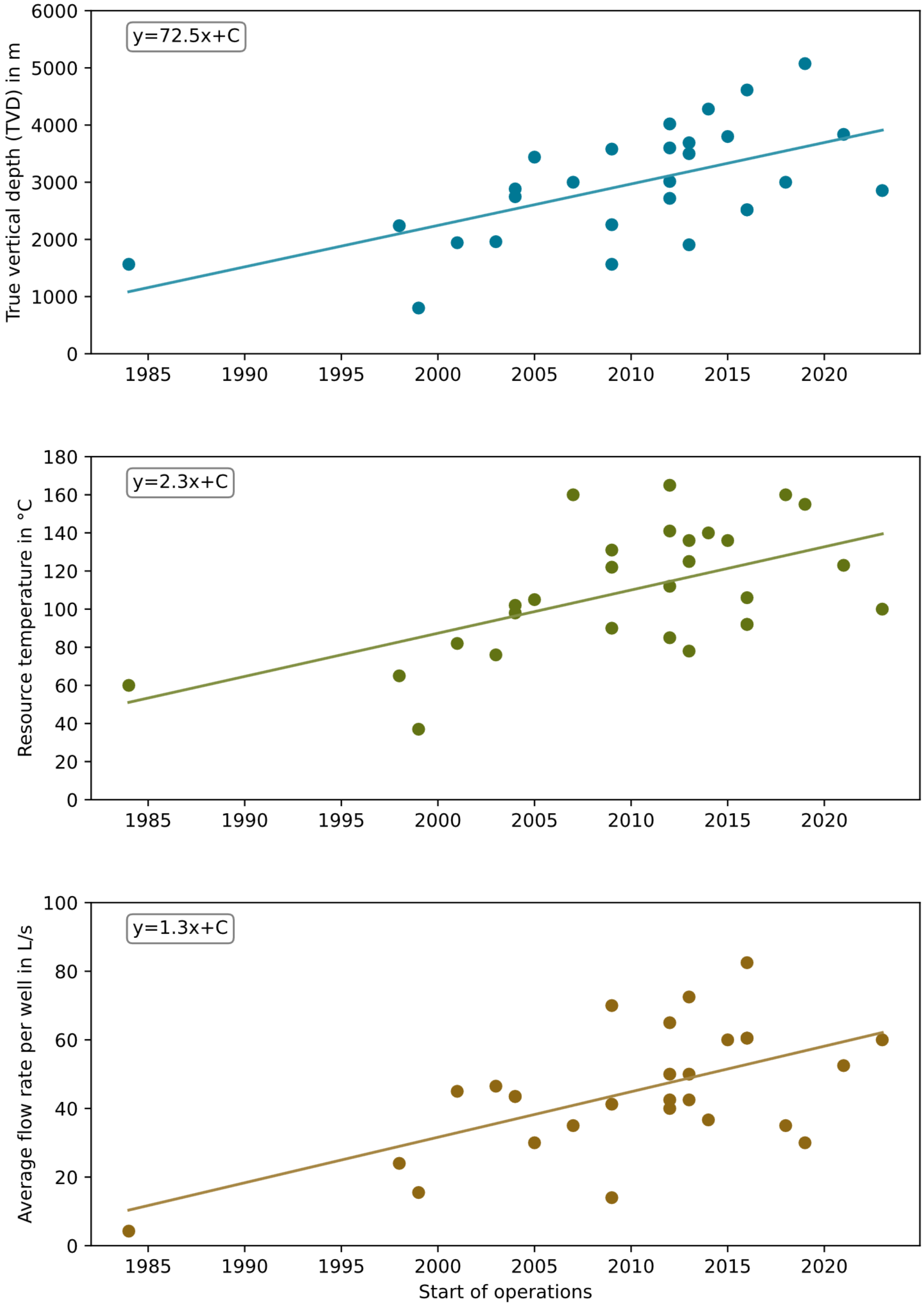

Figure 1: Depth (1a) and temperature (1b) and average flow rates per well (1c) of the considered projects in Germany between 1983 and 2023. Average flow rates are derived from the total flow rate per power plant divided by the well count, including all production and reinjection wells.

The flow rate from reservoirs is directly proportional to the plant's output. Furthermore, there are scale effects from higher flow rates. Other than for reservoir temperature, the flow rate primarily affects plant output but does not directly affect plant costs. This is because well costs are primarily determined by depth. The flow rate is hard to anticipate; therefore, wells are designed for expected flow rates, but flow rates in practice can be considerably lower. This poses an inherent uncertainty in the exploration of hydrothermal resources. In extreme cases with very low flow rates, projects need to be abandoned.

Figure 1c shows that flow rates have increased over time, which can be attributed to improved ways of finding good drilling targets. The flow has increased by 1.3 L/s per year on average. This trend exists despite the expected negative correlation between reservoir depth and flow rate, as water-conducting cracks generally become smaller with increasing depth and pressure. Despite the general trend of increasing flow rates, it can be observed that there is considerable uncertainty in flow rates, even in more recent projects. In at least two cases, lower-than-expected flow rates needed to be compensated for by adding new wells. For example, this was the case for the project in Bavaria in 2005. An alternative interpretation of the increasing flow rates after 2009 is that projects with lower flow rates were not profitable and were abandoned in the first place. This claim, however, is hard to prove, as only a few abandoned projects publish their flow rates.

Our synthesis of the implications for learning and cost dynamics in geothermal energy reveals a nuanced picture. Over time, there is a consistent increase in both drilling depth and target temperature, at rates of 73 meters and 2 degrees Celsius per year, respectively. This trend indicates a shift towards more valuable resources, particularly for electricity generation, which inherently involves higher costs and increased project complexity due to the greater depths and temperatures. Such a shift suggests that while technological learning is advancing, it may be offset by the industry's push into more challenging territories. In the long term, this pursuit of superior resources is expected to lead to lower energy costs, yet exploring current technological boundaries may result in short-term cost escalations.

Additionally, the observed improvement in flow rate by 1.3 liters per second per well annually points to a growing proficiency among project developers in identifying and exploiting quality resources, thereby enhancing energy cost efficiency. This advancement indicates a reduced geological uncertainty, contributing positively to the sector's learning curve. However, it is important to acknowledge a potential selection bias in our analysis, as it excludes projects that were discontinued post-drilling, numbering seven in our dataset. This exclusion may skew the perceived advancements and warrants consideration when interpreting the findings.

3.2 Qualitative results

This section summarizes qualitative findings based on the expert interviews conducted. We separately discuss the individual learning channels and other cost-influencing factors, such as learning by doing, learning by using, learning by interacting, spillovers from other sectors, and changes to regulation and market structure. Furthermore, the key impediments to technological progress, technological complexity and need for customization, regulatory compliance costs, resource scarcity, and market dynamics are described. The key learning mechanisms and impediments to technological progress are listed Table 1 and Table 2, respectively.

Several factors contribute positively to learning and efficiency gains (Table 1). Practical experience, particularly in drilling and project management, including the intricacies of permitting processes, fosters learning by doing, streamlining operations over time. Similarly, operational experience contributes to learning by using, particularly in enhancing geological understanding for drilling and optimizing power plant operations. Spillovers from advancements in drilling and power plant technologies offer significant benefits, enhancing efficiency and reducing the costs of geothermal projects. The market structure is evolving with the entrance of larger, more experienced players who prioritize cost efficiency. This shift is particularly noticeable in the heating market, where long-term contracts and limited competition create a stable demand environment. Furthermore, growing confidence in demand, bolstered by public support for renewable energy and clear decarbonization mandates, encourages investment and innovation in the sector, promising a more rapid advancement in geothermal energy technologies and cost reductions.

Despite some learning in the industry, the advancement of geothermal energy is hindered by a blend of technology-inherent challenges and market structure issues (Table 2). The geology of geothermal sites introduces significant uncertainty and complexity, with the true nature of the resource only becoming clear after well tests. Each plant demands customization, leading to high investment risks and extended planning durations. Additionally, the market structure, characterized by the dominance of local utilities often inexperienced in geothermal projects, exacerbates these challenges. These utilities, typically managing only a single plant, lack the expertise and scale needed for efficient development. The overall market's limited size further impedes progress, preventing the realization of network effects, such as shared data use and collective insurance schemes, and weakening negotiation power with suppliers, notably from the oil and gas sectors. The absence of industry standards also contributes to the slow pace of the cost reduction and technological advancement of geothermal energy.

The findings allow us to estimate the impacts of currently ongoing trends in the industry, even though we excluded projects and technologies that are not yet operational from our survey. Several drivers offer promising prospects for enhancing learning and reducing costs in the geothermal energy sector. As geological knowledge expands, geological uncertainties are expected to decrease further, leading to more predictable and potentially lower costs. The industry will also likely benefit from increased network effects as it grows and more stakeholders engage, fostering collaboration and information sharing. Currently ongoing attempts to standardize project development, even though the extent and timeline of the standardization is not yet clear, promise to streamline processes and reduce costs. A significant shift is expected from the market entry of more experienced and cost-focused firms, which could drive efficiency and innovation. A notable policy change in recent years, shifting subsidies from electricity generation to heating-only projects, is set to impact project design and economics profoundly. In particular, we expect projects to target shallower depths and lower temperatures, which could significantly lower plant construction and operational costs despite reducing the potential energy output.

In sum, the combined weight of the obstacles often surpasses the positive impact of learning factors, which makes a low to slightly negative industry-wide learning rate, as observed in the literature, plausible. However, it is important to acknowledge that the mentioned factors do not impact all projects uniformly. The cost and efficiency of a geothermal project can vary greatly depending on its specific circumstances. For instance, drilling in a geologically familiar area, using parameters from previous projects, can significantly reduce costs compared to exploratory projects in uncharted regions. Moreover, projects that leverage scale effects from drilling multiple wells at a single site can realize further cost reductions. These variances highlight the complexity of the geothermal energy industry and underline the importance of considering these diverse factors for a comprehensive scientific understanding and for driving practical improvements in the field.

Table 1: Key drivers of technological learning according to expert interviews

Learning-by-doing
- **Faster and more reliable drilling** in known underground layers and in successive drillings at one site.
- **Increased know-how about the required flexibility required in the project design**. For example, it has turned out that even neighboring wells can have differing brine temperatures and flow rates, so keeping the designed flow direction open makes sense until well tests have been conducted.
Learning-by-using and learning-by-interacting
- **Improved geological knowledge from measurements and long-term production experience of neighboring plants**.
- **More efficient Organic Rankine Cycle (ORC) turbine systems** with up to 50% higher efficiency.
- **Faster permitting processes that more accurately assess actual risks**, enabled by improved mutual understanding of the project companies submitting project plants and the authorities approving the plans.
- **Increasing heating plant efficiency through lower return flow temperature from heating grids**
- **Longer lasting pumps and reduction of unplanned pump failures** due to more "gentle" use
- **Improved drill bits with better adaptation to the actual geology** due to increased cooperation of drill bit manufacturers with drilling firms.
Spillovers from advances in other sectors
- **Improved drilling rigs, drilling tools, underground and downhole measuring technology, and decision-making methods** from the oil and gas industry. The most notable improvements include automated rigs, polycrystalline diamond (PDC) bits, and 3D measuring.
- **Sealing materials** from the automotive industry
Changes to regulation and market structure and social factors
- **Improved confidence in consumer demand and a strong decarbonization mandate** allow for scale effects due to larger projects.
- **Shift of industry focus from electricity to more stable heating markets** with higher price stability and long-term contracts and less competition**.** The environment with lower business risks facilitates long-term investments and knowledge build-up in the industry.
- **Increased confidence in firm-internal capabilities and understanding of project risks** allows larger companies to carry more risk on their own and rely less on outsourcing of work packages.
Economies of scale and network effects
- **Emergence of a market for project insurance**

Table 2: Key impediments of technological learning according to expert interviews

Technological complexity and need for customization
- **Inherent geological uncertainties:** Despite better knowledge about the underground from existing projects and better measurement methods, there is still considerable uncertainty about a project's success. The uncertainty exists especially in regions with no existing plants.
- **Soil composition, fluid flow rate, temperature, and brine quality individual to each location** require each drilling project and plant to be designed individually, which increases project cost and planning times. Furthermore, there is no standardized or tested equipment for some conditions.
- **Large risk sums too large for the involved stakeholders:** The risk of a project failure after drilling, with a damage sum of several tens of millions of euros, often must be borne by companies or municipalities that do not have other projects to distribute the risks and are too small to cover the risk sum in case of a project failure.
- **Complex and powerplants as one-offs:** Early powerplants, especially with the Kalina technology, were poorly understood and unreliable initially. Due to the dissimilar technology and a generally small number of plants, there were often no examples to learn from in case of issues.
- **Expensive nature of heat transport constrains plant locations and options for mutual backups**
Limited knowledge exchange between market participants
- **Limited exchange of experiences and learnings between subsequent projects among small local companies**
- **Limited exchange of data from earlier underground surveys:** Many underground studies have been conducted in the last decades, the majority for oil and gas exploration. This knowledge, however, is not readily available for new projects. There is no central system to record which surveys have been conducted and who the data owners are.
Regulatory landscape and costs for regulatory compliance
- **High environmental requirements**, e.g., for drilling in groundwater layers and for noise emissions.
- **Lack of a central authority and standardized processes:** As the permitting processes and also subsidy schemes are distributed between multiple authorities, many of them local, each project developer has to develop to learn on their own how to navigate these processes.
- **Costly certification of oil and gas rigs for the European market** restricts the free market for rigs between Europe and other regions, e.g., the Middle East.
- **Safety margins require more material and more expensive materials**, e.g., thicker and higher-grade steel for well casings. Some stakeholders noted that they considered the safety margins put forth by authorities to be unnecessarily high.
Resource scarcity and influences from other markets
- **Increasing wages due to lack of skilled workforce**
- **Increased material prices**
- **Decreased availability of drilling equipment due to industry downturn in the European oil and gas market:** For example, drill pipes and well casings, which could be bought from stock, now have to be ordered.
Market dynamics
- **Lacking cost focus and project management competencies of municipality-owned utilities**
- **Lacking negotiation power due to the small size of the geothermal market and even more granular distribution of projects**
- **Uncertainty in the rig and drilling market due to lacking long-term contracts** as the small utilities usually only have a single project without plannable follow-ups and there is little regulatory long-term target setting.
- **Splitting of drilling projects among typically more than a dozen subcontractors hinders fast and holistic improvements to processes.** The reasons lie in the generally high efforts for coordination and pre-defined contracts with

little leeway for each contractor. The projects are often split in this granular way as no single firm has sufficient knowledge and willingness to carry the risk for the entire project.
- **Lacking industry standards and loss of trust due to past project failures:** The lack of standards in the past and limited knowledge, especially of smaller project developers, has led to many failed projects. Therefore, there is skepticism among local communities and some industry stakeholders, and it only improves slowly over time and with more successful projects.
- **Cultural challenges within public utilities and oil and gas firms** due to the geothermal projects' small-scale and exploratory structure. Utilities often struggle with handling uncertainties, while oil and gas firms are often not used to operating small, flexible business units.

4. CONCLUSIONS

In this paper, we identified learning in the German geothermal industry over the last four decades along several channels. At the same time, we also identify barriers to learning and cost reductions. Furthermore, we quantified the most important technological trends. We showed that there has been progress in finding higher-temperature resources and achieving better yields from the drilled wells. The observed trends suggest both technological progress and the industry's continuous new challenges. The most critical hindrances to technological learning lie in the complexity of projects and the need to customize projects, but also in the market structure, which is not optimal for fostering fast industry-wide knowledge build-up and cost improvements. On the contrary, we identified several areas and mechanisms of technological learning, such as technological spillovers from the oil and gas industry and the knowledge build-up in drilling and operations. In combination, the described factors in the industry enhance the understanding of progress in the industry beyond the previously existing literature on global cost trends. Our findings constitute a first step towards explaining global geothermal learning and cost progress, both retrospectively and as a basis for future development. In addition, our findings inform policymakers and industry stakeholders in their pursuit to enhance learning, decrease costs, and foster the build-out of geothermal energy.

Future research should correlate the findings of this study with actual cost. Moreover, there is a need to evaluate the extent to which the conclusions drawn from the German context are applicable globally. This will involve investigating the transferability of the identified drivers and impediments to other regions and contexts, thereby offering actionable insights and recommendations for the broader geothermal industry. Such studies could significantly enhance the understanding of geothermal energy's role in the global transition to renewable energy sources and inform policy and investment decisions worldwide.

ACKNOWLEDGEMENTS

We thank the interviewees for their valuable time and insights. We also thank Innosuisse for providing the funding necessary to conduct this research as part of the AEGIS-CH project (PFFS-21-48 / Agreement Nr. 5009973).

REFERENCES

Argote, L. (2013). Organizational learning: Creating, retaining and transferring knowledge. *Organizational Learning: Creating, Retaining and Transferring Knowledge*, 1–217. https://doi.org/10.1007/978-1-4614-5251-5/COVER

Argote, L., & Epple, D. (1990). Learning Curves in Manufacturing. *Science*, *247*(4945), 920–924. https://doi.org/10.1126/science.247.4945.920

Arrow, K. J. (1962). The economic implications of learning by doing. *Review of Economic Studies*, *29*(3), 155–173. https://doi.org/10.2307/2295952/2/29-3-155.PDF.GIF

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy 2017 2:9*, *2*(9), 1–9. https://doi.org/10.1038/nenergy.2017.140

Grubler, A. (2010). The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, *38*, 5174–5188. https://doi.org/10.1016/j.enpol.2010.05.003

Huenteler, J., Niebuhr, C., & Schmidt, T. S. (2016). The effect of local and global learning on the cost of renewable energy in developing countries. *Journal of Cleaner Production*, *128*, 6–21. https://doi.org/10.1016/J.JCLEPRO.2014.06.056

International Renewable Energy Agency. (2022). *Renewable Energy Statistics 2022*. www.irena.org

International Renewable Energy Agency. (2023). *Renewable Power Generation Costs in 2022*. www.irena.org

Junginger, M., Sark, W. Van, & Faaij, A. (2010). *Technological learning in the energy sector: lessons for policy, industry and science*. Edward Elgar Publishing. https://doi.org/https://doi.org/10.1016/j.enpol.2005.04.012

Lukawski, M. Z., Anderson, B. J., Augustine, C., Capuano, L. E., Beckers, K. F., Livesay, B., & Tester, J. W. (2014). Cost analysis of oil, gas, and geothermal well drilling. *Journal of Petroleum Science and Engineering*, *118*, 1–14. https://doi.org/10.1016/J.PETROL.2014.03.012

Malerba, F. (1992). Learning by Firms and Incremental Technical Change. *The Economic Journal*, *102*(413), 845–859. https://doi.org/10.2307/2234581

Malhotra, A., & Schmidt, T. S. (2020). Accelerating Low-Carbon Innovation. *Joule*, *4*(11), 2259–2267. https://doi.org/10.1016/J.JOULE.2020.09.004

Papineau, M. (2006). An economic perspective on experience curves and dynamic economies in renewable energy technologies. *Energy Policy*, *34*(4), 422–432. https://doi.org/10.1016/J.ENPOL.2004.06.008

Ricks, W., Voller, K., Galban, G., Norbeck, J. H., & Jenkins, J. D. (2024). The role of flexible geothermal power in decarbonized electricity systems. *Nature Energy 2024*, 1–13. https://doi.org/10.1038/s41560-023-01437-y

Rosenberg, N. (1982). *Inside the black box: technology and economics*. Cambridge University Press. https://doi.org/10.1017/CBO9780511611940

Rubin, E. S., Azevedo, M. L., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, *86*, 198–218. https://doi.org/10.1016/j.enpol.2015.06.011

Sanyal, S. K. (2004). Cost of geothermal power and factors that affect it. *Twenty-Ninth Workshop on Geothermal Reservoir Engineering*.

Sanyal, S. K., & Morrow, J. W. (2012). Success and the learning curve effect in geothermal well drilling - A worldwide survey. *Thirty-Seventh Workshop on Geothermal Reservoir Engineering*.

Stephan, A., Anadon, L. D., & Hoffmann, V. H. (2021). How has external knowledge contributed to lithium-ion batteries for the energy transition? *iScience*, *24*(1), 101995. https://doi.org/10.1016/J.ISCI.2020.101995

Sturm, R. (1993). Nuclear power in Eastern Europe: Learning or forgetting curves? *Energy Economics*, *15*(3), 183–189. https://doi.org/10.1016/0140-9883(93)90004-B

Tester, J. W., Anderson, B. J., & Batchelor, A. S. (2006). *The Future of Geothermal Energy*. http://www1.eere.energy.gov/geothermal/egs_technology.html

Yao, Y., Xu, J. H., & Sun, D. Q. (2021). Untangling global levelised cost of electricity based on multi-factor learning curve for renewable energy: Wind, solar, geothermal, hydropower and bioenergy. *Journal of Cleaner Production*, *285*, 124827. https://doi.org/10.1016/J.JCLEPRO.2020.124827

APPENDIX

Table A1: List of interviewees

Nr.	Type of company	Position
1	Drilling service provider	Drilling engineer
2	Communication agency	CEO
3	Reservoir engineering consulting	CEO
4	Geothermal start-up	Board member
5	Oil and gas major	Geothermal business development manager
6	Insurance	Managing partner
7	Engineering consultancy	Head of engineering
8	Energy utility	Head of geothermal project planning
9	Powerplant operator	CEO
10	Drilling contractor	CEO
11	Powerplant operator	Project planning engineer

Table A2: List of guiding questions for expert interviews

Q1	What roles have you had in the geothermal or related industries?
Q2	Can you explain the past innovations in the industry in the last ca. 20 years?
Q3	Within the projects you recently completed, how would you explain cost differences?
Q4	Can you quantify typical cost and drilling parameters, incl. historical values?
Q5	Can you quantify the costs of recent projects?
Q6	Can you quantify technical parameters of recent projects?
Q7	How promising are recent innovations in the industry in your view?
Q8	Would you say that the approach to projects has changed recently?
Q9	Have there been significant changes in the industry landscape recently in your view?
Q10	Do you have any questions or comments on the interview?
Q11	Can you recommend other experts in the field that we could contact?