NET ZERO WORLD INITIATIVE

Accelerating Global Energy System Decarbonization

Technical Geothermal Roadmap for Indonesia

Patrick Dobson (Lawrence Berkeley National Laboratory)

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Technical Geothermal Roadmap for Indonesia

Patrick Dobson (LBNL), Aulia R. Pratama (MEMR), Bruce Hamilton (ANL)

Foreword

The U.S. Department of Energy's GeoVision study (2019) examined a number of scenarios for the future of geothermal energy in the United States. One of the key findings of this study was that technology advances were deemed to be critical for geothermal deployment to grow significantly faster than the current growth trend, defined as business as usual. Technology advances in exploration, drilling, and resource utilization would result in lowering the cost and risks associated with conventional geothermal resources, as well as allowing for the commercial development of enhanced geothermal systems, which represent a much larger resource base than conventional hydrothermal systems. Implementation of these technology advances could have a similar impact on geothermal resource utilization in Indonesia and would greatly advance the national goal of decarbonizing the electrical grid in Indonesia by 2060. This study, as part of the U.S.-Indonesia Net Zero World program, provides a series of recommendations to help with the transfer of specific technologies to Indonesia's geothermal sector to accelerate the successful exploration and development of Indonesia's abundant geothermal resources for power generation and other important applications.

Preface

The Net Zero World (NZW) Initiative is a whole-of-government partnership between the U.S. and other countries to accelerate global energy system decarbonization. Through NZW, nine U.S. government agencies and 10 U.S. Department of Energy (DOE) laboratories are partnering with countries to support creation and implementation of highly tailored, actionable technology roadmaps and investment strategies to achieve net-zero, resilient, and inclusive energy transitions. It will raise and implement climate ambition pledges and accelerate transitions to net-zero, resilient, and inclusive energy systems in every region of the world.

Geothermal is regarded as a crucial resource to provide baseload capacity in Indonesia's path to net zero emissions from power generation by 2060. Indonesia has 362 prospect areas with a total of 23.5 GW of potential resources for geothermal power with most of these resources located in the regions where demand also exists, namely Sumatra and Java. The latest Ministry of Energy and Mineral Resources (MEMR) roadmap aims for geothermal capacity to grow from 2.6 GW in 2024 to 10.5 GW by 2035.

The NZW Collaborative Work Program with the Government of Indonesia (GOI) includes technical assistance and investment mobilization facilitation to accelerate deployment of geothermal energy projects. A NZW DOE/lab team will coordinate this assistance with the GOI's Ministry of Energy and Mineral Resources, other Indonesian stakeholders, U.S. government agencies, international organizations, and industry. These activities include Zoom conference calls with key geothermal stakeholders in Indonesia, participation in geothermal workshops and conferences in Indonesia, and virtual and face-to-face discussions with members of Indonesia's geothermal community.

The goal of this roadmapping exercise is to identify and discuss key technical challenges and discuss how implementation of geothermal technology advances and the development of a publicly available compendium of relevant data sources could reduce the risks, costs, and time associated with geothermal exploration and development activities and expand the potential resource base by including moderate enthalpy systems and superhot and EGS systems, thus accelerating geothermal deployment in Indonesia. This activity will utilize past evaluations of the Indonesian geothermal sector, examples from current roadmapping exercises being conducted in other parts of the world, and the insights and knowledge of various stakeholders of the Indonesian stakeholder community through virtual and in-person discussions to develop a series of recommendations that could be taken to address technical challenges that have hampered exploration and development efforts. Continued partnership through NZW between the U.S. and Indonesia can help address these challenges.

Acknowledgments

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We wish to thank the support of the U.S. Embassy in Indonesia, in particular Amy Padilla and Rosabelle Purnama, for their efforts in arranging our meetings with key geothermal stakeholders in Indonesia. We also wish to thank the members of the Indonesian Geothermal Association (INAGA), who kindly participated in Zoom calls to share their insights and guidance, to Baker Hughes for inviting us to participate in their U.S.-Indonesia geothermal workshop, and to the organizers of the Indonesia International Geothermal Convention and Exhibition (IIGCE) conference for inviting us to present an early version of our study at the meeting. We thank Prof. Sam Noynaert of Texas A&M for generously sharing detailed information relating to the geothermal drilling physics-based limiter redesign workflow. We thank Jon Weers (NREL) for sharing detailed information on the Geothermal Data Repository. We thank Helen Doran of Project InnerSpace for sharing information on the early GeoMap™ representation of Indonesia's geothermal resources. We thank Mitch Stark for sharing his insights on the challenges of identifying and evaluating well drilling targets. We thank Lauren Boyd (U.S. DOE GTO) and Jim Stimac for generously sharing their suggestions for this roadmap. We also wish to thank the leadership of MEMR, NZW, and DOE for their continued support of this project. Finally, we thank the many stakeholders of Indonesia's geothermal community for sharing their ideas and suggestions with our team during our focus group discussion held at the Ministry of Energy and Mineral Resources office in Jakarta.

List of Acronyms

ADB	Asian Development Bank
AGS	Advanced geothermal system
ASEAN	Association of Southeast Asian Nations
BPP	Basic Cost of Generation (average cost of electricity generation for PLN)
CATF	Clean Air Task Force
DEM	Digital Elevation Model
DEN	National Energy Council
DOE	Department of Energy
EGS	Enhanced geothermal system
ESP	Electrical submersible pump
ETIP-DG	European Technology and Innovation Platform on Deep Geothermal
FORGE	Frontier Observatory for Research in Geothermal Energy
FIT	Feed-in tariff
GDR	Geothermal data repository
GEODE	Geothermal Energy Oil and Gas Demonstrated Engineering
GIS	Geographic information system
GOI	Government of Indonesia
GTO	Geothermal Technologies Office
GW	Gigawatt
HT-TES	High temperature thermal energy storage
IBRD	International Bank for Reconstruction and Development
IEA	International Energy Agency
IIGCE	Indonesia International Geothermal Convention and Exhibition
INAGA	Indonesia Geothermal Association
ITB	Institut Teknologi Bandung
IRR	Internal rate of return
JBIC	Japan Bank for International Cooperation
JICA	Japan International Cooperation Agency
LCOE	Levelized cost of electricity
LiDAR	Light detection and ranging
MEMR	Ministry of Energy and Mineral Resources
MIGA	Multilateral Investment Guarantee Agency
ML	Machine learning
MW	Megawatt
MWD	Measurement while drilling
NCG	Non-condensable gas
NCPA	Northern California Power Agency
NGDS	National Geothermal Data System
NREL	National Renewable Energy Laboratory
MSE	Mechanical specific energy
NZW	Net Zero World
OEDI	Open Energy Data Initiative
ORC	Organic Rankine Cycle
PDC	Polycrystalline diamond compact
PFA	Play fairway analysis

PGE	Pertamina Geothermal Energy
PLN	PT Perusahaan Listrik Negara
PPA	Power purchase agreement
PSPE	Preliminary survey and exploration assignment (Wilayah Penugasan Survei Pendahuluan dan Eksplorasi Panas Bumi)
R&D	Research and Development
ROP	Rate of penetration
U.S.GS	U.S. Geological Survey
VSI	Volcanological Survey of Indonesia
WKP	Geothermal working areas (Waliyah Kerja Panas Bumi)

Executive Summary

The technical geothermal roadmapping exercise described by this report is part of the NZW Collaborative Work Program with the Government of Indonesia. Indonesia currently has the second largest installed geothermal power generation capacity in the world and has abundant undeveloped resources that allow for continued expansion of its geothermal resource development, which can serve to contribute to the country's goal of achieving net zero emissions for power generation by 2060. The DOE GeoVision study (2019) highlighted the importance of technical improvements as the key for accelerating the development of geothermal resources in the United States by reducing the costs and risks to make geothermal more competitive, and this also applies to Indonesia. The main objective of the roadmap is to identify and discuss key technical challenges and discuss how implementation of geothermal technology advances could reduce the risks, costs, and time associated with geothermal exploration and development activities and expand the potential resource base to include unconventional resource types, thus accelerating geothermal deployment in Indonesia.

The roadmap report is organized into the following sections. The report begins with an introductory section that highlights the importance of technology advances that can facilitate improved subsurface characterization, reduced drilling costs, improved reservoir performance, and make utilization of unconventional geothermal resources, such as lower enthalpy, enhanced geothermal systems (EGS), and advanced geothermal systems (AGS), commercially viable, thus expanding the potential geothermal resource base. Such improvements are critical if Indonesia is to achieve its stated goal of expanding the current installed geothermal capacity of 2.6 GW to 10.5 GW by 2035.

Section 2 provides a review of past studies of geothermal resource development in Indonesia, with a distillation of common themes, which include: 1) government investment in early phase exploration activities and development of a geothermal database to help derisk exploration, 2) improved drilling technologies, better well targeting, and sharing drilling learning curves to reduce costs, shorten drilling timelines, and improve well success, and 3) improved geochemical strategies, use of binary power plants to increase field productivity, development of mitigation strategies to deal with geologic hazards, and improved public outreach to help derisk development and exploitation activities.

Section 3 provides an overview of other geothermal roadmap studies conducted around the world to highlight identified technology challenges and improvements. The cross cutting themes from these studies include the areas of 1) resource assessment (publicly available databases and 3D integrated models), 2) resource access (improved drilling and well completion methods, and development of high temperature downhole tools), 3) reservoir management (well stimulation, improved reservoir models, mitigation of induced seismicity, managing scaling and corrosion, and improved downhole pumps), 4) resource utilization (improved power plant efficiencies, cascaded uses, expanded uses to include moderate and lower temperature resources as well as EGS, AGS, and superhot resources), 5) technology development and transfer (investment in research and development (R&D), technology transfer from the oil and gas industry), and 6) improved community outreach to gain social acceptance.

Section 4 summarizes the current status of geothermal resource development in Indonesia and describes new developments that are currently in progress. It also briefly describes the Ministry of Energy and Mineral Resources (MEMR) programs to help accelerate geothermal development in the country, such as the government exploration drilling program designed to help derisk new prospects.

Section 5 provides a summary of initial feedback from the Indonesian geothermal community on what are seen as key challenges that the industry faces in expanding existing exploration and development projects. Initial feedback was obtained from Zoom calls with members of the Indonesia Geothermal Association (INAGA) and interactions with geothermal community members following presentations of the initial results of this work at a U.S.-Indonesia geothermal workshop hosted by Baker Hughes and the Indonesia International Geothermal Convention and Exposition. The final results of our study were presented at a workshop hosted by MEMR on January 8, 2025, at the MEMR office, with over 100 people in attendance, where the participants broke out into four topical groups centered around reducing resource risk, reducing drilling costs and risks, expanding geothermal utilization beyond conventional hydrothermal systems, and workforce development, community engagement, and social acceptance, with technology transfer and development as a cross cutting theme. The audience members provided very useful feedback that was incorporated in the final report, as captured in Section 7.

Using the results of the previous sections, Section 6 describes the potential types of technologies that could be used to accelerate geothermal exploration and development activities in Indonesia. These can be categorized in the following groups: 1) database development and sharing; 2) resource assessment methods; 3) geochemical modeling; 4) well targeting; 5) drilling; 6) utilization of geothermal resources beyond conventional high temperature hydrothermal systems; 7) technology transfer and development; and 8) community outreach and social acceptance. Specific examples for each of these topic areas are described in detail, along with the impact that adoption of these methods could have on geothermal activities in Indonesia. For example, recent technology advances in geothermal drilling have resulted in over a 50% reduction in drilling costs and times for wells drilled at the Utah FORGE and Fervo Cape Modern sites - if similar advances could be implemented for geothermal drilling in Indonesia, this could result in significant cost and time savings.

Section 7 then provides a detailed discussion of potential actions that could be taken to help accelerate geothermal development in Indonesia with a focus on technical issues based on the topics discussed in the previous section. Many of these technologies already exist, so the challenge is to transfer this capability to Indonesia. Methods of technology transfer include interactions with the oil and gas industry, utilization of capabilities that multinational service companies have related to drilling, and international collaboration. Continued government investment in R&D, development of industry-university research consortia, as well as creation of geothermal startups could also help stimulate geothermal technology advances. It will also be important to support workforce development efforts as well as strengthen community outreach to gain social acceptance for increased development of geothermal resources within Indonesia.

Section 8 provides a few concluding remarks to the report, highlighting how international collaboration can play a major role in technology transfer, and that expansion of geothermal resource deployment can make a significant contribution to Indonesia’s goal to achieve its net zero carbon goals.

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1 Introduction

The goal of the NZW geothermal roadmapping exercise is to identify key technical challenges and suggest solutions to help advance the deployment of geothermal resources in Indonesia. This effort is part of the NZW Collaborative Work Program with the Government of Indonesia. The U.S. Department of Energy's (DOE) GeoVision study (2019) highlighted the importance of technology advances needed to significantly reduce the costs and risks of geothermal exploration and development activities to ensure that geothermal resources are competitive with other energy resource options (Figs. 1 & 2). If technology advances are not realized, then the current business-as-usual trend results in very little geothermal resource development growth in the U.S. between now and 2050.

The DOE Geothermal Technologies Office (GTO) has invested in targeted technology research and development (R&D) to address key challenges, with a focus on enhanced geothermal systems (EGS), in part due to the much larger potential resource base associated with such systems. The DOE GTO established the Frontier Observatory for Research in Geothermal Energy (FORGE) near Milford, Utah, and has invested over $200 million to date in developing a test bed to develop and test technologies related to improving EGS reservoir characterization, reservoir access (drilling), reservoir creation and productivity (stimulation), and reservoir sustainability. DOE also launched the EGS Earthshot™, whose goal is to reduce the cost of EGS power generation by 90% by 2035 (Augustine et al., 2023). The overall program goal is to supply 60 GW of EGS and hydrothermal resource deployment in the U.S. by 2050 (DOE, 2022).

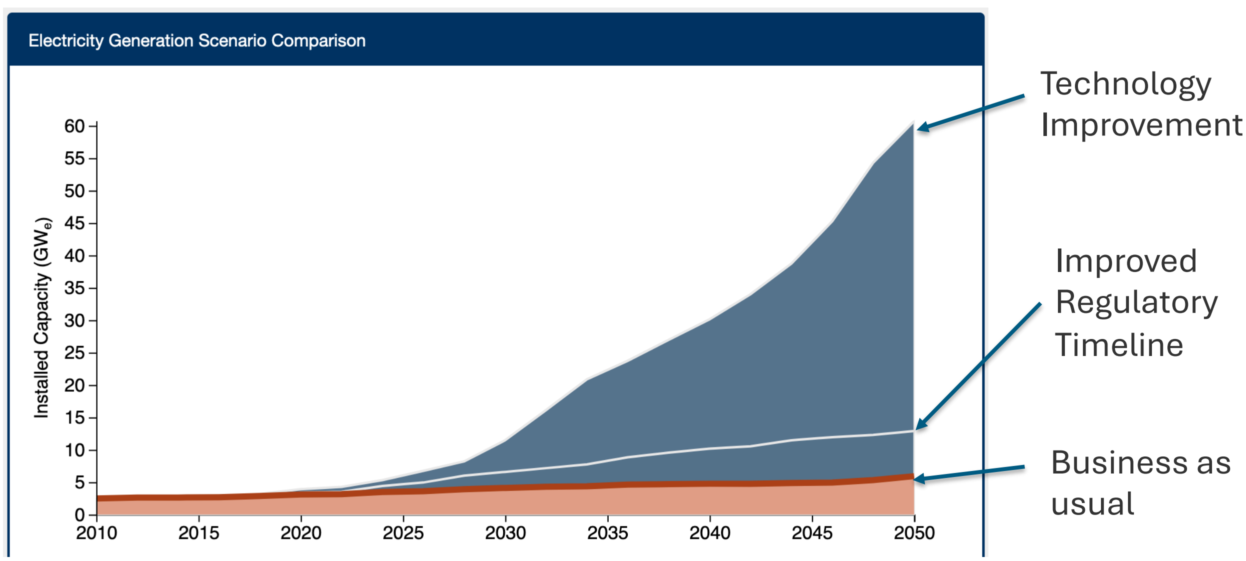


Figure 1. Comparison of different future geothermal power generation scenarios in the United States from the 2019 GeoVision study (https://apps.openei.org/geovision/electricity-generation)

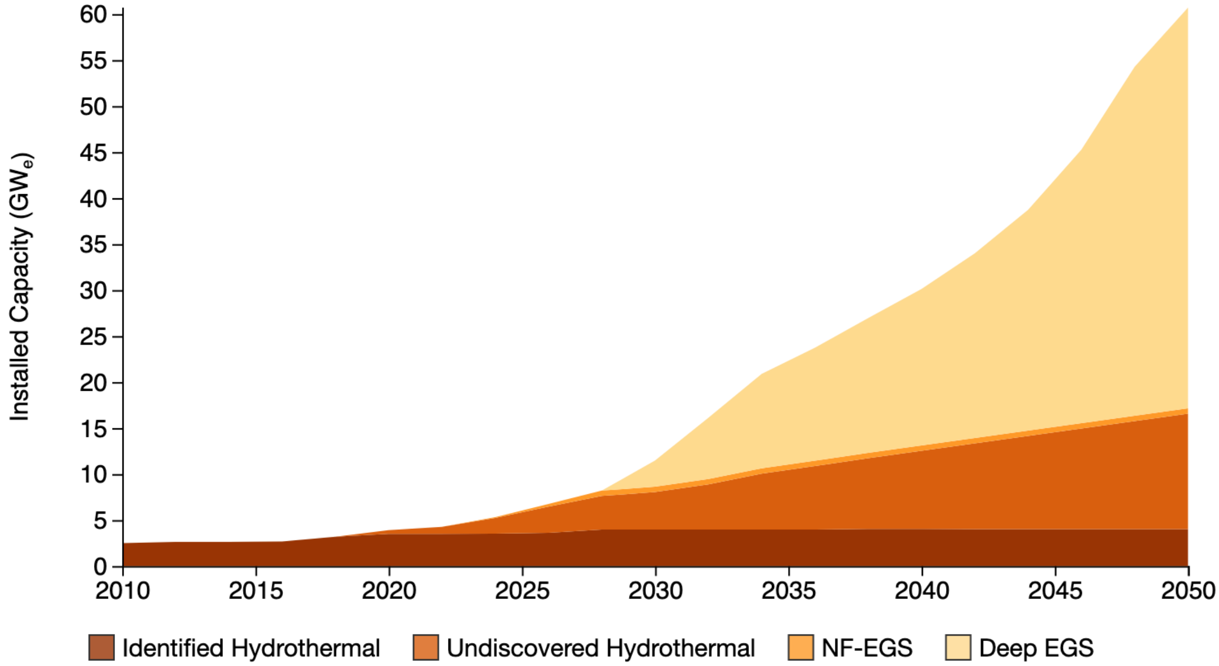


Figure 2. Depiction of the different types of resource development under the Technology Improvement scenario of the GeoVision study (2019). Note that EGS resource development will not occur under the business-as-usual scenario, as technology improvements are required for these resources to become commercially viable. However, if these advances are achieved, 70% of the U.S. geothermal resource capacity is predicted to be derived from EGS resources by 2050, when a total installed capacity of ~60 GW is expected. (https://apps.openei.org/geovision/electricity-generation)

Advances in technologies related to subsurface characterization, drilling, well completion and stimulation, and resource utilization and management can result in shorter project times and lower project costs, making geothermal resource development a more attractive option. In addition, these technology improvements can also make enhanced geothermal systems (EGS) and advanced geothermal systems (AGS) economically viable options, which would significantly expand the potential geothermal resource base. Applying these same technology advances to Indonesia's geothermal sector could provide a similar boost to help realize the GOI's Ministry of Energy and Mineral Resources (ESDM) goals of increasing geothermal power generation in Indonesia from 2.6 GW in 2024 to 10.5 GW by 2035.

2 Previous evaluations of the status, challenges, and path forward for development of geothermal resources in Indonesia

This section summarizes the key findings and recommendations of prior evaluations and roadmapping exercises for geothermal power in Indonesia, with a focus on technical aspects. Note that many of these studies are focused on regulatory and financial aspects. The studies (in order of their publication date) are as follows:

- West Japan Engineering Consultants, Inc. (2007) Master plan study for geothermal power development in the Republic of Indonesia.
- GeothermEx, Inc. (2010) An assessment of geothermal resource risks in Indonesia
- PT Castlerock Consulting (2010) Ministry of Energy and Mineral Resources. Phase 1 report: Review & analysis of prevailing geothermal policies, regulations and costs
- WWF (2012) Igniting the ring of fire – A vision for developing Indonesia's geothermal power
- Meier, P., Randle, J.B., and Lawless, J.V. (2015) Unlocking Indonesia's geothermal potential
- Purwanto, E.H. (2019) Assessment of exploration strategies, results and costs of geothermal fields in Indonesia
- Purwanto et al. (2021) An updated statistic evaluation of drilling performance, drilling cost, and well capacity of geothermal fields in Indonesia
- JICA et al. (2023) Project to develop medium- and long-term geothermal development policy in Indonesia Phase 2.

2.1 WestJEC (2007) Master plan study for geothermal power development in the Republic of Indonesia

- Current government policies need to be changed to achieve the master plan goal for geothermal growth, along with improved government technical support
- Focus should be on large-scale, lower cost development projects
- Need for high quality and quantity resource data to facilitate private development
- Main barriers are resource development risk and large up-front investment requirements.

As of 2004, the installed capacity for Indonesia was 807 MW. Ten recommendations were made to achieve the master plan growth goals – most of them were related to policy, government coordination, regulatory framework, and financial incentives. The recommendations with technical components were:

- Promotion of geothermal resource surveys by government to reduce resource risk
- Capacity building of geothermal workforce and upgrading of instrumentation
- Multipurpose utilization of geothermal energy
- Reduction in development costs (such as drilling)
- Development of domestic technology industry base to support geothermal.

A diagram illustrating all of the project recommendations is shown below (Fig. 3) – the green boxes highlight the technical topics.

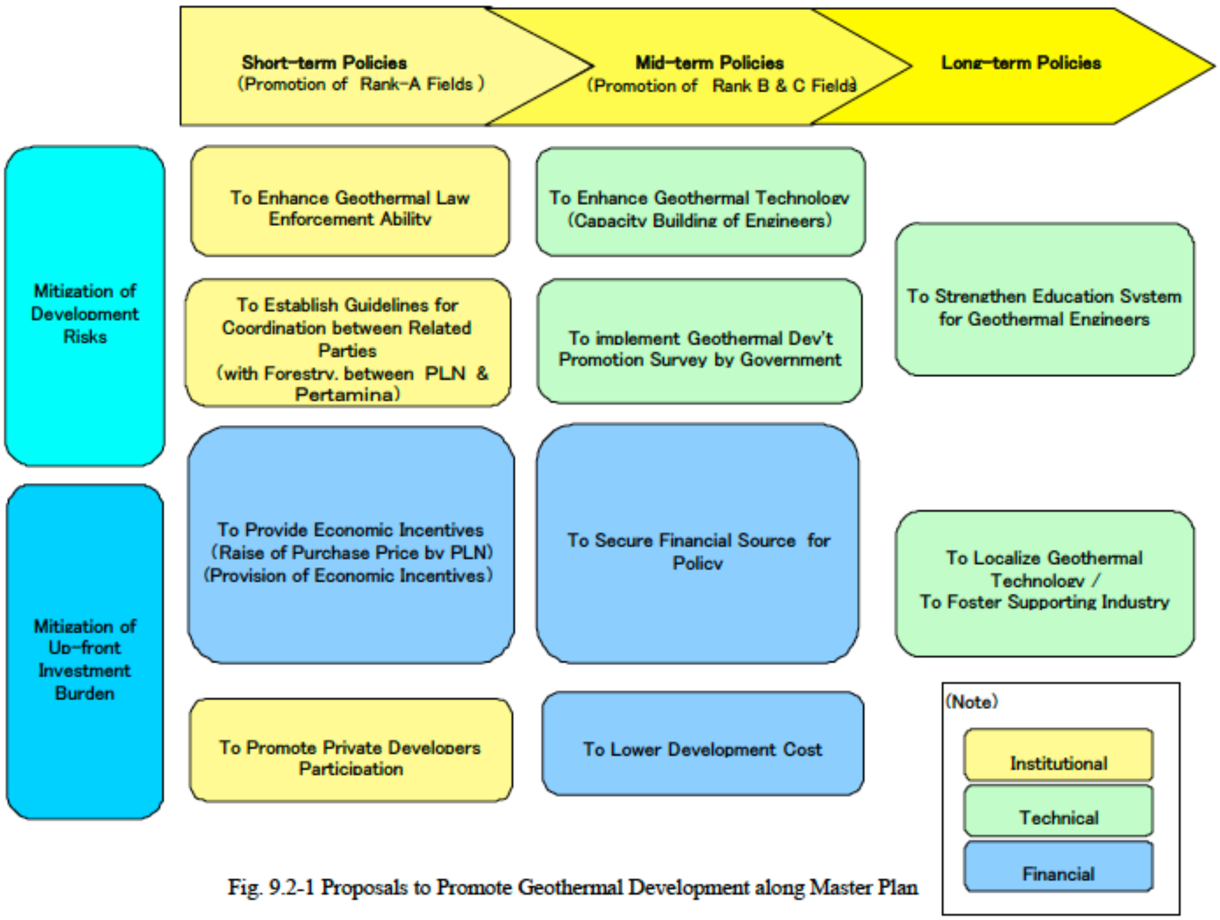


Figure 3. Schematic master plan to promote geothermal development in Indonesia (WestJEC, 2007)

Key activities include:

- Nationwide geothermal resource survey
- Additional field data collected from 23 selected fields
- Electric sector study (demand and supply, transmission system, etc.)
- Environmental and social impacts
- Policy study
- 73 target fields (spreadsheet with resource size, initial capital investment/KW, etc.) → 49 highest ranked prospects
- Development of geothermal development database (Center for Geological Resources)
- Incorporation of geothermal development master plan within National Electricity Development Plan (based on energy mix policy).

Geothermal database includes:

- Country-wide assessment, which includes resource potential, power plant, prospective area, development process, business scheme, investigation status, and load map and action plan

- Individual field assessment, which includes location, concession, reservoir conceptual model, chemical conditions, well productivity, and resource potential.

Key barriers seen as:

- High cost of geothermal energy
- Resource development risks
- Large up-front investment requirement.

Other technical topics of interest that were considered include:

- Rural electrification on small islands
- Avoided greenhouse gas emissions.

2.2 GeothermEx, Inc. (2010) An assessment of geothermal resource risks in Indonesia

- Elevated geothermal exploration and development risks and costs have hampered efforts to expanding deployment
- Price of geothermal energy higher than other energy sources
- Variety of geothermal resource types in Indonesia
- Project risk highest during exploration phase of project
- Regional exploration often conducted by government
- Detailed surface exploration consists of geologic mapping, sampling and analysis of fluids from thermal features, and geophysical surveys
- Exploration drilling consists of temperature gradient wells and deep exploratory wells – costly but necessary process
- Flow testing from deep wells used to confirm resource size
- Increased well success with development drilling (up to 90%)
- Power plant and surface installations also costly – need to be properly operated and maintained
- Other risks include:
    - Induced volcanic eruptions
    - Interference with surface thermal features
    - Subsidence
    - Injection-induced seismicity.

2.2.1 Identification and mitigation of geothermal development risks

- Government derisking of exploration activities (examples from Australia, Japan, Kenya, the Philippines, Turkey, U.S.A, New Zealand, Iceland, Germany, Costa Rica, Chile, Mexico, El Salvador, Guatemala)
    - Regional reconnaissance and prospect identification
    - Detailed surface exploration
    - Temperature gradient drilling

- Drilling of exploratory wells
    - Demonstration projects
    - R&D activities and grants
    - Loans and loan guarantees
    - Tax exemptions and credits
    - Renewable energy incentives
    - Resource insurance
    - International financing support (WB, IDB, BCIE, UNDP)
- General international trends suggest less government control over time
- Uncertainties in prices of fossil fuels and concerns with climate change are leading to government support of renewable energy sources, including geothermal
- Private investment in geothermal varies by country, depending on perceived country risks and market conditions
- Resource risks can be reduced, but electricity market access, government subsidies, loan guarantees, and reduced government restrictions are seen as more powerful incentives for geothermal development.

Measures to reduce resource risk include:

- Development of a complete and accurate catalog of geothermal prospects
- Simple and low-cost regulatory and permitting process
- Government funded exploratory drilling of prospects to derisk areas
- Cash grants or cost-sharing for drilling exploratory wells
- Loan guarantees and reservoir insurance.

2.2.2 Geothermal project risk in Indonesia

- Early geothermal exploration efforts in Indonesia, conducted by Pertamina and VSI, with government assistance from New Zealand and Japan, successfully identified several geothermal systems, most of which were later commercially developed
- Project delays due to environmental and financial uncertainties ended up driving project costs
- Resource risk issues that were encountered included acidic fluids, elevated non-condensable gases, and phreatic eruptions
- The Kyoto Protocol's Clean Development Mechanism led to sales of credits for greenhouse gas reductions, which were obtained for the Salak project, improving project economics.

2.2.3 Geothermal resource risk factors

2.2.3.1 Adequate resource base

GeothermEx created a series of plots (Fig. 4) depicting the range of estimated geothermal reserves for all the prospects in Indonesia assessed by Pertamina. These indicate a log-normal distribution of resource size, with 50% of the resources having at least 100 MW of proven plus probable reserves, where more than 50 fields (~70% of all areas) having a reserve base of at least 50MW. This analysis suggests that there are many potential sites for commercial development in Indonesia.

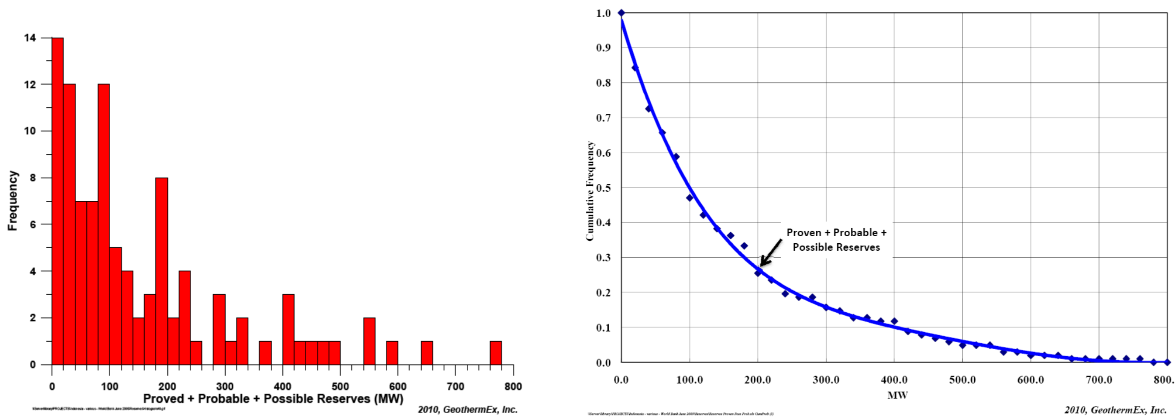


Figure 4. Histogram of estimated geothermal reserves for all evaluated geothermal prospects in Indonesia, along with cumulative frequency plot (GeothermEx, 2010)

2.2.3.2 Adequate well productivity

GeothermEx analyzed the statistics for 215 deep geothermal wells in Indonesia. Using a threshold of 2 MW for defining a "successful" well, the drilling success rate is about 62%. However, this includes both exploration and development wells – the success rate for development wells alone is generally higher. Using 3 MW as the cutoff for commercial wells, a log-normal distribution of well productivity is observed, with a median output of 9 MW. This average output compares favorably with high temperature geothermal fields around the world, indicating that Indonesia has adequate well productivities.

If only more modern (post-1990) wells are included, four modes of wells are observed – one from 3-5 MW (representing tight, marginal wells), another from 7-9 MW (representing typical wells from liquid-dominated reservoirs), a third from 15-19 MW (from saturated steam reservoirs), and a fourth from 27-31 MW (generally from very high temperature (>300°C) fields).

2.2.3.3 Acceptable drilling cost per well

Drilling costs are largely a function of well depths, which are governed by the depth of the geothermal reservoir. Geothermal well depths in Indonesia generally range from 1 to 2.8 km, similar to the range found for geothermal wells around the world. Also, well drilling costs were observed to be slightly lower on average than costs around the world, and that drilling success rates are similar and well outputs are slightly higher than world values, the cost per MW well capacity is slightly lower than world values, with values ranging from $100,000 to $1,100,000/MW well capacity, with most wells being around $400,000/MW well capacity.

2.2.3.4 Benign fluid chemistry

Most fields in Indonesia do not have serious fluid chemistry issues, so they appear to have similar fluid risk profiles to other countries.

2.2.3.5 Effects of learning curve on resource risk

There has been an initial increase in drilling success rate with time, followed by a period where the success rate has plateaued. During this time, however, the well capacity has gradually increased, improving the overall performance of the wells that have been drilled. In looking at a specific field example, Kamojang, there is a dramatic increase in drilling success between the exploration and development phases of the project. The drilling rate (m/d) also seems to have improved with time (Fig. 5).

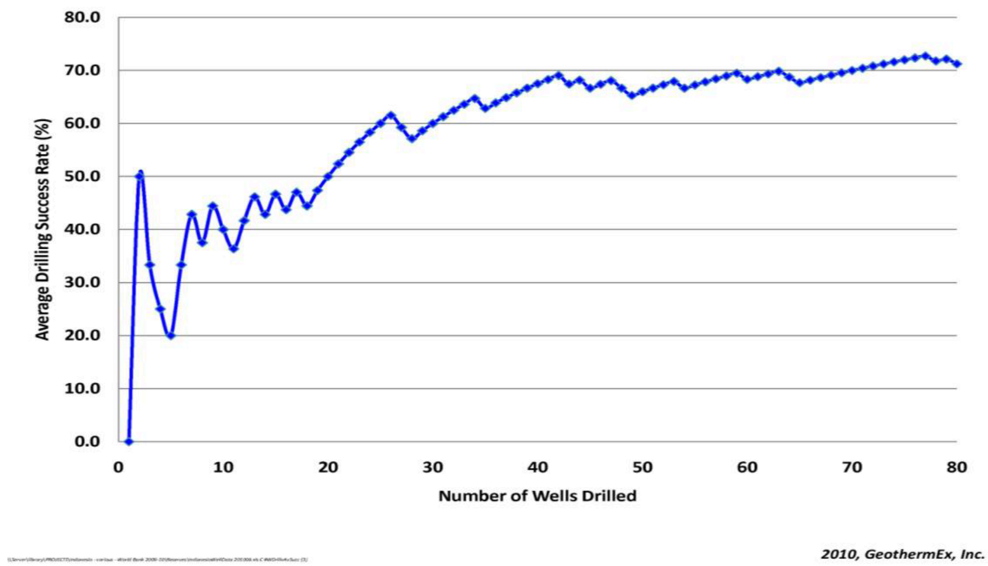


Figure 5. Drilling success rate vs. # wells drilled at the Kamojang field, Indonesia (GeothermEx, 2010)

2.2.4 Non-technical risks

However, there are other non-resource risks that do come into play. These include:

- Country risks
    - Requirement that power be sold to PLN
    - Uncertainty that PLN will be able to pay for electricity at negotiated rates
    - Abrupt government policy changes
    - Complex regulatory framework
    - Bureaucratic delays in issuing permits
    - Lack of transparency in decision-making process
- Economic risks
    - Lack of market-determined price for electricity
    - Use of cheap coal-fired power as standard for electricity pricing
    - Need for high internal rate of return to compensate for perceived country risk
    - Reservation of attractive geothermal prospects by PLN

    - Requirement for Indonesian equity partner
    - Lack of financial incentives
- Financial risks
    - Difficulty in obtaining financing and high interest rates due to perceived country risk
    - Difficulty in obtaining and high cost of insurance due to perceived country risk
    - Difficulty in obtaining equity partners as a result of perceived country risk
- Project development risks
    - Remote locations, leading to logistical challenges and delays
    - Uncertainty on adequacy of prior exploration activities, requiring additional exploration activities
    - Environmental and social impacts on preserved forests or agricultural activities and disruption of village life.

The country risk is the main issue confronting most developers, with a requirement to have an internal rate of return higher than 20% to compensate for this.

Ways to mitigate project risk include:

- Project insurance
- Tax exemptions, credits, and holidays
- Risk-sharing with local and national governments and other entities (such as grants, cost-sharing, surface exploration data, etc.)
- Guaranteed access to markets and obtaining needed electricity prices for green energy (set-asides or special tariffs)
- Vehicles to guarantee payment for electricity, such as escrow accounts
- Special contract terms, such as selling carbon credits, international arbitration, etc.

Suggestions to mitigate exploration and development resource risk in Indonesia include:

- Government of Indonesia (GoI) could update the national geothermal resource inventory and conduct additional exploration surveys to confirm resources – there are 56 sites that could use additional exploration to confirm their resource potential
- GoI could conduct discovery and confirmation drilling to reduce development risk
- GoI could provide cost-share for development drilling
- GoI could provide insurance subsidy for development drilling activities
- GoI could provide price incentive for off-take price to compensate for exploration and development risks.

2.3 PT Castlerock Consulting (2010) Ministry of Energy and Mineral Resources. Phase 1 report: Review & analysis of prevailing geothermal policies, regulations and costs

The goal of the PT Castlerock report was to support development and implementation of policies and regulations to ensure the success of the GoI's geothermal power program. This work consists of three phases: 1) Review current conditions and formulate policy options; 2) Facilitate selection of a specific policy package, and 3) Assist the GoI with its implementation. The report contains the analysis and findings of Phase 1.

Six specific activities were conducted under Phase 1

1. Assess the levelized cost of electricity (LCOE) for geothermal power and coal-fired power generation
    - Geothermal is more costly than coal, but this gap may reflect the value of environmental externalities
    - There is a wider range in geothermal costs due to higher uncertainties in geothermal resources
    - Larger geothermal fields tend to have lower LCOE
2. Review current and pending regulations governing geothermal development
3. Conduct due diligence on the GoI's geothermal development targets
    - Better screening and target setting is required for projects to be successful
4. Review prevailing processes for new and legacy geothermal working areas (WKP)
    - Standards should be improved to determine the readiness of new geothermal working areas
    - The geothermal development process needs to be reconciled with Indonesia's public-private partnership framework
    - The draft proposal to require PLN to have an offtake agreement should be instituted
    - The capability of procurement committee members should be strengthened
5. Assess risks throughout the geothermal value chain
    - 34 principal risks were identified in Exhibit 5.3 of the report – many of these can be mitigated through improvements in geothermal regulatory processes
6. Assess the total increment cost gap between geothermal and coal-fired power.

Based on the above analysis and findings, **four basic policy areas were identified** to ensure the success of the GoI's geothermal power program

1. Fund the incremental cost gap
    - Increase the subsidy to PLN
    - Increase in tariffs

- Voluntary green electricity scheme
- Sale of carbon credits

2. Address geothermal exploration risks
   - Improve the consistency and completeness of geothermal resource data included in tender documents
   - Develop risk mitigation scheme for developers
   - Balance allocation of risk between GoI and developers
3. Establish a segmented pricing framework
   - Cost-plus, where price is based on project costs plus reasonable return on capital
   - Market-based, where price is set by competitive bidding
   - Feed-in tariffs, where prices are defined by technology class
   - Substitute-based, where price is based on the cost of the conventional supply alternative
   - Different geothermal working areas will have different exploration risks and their locations will determine the nature of the existing electricity market – thus different pricing approaches should be adopted based on the location, resource size (small or large), and resource risk (proven or unproven)
4. Rationalize the new geothermal working area tender process.

2.4 WWF (2012) Igniting the ring of fire – A vision for developing Indonesia's geothermal power

The Indonesian government has identified abundant geothermal resources in the country and has set ambitious goals to increase the deployment of these resources to the electricity grid. Such a step would reduce the burden of using fossil fuels, improving energy security, and would also reduce greenhouse gas emissions. The government's energy and fossil fuel subsidies, instituted to ensure the availability of cheap energy, amounted to ~25% of the total government expenditure in 2008, and has led to increased greenhouse gas emissions (Fig. 6) and provide a disincentive for energy efficiency measures.

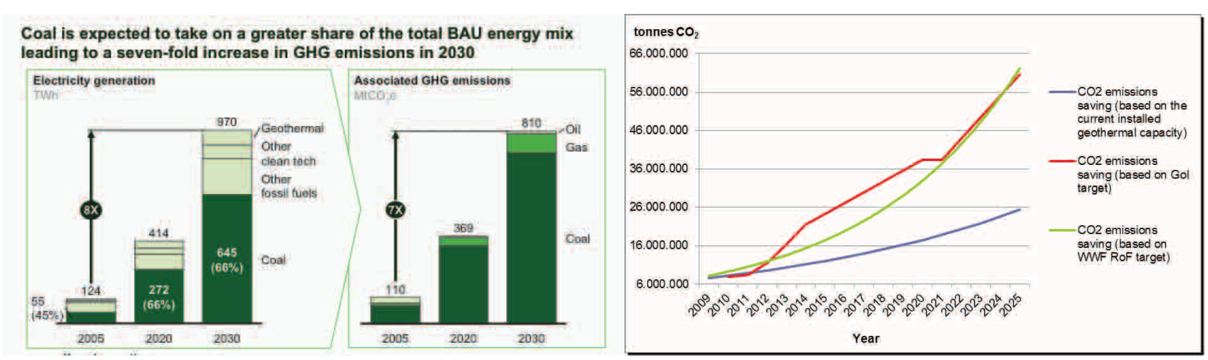


Figure 6. Graphs indicating how increased use of coal will greatly augment GHG emissions, and how increased utilization of geothermal power can reduce these emissions (WWF, 2012)

There are a number of risks that pose challenges to increased development of geothermal resources. One is the risk associated with PLN being able to pay higher tariffs for geothermal energy. A second is related to the resource risk and the costs of geothermal exploration. Geothermal development requires significant up-front equity, which is a challenge for project financing. There is also limited grid capacity, which may limit the ability to deliver geothermal energy to customers. Geothermal projects may also encounter social and environmental impacts, which can increase the cost and time needed to realize these projects. There are regulatory and permitting challenges that also present issues with transparency, efficiency, and coordinating efforts between the central government and local authorities. Many geothermal resources are in protected forest areas, so it is important that projects in these areas are designed to minimize the impacts on these areas and are conducted under the appropriate conditions. Gunung Salak has been developed in a protected tropical rainforest ecosystem, and the project implemented measures to minimize forest usage and control land clearing – it is now part of Gunung Halimun-Salak National Park.

Obtaining financing for geothermal projects is often a major hurdle. The GoI has instituted a number of supporting programs to facilitate this process.

Carbon financing through the advanced sale of emission reductions can also help boost the financial viability of geothermal development projects. It will be important to demonstrate the environmental integrity of such offsets as the carbon credit market continues to evolve.

The report has a series of recommendations to accelerate the development of Indonesia’s geothermal resources. These include:

- Institutional reforms to provide a clear mandate of which agency leads the process of geothermal energy acceleration. A variety of government agencies are involved in geothermal resource development, including the Ministry of Energy and Mineral Resources (MEMR), the Ministry of Forestry, the National Energy Council (DEN), the Presidential Unit for Development Monitoring and Oversight (UKP4), the Ministry of Finance, and the PLN. Additional provincial and district government agencies are also involved, leading to a confusing and long path for projects to negotiate.
- Institutional capacity building at regional government levels to facilitate the energy planning and tendering process
- Reduce or eliminate fossil fuel subsidies and provide capital to support sustainable geothermal energy development
- Improvement of the economic incentives program to accelerate geothermal energy development, so that geothermal energy prices can be bankable and reflect location-dependent project risk
- Reduction of exploration and early-stage development risks by improving completeness and reliability of exploration data and implementing risk-mitigation measures, such as access to government guarantees for geothermal projects.
- Stimulating commercial financial institutions to support geothermal energy development and formulating financial instruments that can reduce resource risk
- Expanding the grid to provide electricity access to local communities

- Develop collaborations with key stakeholders to create sustainability standards to manage environmental and socio-cultural impacts
- Developers, investors, and government agencies should anticipate and mitigate the social and environmental impacts of geothermal projects. Up to 42% of Indonesia's identified geothermal resource areas are located in protected forest areas. Thus, it is critical to develop measures that will balance geothermal development with forest conservation. Early and continuous consultation with local stakeholders is critical to gain public acceptance, and developing multi-stakeholder monitoring teams will increase confidence in ensuring that mitigation measures are properly implemented so that forest ecosystems are preserved
- Develop different strategies to lower the transaction costs of Indonesia's decentralized governmental regulatory and permitting framework related to geothermal development.

2.5 Meier et al. (2015) Unlocking Indonesia's geothermal potential

This study, conducted jointly by the World Bank and the Asian Development Bank (ADB), identifies the main issues that have hindered the development of geothermal resources in Indonesia, and provides recommendations on ways to improve the regulatory framework, financial incentives, the tendering process, and other financing issues. Four major areas were identified as key issues that need to be addressed; they are:

- Clarifying the role of the state by resolving the competing interests of the Ministry of Finance, PLN, Pertamina, and MEMR, and clearly defining the roles that each of these entities should play.
- The tendering process needs to be improved using examples such as the procurement rules of the ADB and the World Bank to improve transparency. This involves improving the quality of geological, geophysical, and geochemical resource information available to potential bidders to reduce resource risk, preferentially with subsurface resource data based on drilling also included. Having a technically qualified, central tender entity to conduct tenders could help improve the process.
- Returning to tender-determined tariffs is recommended, as fixed prices would result in developers being selected on non-price qualifications. Tariff setting should be an evolving process, based on a published methodology and stakeholder consultation. Ceiling prices should be determined based on the benefits of geothermal energy, including avoided costs of PLN, local economic development, and avoided greenhouse gas generation.
- The prospective power purchase agreement terms should be provided at the time of tender, instead of being subjected to post-tender negotiation. A single tariff escalation formula consistent with international best practices for renewable energy projects should be adopted. While PPA renegotiation is primarily a matter for the developer and PLN, there is a benefit for MEMR to issue a policy statement that sets out the principles that should apply associated with issues such as delays, changes in project size, and changes in power plant unit sizes. The PPA should also specify the arrangements for connection to transmission lines, how the costs are recovered, and how the line is maintained after the start of commercial operation.

Other issues that were identified by this study include:

- Estimates of the actual geothermal resources in Indonesia appear to be inflated, and non-systematic. Having a transparent methodology on how these estimates were determined would increase confidence and potentially reduce resource risk.
- It is important to properly assess the relative value of geothermal energy compared with thermal energy sources, in terms of both local and global environmental impacts and the avoided costs of PLN's thermal fuel subsidies. This information can be combined with geothermal supply curves plotting LCOE vs. cumulative power plant capacity for each region to determine how much geothermal deployment under reasonable economic conditions makes sense based on current resource knowledge.

The report goes into detail on tariff design and compares feed-in tariffs (FIT) with avoided cost tariffs. There is a history of issues with fixed FITs, as they can lead to overcapacity at high prices, program abandonment, and backlash from consumers and governments. Avoided cost tariffs are based on the benefits of renewable energy and are not specific to any single renewable energy technology. Competitively determined tariffs provide the most effective way to get developers to compete. The use of ceiling prices could ensure that the bid price is reasonable and that it does not exceed the benefits of the project – there may be a benefit to not disclosing this ceiling prior to the tender to avoid bidders coming up with a price just below the ceiling value. The ceiling values need to be assessed over time to ensure that they are still valid based on prevailing market conditions. Determining an appropriate ceiling cost can be challenging, given that production costs can be quite variable, and could exceed the perceived benefits (i.e., avoided costs) of a project, which in turn can be challenging to quantify. In addition, deals are negotiated numerous years before project completion, when costs may have changed significantly, thus impacting project economics. Whatever approach is adopted, it is important that the process be transparent in nature to all stakeholders. Success of a renewable energy credit is dependent on the credible recovery of incremental costs of renewable energy. Also, setting tariffs should be considered an ongoing process, with updates based on production cost models and involving stakeholder consultation.

There are different market and power generation conditions throughout Indonesia, so tariff ceilings would likely differ based on location. In general, calculation of the avoided cost benefit of geothermal power should be determined using coal-fired power plants, given that is the primary source of power generation. A wide variety of factors go into these calculations, such as avoided fixed and variable costs of thermal generation, the effects of fuel price volatility, local and global avoided environmental impacts associated by using geothermal instead of fossil fuel power generation, and local economic development benefits.

Government subsidies are likely to be required to cover the incremental costs of geothermal energy. These costs will vary from project to project, and also by location, such that as more geothermal resources are developed, it may be necessary to raise the tariff ceiling, as the lower development cost resources have already been developed from the supply curve.

Initial derisking of prospects through collection of geothermal exploration data can reduce the development risks of a project, reduce exploration failures, and increase participation in tenders. These exploration costs could be recovered at the time of tender, or at the time of financial closure, which would be the lowest cost option.

One persistent challenge is balancing the conflicting objectives of the main government stakeholders. The Ministry of Finance is concerned about the subsidies provided to PLN to cover the incremental costs of geothermal energy. Within Pertamina, there is a reluctance to allocate equity capital to Pertamina Geothermal Energy (PGE), when higher returns are available from Pertamina's oil and gas enterprises. The MEMR has the role of promoting geothermal energy development, but it depends on these other government agencies to see that this takes place.

Geothermal exploration and development projects are capital intensive and take many years before they start generating revenue. Debt financing of the exploration phase is challenging, as banks are reluctant to provide financing during this stage when exploration risk is high. Having a stable and predictable tariff regime, along with payment guarantees for PLN's off-take obligations, would serve to reduce some of the financial risk associated with these projects. International lenders, such as the International Bank for Reconstruction and Development (IBRD), Asian Development Bank (ADB), Japan Bank for International Cooperation (JBIC), and the Japan International Cooperation Agency (JICA), have participated in financing geothermal development projects in Indonesia. The Multilateral Investment Guarantee Agency (MIGA) can provide guarantees that would lower the cost of debt for a project.

The Indonesian government established a Geothermal Fund, which has been proposed to provide loans to developers for up-front exploration drilling. These funds could also potentially be used to cover the costs of the government's resource assessment conducted prior to putting a prospect out for tender. Other schemes to reduce resource risk include drilling insurance, direct grants, and revolving funds.

The report also mentions a number of technology options to improve the cost effectiveness of geothermal projects and to speed up the development process. These options include:

- Retrofitting existing projects with binary bottoming plants
- Using larger power plant units
- Being flexible in development options.

2.6 Purwanto (2019) Assessment of exploration strategies, results and costs of geothermal fields in Indonesia

This study provides an analysis of exploration methods and strategies, timelines, results, and costs of five geothermal projects in Indonesia, with a comparison to exploration costs in other countries.

Project costs increase from the exploration phase to the development phase to the construction phase of the project; the actual costs will depend on a range of factors, including the size of the project, the location and availability of infrastructure, the project schedule, the type of development, the developer, and the types of project financing used for the project. Past estimates of project costs in Indonesia range from $3.27 to $4.97 million/MW.

Geothermal exploration activities in Indonesia have been conducted by a variety of entities, including the Geological Agency of MEMR, Pertamina, PLN, and a number of private companies. Changes in the installed capacity from 1990 to 2019 are depicted in Fig. 7.

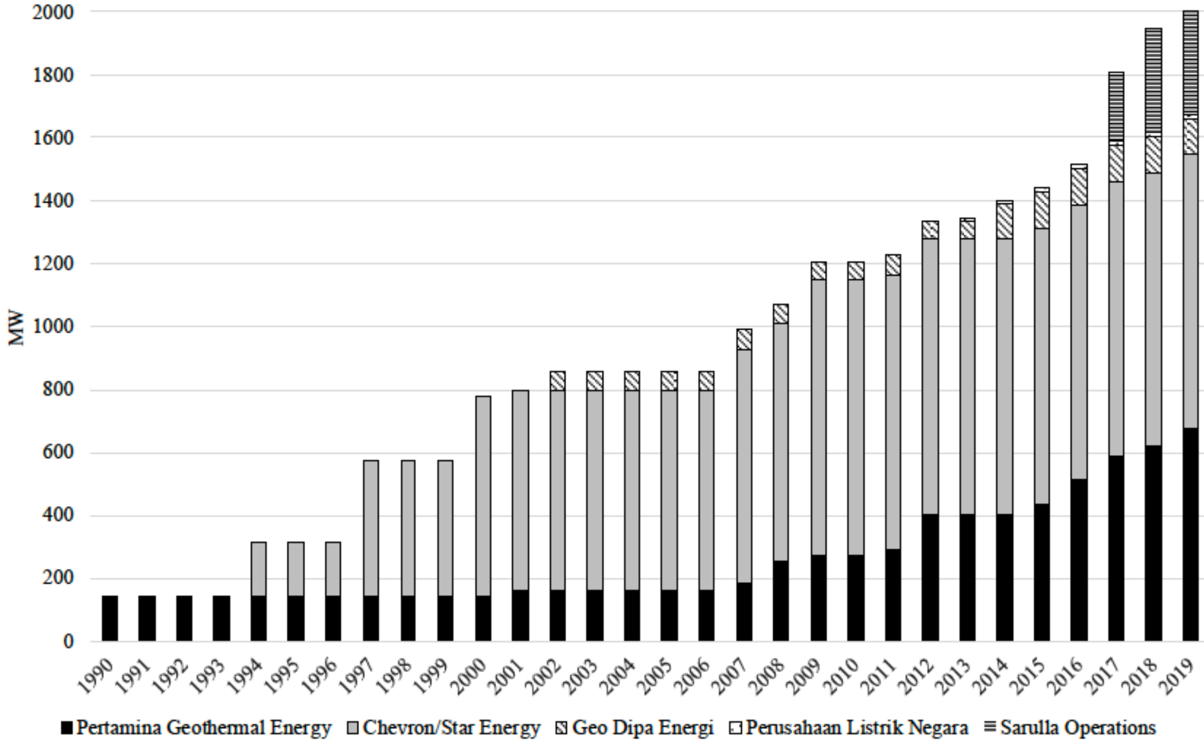


Figure 7. Plot of changes in installed capacity in Indonesia from 1990 to 2019 (Purwanto, 2019)

An analysis was then conducted on how five different geothermal fields were explored and developed. The resources are different in size and were developed in different ways. They do share some common aspects – these are listed below.

Exploration methods

- All projects conducted geologic mapping, with special attention paid to structures.
- In all but one project, LIDAR data was used to improve the identification of faults
- Geochemical sampling and analysis from geothermal features were used to estimate resource temperatures using geothermometry
- MT surveys were used to identify the clay cap alteration zone
- Some areas also utilized gravity and MEQ surveys to characterize the subsurface features.

Well targeting

- MT data was used to identify the top of the reservoir (base of the clay cap)
- Structural mapping and LIDAR were used to target faults
- Some projects used 3D visualization software and information from previous wells
- Directional drilling utilized.

Infrastructure

- Projects located within protected forest lands minimized the number of roads and well pads to reduce environmental impacts.

A number of the projects experienced delays due to changes in the owners/investors participating in the projects. For the smaller projects, there were less extensive exploration surveys, fewer wells drilled, and smaller teams working on the project to keep costs down. The exploration well success rates (deemed as wells with > 2 MW capacity) varied between projects, ranging from 33 to 67%. The number of exploration wells varied from 2 to 10 for these projects, with drilling depths ranging from 984 to 2723 m. Four of the five projects had power density values from 6-15 MW/km^2 – only the small project had a higher (30 MW/km^2) value.

The fraction of the exploration costs related to drilling ranged from 34% up to 81%. In two cases where drilling costs constituted the bulk of the exploration costs, relatively little was spent on geoscientific surveys and land acquisition and civil construction, whereas for the projects where drilling costs were less than half of the total exploration costs, they had elevated land acquisition and construction costs (due to their remote and rugged locations), as well as higher overhead and administrative costs associated with the projects. Project costs were relatively minor during the first few years of the projects (mostly related to geoscientific surveys) but ramped up with road and pad construction and drilling activities in the later years of the projects. For all but the small (10 MW) project, the exploration costs were estimated to constitute between 15-28% of the total project costs. The exploration phase of all of the projects lasted three years for one project, but at least 7 years for the rest of the projects, with two of the projects taking 9 years to complete that phase due to project delays.

A comparison of Indonesian exploration costs with those from other geothermal projects around the world suggests that Indonesia has higher costs than most other countries. In some countries, such as New Zealand, government exploration activities have significantly derisked additional exploration and development of geothermal resources, with a high drilling success rate (70%). In general, the higher exploration costs are directly related to the higher drilling costs in Indonesia. Some of the limiting factors identified for geothermal projects in Indonesia include:

- High infrastructure costs due to remote locations and lack of existing infrastructure
- Expensive drilling, especially during the exploration phase (average cost of $7.6 million/well)
- Small-scale prospects located in isolated areas
- Funding not readily available to support exploration activities.

Recommendations include:

- Have more accurate resource estimates through the use of heat-in-place and numerical reservoir models
- Increase government supervision to reduce timeline and cost overruns
- Improve drilling contract terms (mixed contracts involving day rates, depth, and lump sum) to reduce drilling costs by providing the right incentives for rapid, lower cost drilling
- Have government drilling help derisk green field areas
- Increase incentive schemes to support geothermal exploration costs
- Use insurance schemes to reduce drilling risks
- Utilize cluster-based development of multiple resources when exploring and developing isolated and small-scale projects.

2.7 Purwanto et al. (2021) An updated statistic evaluation of drilling performance, drilling cost, and well capacity of geothermal fields in Indonesia

This study presents a statistical analysis of drilling performance from 203 wells drilled between 2011 to 2019 from a variety of geothermal fields in Indonesia. Geothermal drilling in Indonesia began in the 1960s, with hundreds of wells drilled between 1996-2000, 2006-2010, 2011-2015, and 2016-2019 (Fig. 8). These wells typically ranged in depth from 1200 to 2800 m, reflecting different reservoir depths.

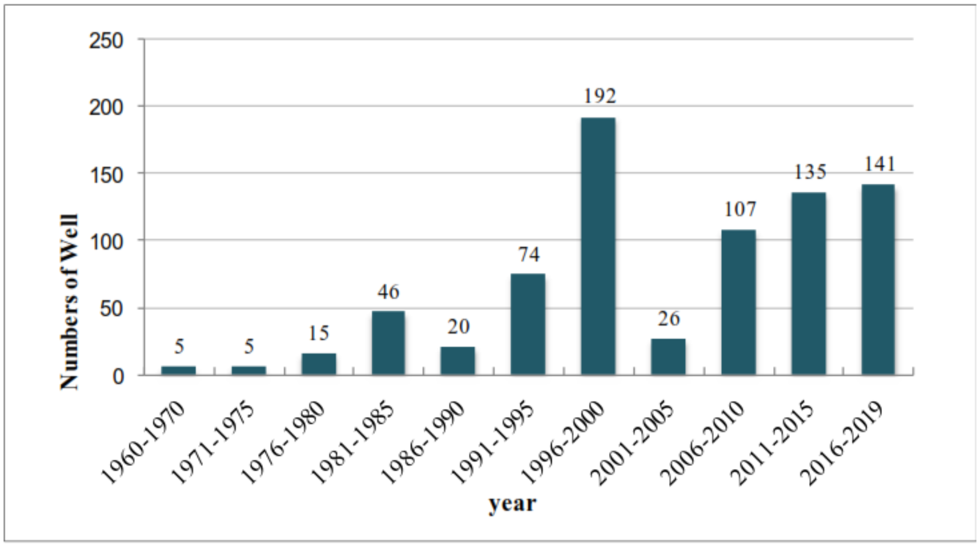


Figure 8. Geothermal drilling activity in Indonesia from the 1960s until 2019 (Purwanto et al., 2021)

One key observation was that a learning curve indicating improved drilling performance occurred between the exploration to field development phase. A summary of the lessons learned are highlighted in Fig. 9 and a comparison of the drilling cost per meter in different geothermal fields in Indonesia is depicted in Fig. 10. Similar to observations made in the previous study by Purwanto (2019), Purwanto et al. (2021) noted that geothermal drilling costs in Indonesia were quite a bit higher than most other countries, with the exception of the Philippines (Fig. 11). In addition to the contributing factors to these elevated costs noted in the previous section on the Purwanto (2019) study, another important issue leading to higher drilling costs noted by Purwanto et al. (2021) was the competition between the oil and gas industry and geothermal industry to access drilling rigs, as the rig rental price in Indonesia is highly influenced by world oil price. One important suggestion made to help reduce these elevated drilling costs is to accelerate the learning curves of the geothermal drilling industry by sharing experiences and essential data; this can be facilitated by the government.

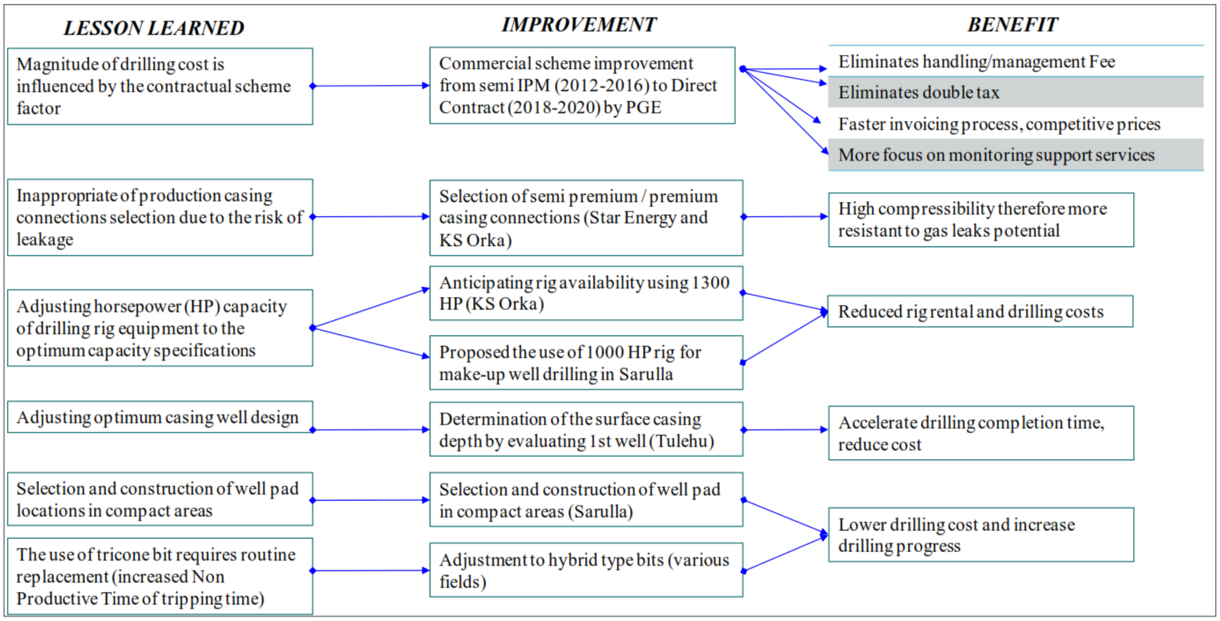


Figure 9. Lessons learned and improvement in geothermal drilling in Indonesia (Purwanto et al., 2021)

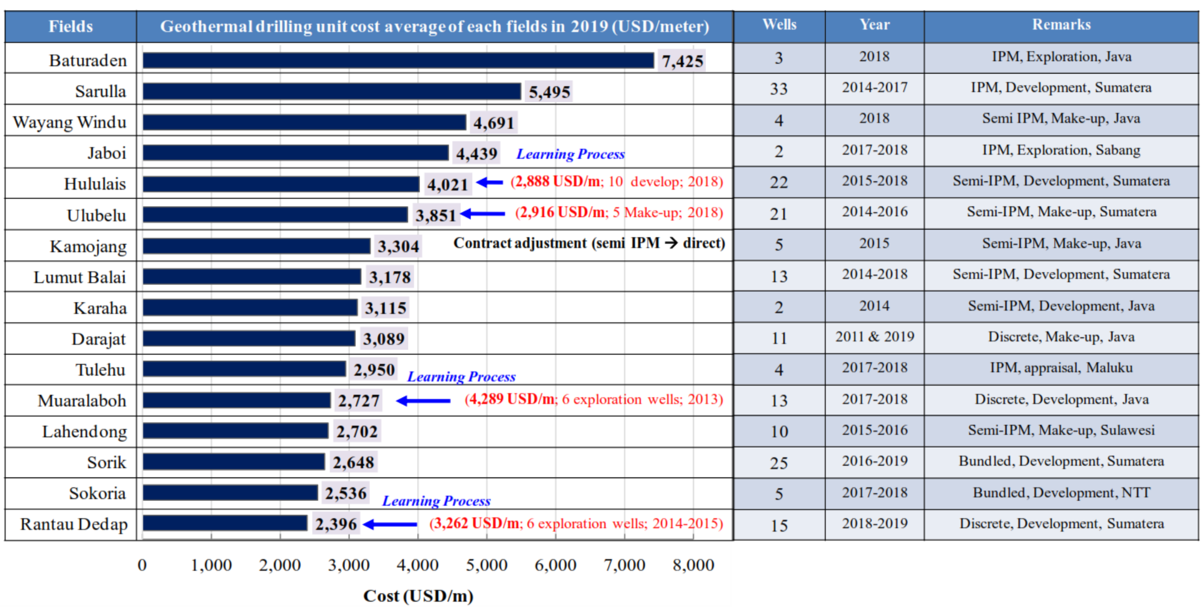


Figure 10. Comparison of drilling cost per meter for different geothermal drilling campaigns in different geothermal fields in Indonesia (Purwanto et al., 2021)

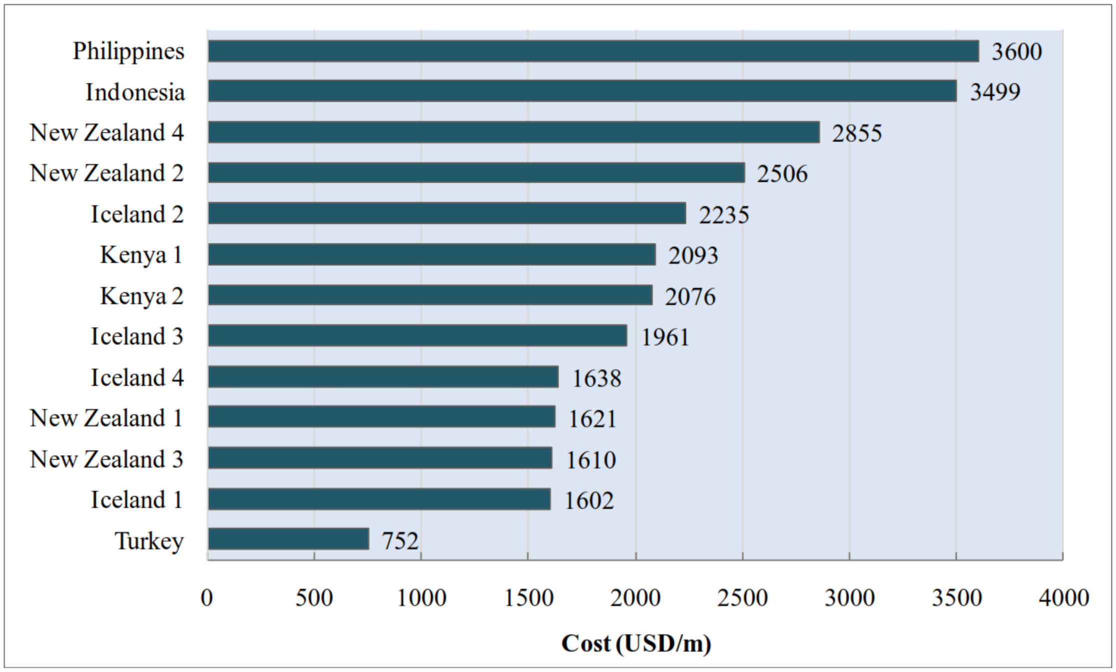


Figure 11. Estimated average geothermal well drilling costs per meter, adjusted to 2019 dollar value (Purwanto et al., 2021).

2.8 JICA et al. (2023) Project to develop medium- and long-term geothermal development policy in Indonesia Phase 2

This study provides an analysis of potential bottlenecks associated with geothermal projects in Indonesia. It provides a review of Indonesia's master plan for geothermal development in the context of Indonesia achieving carbon neutrality in the power sector by 2060. Of the planned renewable power generation envisioned over the next 10 years, geothermal would constitute about 8% (or 3.335 GW) of the total additional installed renewable energy capacity over this timeframe, with the potential to grow even larger by the 2030 target date.

The study implemented a financial model to evaluate the 183 geothermal field candidate sites from the MEMR database to evaluate their economic viability measured in internal rate of return (IRR) based on the estimated generation capacity, the costs related to exploration and drilling, development, the capital costs for power plant development, the distance to transmission lines, the project location, and the costs for project financing – the structure of this model is depicted in Fig. 12. Projects in remote locations would have higher ceiling prices than the national average cost of electricity generation for PLN (BPP) but also would incur higher development costs. Projects were analyzed based on their province, the development pathway taken, the exploration status and type of PPA, and by other key issues, such as whether the resource is located in a nature reserve. If the projects have a calculated IRR higher than the target value, then they are deemed to be financially feasible.

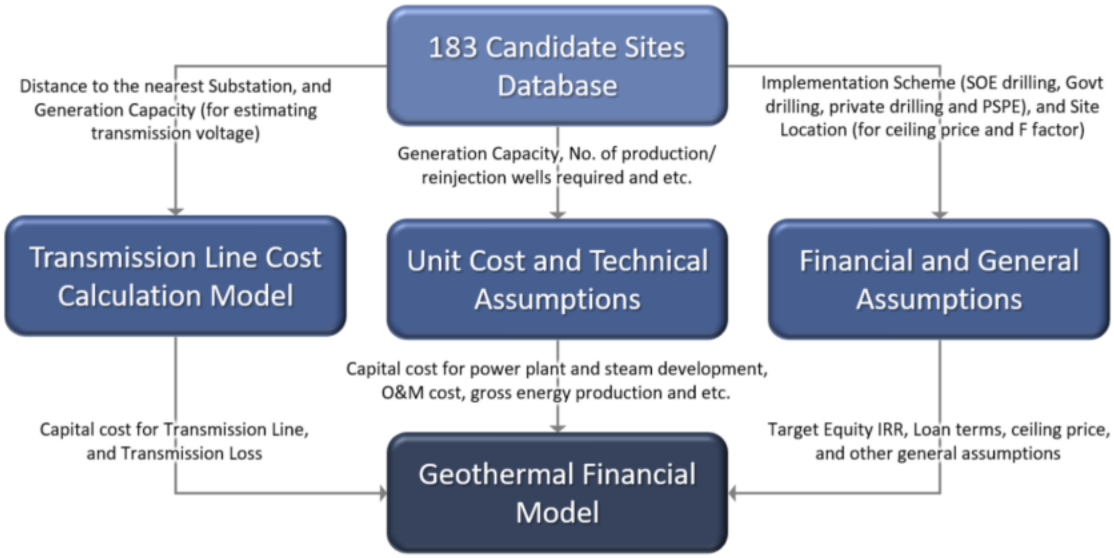


Figure 12. Geothermal financial model structure (JICA et al., 2023).

Key recommendations from this analysis include the following:

- Build on the derisking facility platform to ensure a good project track record
- Continued collaboration between the Ministry of Energy and Mineral Resources and the Ministry of Finance, with continuation of government drilling activities to help reduce project risk
- Adjustment of "Location Factor" on Presidential Reg. No.22/2022 for eastern Indonesia and remote islands
- Refine economic policies on tariff and incentives to ensure financial viability in the view of private developers
- Pursue integrated development activities, such as green hydrogen production
- Expand financial mechanisms to promote renewable energy.

2.9 General observations related to technical components of these studies

There are several common themes identified from the studies above; the more technical topics are briefly summarized below.

1. **Derisking of exploration**
    - Government investment in early-stage geoscience exploration and drilling to better characterize geothermal prospects
    - Development of an accurate catalog of geothermal prospects that provides realistic resource assessment using accepted methodology, along with uncertainty
2. **Reduction in costs and timelines**
    - Improve drilling technologies to reduce cost and time needed to drill wells
    - Improve well targeting using 3D visualization and integration of new data to continuously improve conceptual model of system

- Reduce number of roads and well pads needed to lower costs and minimize environmental impacts
- Sharing drilling learning curve experiences could lead to industry-wide lower costs

3. **Derisking of development and exploitation**
   - Develop strategies to deal with acidic fluids, high NCGs, and scaling
   - Consider using binary power plants as bottoming cycle to increase field productivity
   - Develop mitigation approaches to address volcanic and seismic hazards
   - Conduct outreach with all stakeholders, including local communities, throughout all phases of the project, to ensure that good communication exists and that the project obtains public acceptance.

3 Technical priorities identified by geothermal roadmaps in other countries

The following reports were evaluated to identify key technical topics that could help advance the deployment of geothermal resource utilization around the world.

- IEA Technology Roadmap – Geothermal heat and power (2011)
- European Technology and Innovation Platform on Deep Geothermal (ETIP-DG) (2018). Strategic research and innovation agenda
- FORGE roadmap (2019)
- DOE Geothermal Technologies Office Fiscal Years 2022-2026 Multi-year program plan (2022)
- DOE Pathways to commercial liftoff: Next-generation geothermal power (2024)
- IEA The future of geothermal energy (2024).

Each of these studies is summarized below, with a focus on identifying technology advances that could increase geothermal deployment by lowering costs and risks.

3.1 IEA Technology Roadmap – Geothermal heat and power (2011)

The International Energy Agency (IEA) roadmap "identified primary actions and tasks that must be addressed to accelerate geothermal development globally". The report provides a description of the current status of geothermal at the time of the study, describes a vision for future deployment of geothermal resources for power production and heat use, lays out milestones for technology improvements, and discusses the policy framework needed to overcome barriers.

The roadmap adopted the IEA Energy Technology Perspectives BLUE high-renewables scenario, in which 75% of the world's electricity production will be sourced by renewable energy by 2050, and that geothermal will contribute 1400 GWh annually to this mix. This would require that EGS would become commercially viable by 2030, with 100 GW installed capacity for EGS and 100 GW installed capacity for conventional hydrothermal resources. About 30% of this deployment would occur in developing Asia (mostly Indonesia and the Philippines). The use of geothermal resources would result in significant reductions (760 megatons) in CO_2 emissions annually. Rapid growth in use of geothermal resources for heat use for heating and agricultural and industrial applications is also envisioned, with the global annual direct use in 2050 estimated to be around 1,600 TWh of thermal energy. Throughout this process, cost reductions through improved technologies are predicted for all applications.

To achieve these ambitious goals for increased geothermal deployment, the following enabling processes are recommended:

1. **Geothermal resource assessment**
    - Compile and expand geoscience databases to create a publicly accessible database of geothermal resources
    - Develop integrated approach for identification and assessment of different geothermal resources

- Develop geothermal tools and models for identifying hidden hydrothermal systems and EGS resources

2. **Accessing and engineering the resource**
    - Develop cheaper and more advanced drilling technologies
    - Improve hard rock and high temperature drilling technologies
    - Improve downhole instrumentation and monitoring technologies
3. **Hybrid uses of geothermal resources**
    - Increase efficiency and performance of combined heat and power production
    - Develop cascaded uses
4. **Enhanced Geothermal Systems (EGS) and other advanced geothermal technologies**
    - Develop EGS pilot plants in different geologic environments
    - Develop standardized chemical, thermal, and hydraulic stimulation techniques
    - Improve management of environmental and safety concerns, especially risk associated with induced seismicity
    - Develop methods to monitor and manage long-term utilization of EGS reservoirs
    - Scale up EGS plants by developing modules in series and/or in parallel
    - Explore alternative ways to exploit hot rock resources
    - Explore feasibility of exploiting supercritical fluids
    - Explore feasibility of utilizing co-produced hot water from oil and gas wells
    - Explore feasibility of exploiting off-shore hydrothermal resources.

Each of these action items is assigned to different stakeholders (government, research institutions and universities, industry, and financial institutions) and given a timeframe in which the work should be accomplished. The roadmap then addresses a number of regulatory framework and support incentives, market facilitation and transformation, and notes the need for increased R&D funding and public-private partnerships. International collaboration is also called upon, especially to address barriers to geothermal development in developing countries. A short case study is presented for Indonesia.

3.2 European Technology and Innovation Platform on Deep Geothermal (ETIP-DG) (2018). Strategic research and innovation agenda

A series of research and innovation actions were identified as critical to enable the achievement of the ETIP-DG Vision study goals. These actions are centered around the following challenges:

- Prediction and assessment of geothermal resources
- Resource access and development
- Heat and electricity generation and system integration

- Cross-cutting challenges associated with the shift from research and innovation to deployment and knowledge sharing.

Following a summary of the current status of each topic being reviewed, specific technology development and innovation items were identified for each of these general areas. Summaries for each of these suggested technological improvements are listed for each major category.

3.2.1 Prediction and assessment of geothermal resources

- Improved pre-drilling exploration methods
- Advanced investigation and monitoring technology
- Exploration workflows – conceptual models, reservoir characterization, performance and decision models
- Exploration catalogues – reservoir analogues, rock properties and model constraints
- Assessing resource potential
- Beyond conventional resources.

3.2.2 Resource access and development

- General topics
- Advancement towards robot drilling technologies
- Rapid penetration rate technologies
- Green drilling fluids
- Reliable materials for casing and cementing
- Monitoring and logging while drilling
- High-temperature electronics for geothermal wells
- Effective and safe technologies for enhancing energy extraction
- Total reinjection and greener power plants
- Reducing corrosion and scaling and optimizing equipment and component lifetime
- Efficient resource development
- Enhanced production pumps.

3.2.3 Heat and electricity generation and system integration

- Advanced binary plants
- Innovative design and integration of binary cycle technology into new and existing flash plants
- High temperature binary power plants
- Power cycles and mitigation for super high-temperature resources, high-enthalpy steam direct expansion
- Flexible production of heat and power
- High-temperature thermal energy storage (HT-TES)
- Developing hybrid plants
- Exploiting mineral production from geothermal sources
- Generating different voltages for smart grids.

3.2.4 From R&D&I to deployment

- Setting the right policies

- Engaging with the public and other stakeholders
- Reinforcing competitiveness
- Geothermal deployment support schemes
- Establishing a legal and regulatory framework
- Embedding geothermal energy into the circular economy
- Harmonized protocols for defining the environmental and health impacts of geothermal energy and mitigation planning
- Human deployment.

3.2.5 *Knowledge sharing*

- Sharing underground data – unlocking subsurface information
- Organizing and sharing subsurface information
- Shared research infrastructures.

3.2.6 *Next generation of technologies*

- Geothermal resource assessment through deep probing earth observation
- Geothermal energy buffers
- Develop biologically inspired robots for revolutionary drilling: more efficient, less costly when automated, safer, environmentally friendly
- Create an underground energy system
- Use of IT tools for data mining and machine learning for resource assessment, access to the resource, and generating energy
- Connecting the reservoir to the surface: reliable and resilient data transfer
- Produce energy from offshore geothermal installations.

3.3 FORGE roadmap (2019)

The U.S. Department of Energy (DOE) commissioned a roadmap to guide the research directions for the Frontier Observatory for Research in Geothermal Energy (FORGE). The primary objective was to provide technical research recommendations on Enhanced Geothermal Systems (EGS) for the 5 years when this facility was to be in operation. Three critical research areas were identified: stimulation planning and design, fracture control, and reservoir management. The enabling R&D associated with these areas were identified as subsurface characterization, drilling, well completions, and induced seismicity management. The goal of these research recommendations is to overcome key technical challenges that would then permit the economic and large-scale deployment of EGS resources. Fig. 13 provides a broad overview of these recommendations.

Critical Research Areas

	Stimulation Planning and Design	Fracture Control	Reservoir Management
Definition	Research that supports efforts to design and optimally stimulate a well in accordance with natural subsurface characteristics	Research that supports efforts to develop an optimal fracture network as well as increase understanding of the resulting fracture system	Research that supports efforts to sustain long-term heat exchange in the system
Core R&D Actions	• Develop new **well configurations and well field designs** for optimal reservoir stimulation and operation • Develop **new and adapt existing fracturing technologies** and **procedures** for EGS	• **Optimize design of fracture procedures** to reservoir conditions • Develop **alternative injection practices and procedures** • Understand the effect of different **stimulation types** on the resulting fracture system • Develop methods for successful **zonal isolation** during stimulation at high temperatures and pressures	• **Predict and monitor changes** in the fractures system over time • Engineer **solutions to compromised or other unwanted changes** in reservoir permeability that can disrupt operation
Supporting R&D Actions	• Quantify **vertical and horizontal stress** at higher resolution • Correlate **wellbore stress measurements** beyond the wellbore • Correlate **in situ elastic rock property measurements** beyond the wellbore • **Reduce uncertainty** of optimized residence times and reservoir volumes	• **Predict induced seismicity** with higher reliability and accuracy • **Predict changes** in permeability, volume, conductivity, and other factors impacting heat exchange during fracture creation • Conduct **real time in situ monitoring** of key variables to track stimulation and heat exchange potential	• Incorporate in situ, **permanently installed monitoring instrumentation** in wellbore • Develop **active reservoir management** processes, procedures, and tools, including zonal isolation, to avoid thermal breakthrough and optimize flow rate • Resolve **fracture connectivity** and estimate reservoir volume

Figure 13. Identified critical research areas and associated core and supporting research and development actions for Enhanced Geothermal System development at the Utah FORGE site (McKittrick et al., 2019).

3.4 DOE Geothermal Technologies Office Fiscal Years 2022-2026 Multi-year program plan (2022)

Based on the findings of DOE's GeoVision study, this document lays out a five-year plan of R&D priorities for DOE GTO. These priorities are meant to help DOE achieve the following strategic goals for the United States:

1. Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of EGS and hydrothermal resource deployment by 2050.
2. Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 GDH installations and by installing GHPs in 28 million households nationwide by 2050.
3. Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment.

Six primary research areas were identified, which include:

1. **Exploration and characterization**
    - Improve subsurface/in-situ measurement tools and techniques
    - Improve surface-based geophysical and remote sensing techniques
    - Improve techniques to estimate reservoir temperatures and processes
    - Map stress and strain data
    - Conduct regional geologic mapping
    - Extend play fairway analysis and enhance multidisciplinary methods
    - Develop 3D modeling techniques, software, and innovative data processing and analysis
2. **Subsurface accessibility**
    - Improve rock reduction rate
    - Improve decision making while drilling
    - Manage lost circulation and drilling fluid
    - Improve casing and cementing
    - Reduce casing and cementing costs
    - Research materials and manufacturing method enhancements
    - Conduct high-temperature electronics research
3. **Subsurface enhancement and sustainability**
    - Better predict response through laboratory and field testing and observations
    - Improve coupling of numerical/analytical modeling and validation
    - Investigate advances in stimulation technologies and techniques
    - Assess and test zonal isolation and downhole flow control
    - Conduct real-time data collection, analysis, and response
    - Develop advanced monitoring and characterization systems
4. **Resource maximization**
    - Enhance geothermal representation in grid and cost models
    - Validate models and characterize uncertainty
    - Improve capacity expansion and production cost modeling
    - Develop and demonstrate geothermal grid service technologies
    - Identify additional roles for and increase the use of geothermal heat pumps in storage
    - Increase the use of geothermal district heating and cooling systems

- Investigate opportunities for critical materials
- Assess the potential for geothermal desalination
- Evaluate the value of hydrogen production from geothermal

5. **Data, modeling, and analysis**
    - Assess opportunities for innovative financing
    - Analyze revenue opportunities for added value streams
    - Prepare market report and trend analyses
    - Improve geothermal project cost and performance data
    - Advance performance cost modeling capabilities
    - Assess cybersecurity and vulnerability
    - Reduce development timelines through analysis and interagency collaboration
    - Reduce nontechnical barriers
    - Develop technical assistance and training resources
    - Contribute to and develop energy planning tools
    - Conduct resource assessments across the geothermal spectrum
6. Geothermal integration and awareness
    - Machine learning
    - Advanced manufacturing
    - Technology commercialization
    - Energy transitions
    - Stakeholder engagement.

3.5 DOE Pathways to commercial liftoff: Next-generation geothermal power (2024)

This report describes the market opportunity, current challenges, and potential solutions for the commercialization of next-generation geothermal power. It provides an overview and value proposition for next-generation geothermal technologies, describes how next-generation geothermal technologies can enhance its market potential through cost reductions, elucidates the pathway for commercial success by reaching liftoff and then achieving the scale needed to contribute to the U.S.'s green energy transformation, and then highlights key challenges and potential solutions. Next-generation geothermal systems consist of EGS and closed loop systems that provide the opportunity to greatly expand the resource base beyond conventional hydrothermal geothermal resources.

The main challenges that were identified by this study are as follows:

- High upfront costs and risks constraining project financing and expansion throughout the country

- Perceived and actual operability risk for deployments
- Long and unpredictable development lifecycles
- Existing business models undervalue the potential of next-generation geothermal
- Community opposition in some instances.

Some of the technology solutions to these challenges include:

- Creation of a validation suite of projects in varied geologies to demonstrate the viability of next-generation technologies during the lift-off phase
- In-field testing and innovation at active geothermal systems
- Strategic demonstration siting and data dissemination from early deployments to demonstrate sustained power production
- Technology advancements to allow some exploration and development steps to proceed in parallel
- Leverage flexible geothermal operations to increase the value of generated power
- Development and implementation of induced seismicity and environmental monitoring best practices
- Early, frequent, and transparent community engagement.

The pathway to the envisioned scale of deployment has three phases (Fig. 14). The first phase, demonstrating liftoff of new-generation geothermal systems, would be to develop 2-5 GW of new-generation resources by 2030 to demonstrate the technical and economic feasibility of this technology. The next phase would be to expand the viability of these resources in competitive regions over the next decade (2030-2040). The final phase to achieve scale (88-125 GW total deployment) would be to expand the next-generation geothermal footprint throughout the country.

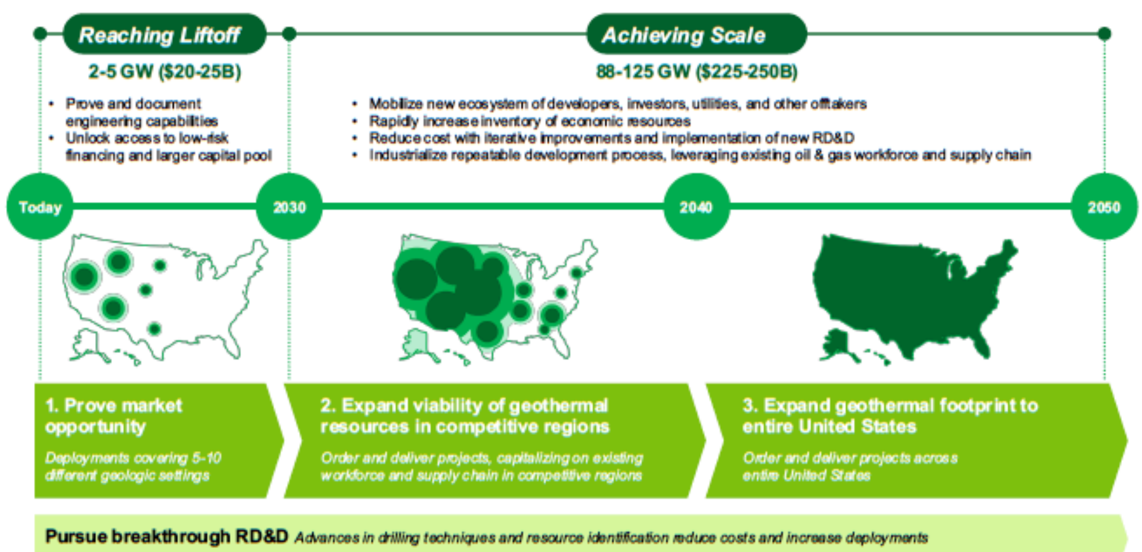


Figure 14. Pathway to commercial liftoff and scale for next-generation geothermal power in the U.S. (Blankenship et al., 2024)

3.6 IEA The future of geothermal energy (2024)

This report highlights how technology advances are creating new opportunities for increased deployment of geothermal resources around the world. While currently geothermal energy represents less than 1% of the world's energy demand, the IEA report notes that with continued technology improvements and cost reductions, geothermal could provide up to 15% of the world's electricity supply by 2050. Many of the needed skills and capacities already exist in the oil and gas industry, and these could be transferred to geothermal applications. Government policies are needed to advance geothermal as part of the solution of the clean energy transition process. While streamlined permitting processes would be helpful, there must be environmental and social guidelines in place to protect neighboring communities. Increased international collaboration and data sharing are needed to advance geothermal activities around the globe. New resource utilization approaches, such as enhanced geothermal systems (EGS), closed loop or advanced geothermal systems (AGS), and superhot rock systems, would allow tapping geothermal resources in many more locations than just where conventional hydrothermal resources are found, greatly increasing the potential geothermal resource base. Using a heat-in-place method for resource estimation, the report estimates that the Association of Southeast Asian Nations (ASEAN) have about 125 TW of technical potential for EGS power generation, representing 15% of the global estimate. Using the same GeoMap™ analysis, Indonesia is also estimated to have over 60 terawatts of lower grade (90°C) heat potential at depths less than 3 km, which potentially could serve for many direct use applications.

The report also identifies some key technical challenges that need to be addressed for geothermal deployment to expand significantly: these include induced seismicity, cheaper and faster drilling, improved well completion methods, and temperature-resistant downhole tools to better characterize the subsurface. These technology advances will require significant investments. Leveraging skills, data, and technologies from the oil and gas industry could help advance the development of next-generation geothermal technologies, especially in the realm of drilling, well completion, reservoir stimulation, and reservoir modeling. Transferring these skills and technologies to geothermal could result in significant cost reductions. Fig. 15 illustrates some of the commonalities between the oil and gas and geothermal industries.

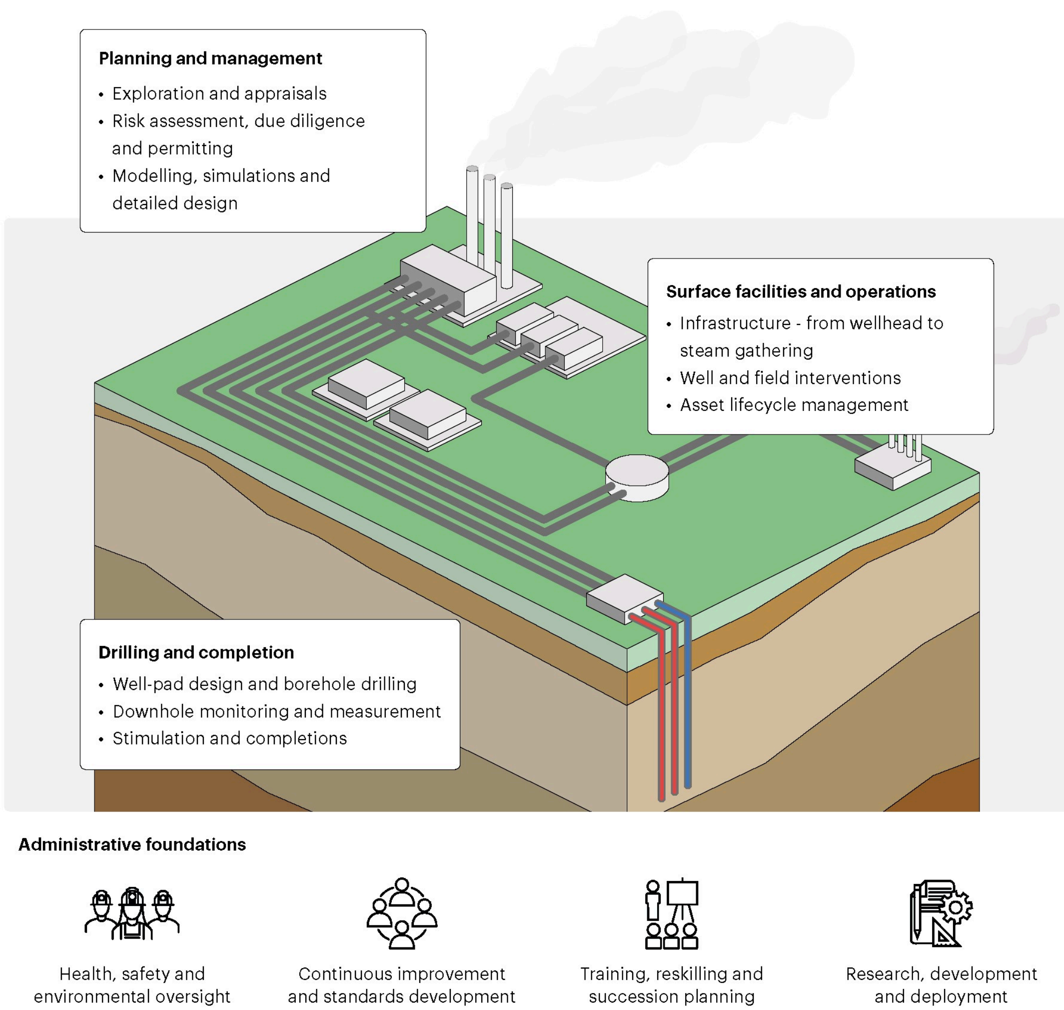


Figure 15. Synergies between oil and gas and geothermal industries (IEA, 2024)

Other potential uses of geothermal resources that were highlighted in the IEA report include district heating and cooling, thermal energy storage (which can provide seasonal flexibility to adjust for when energy is most needed), and extraction of dissolved critical mineral constituents, such as lithium, from geothermal brines.

In addition to the identified technical challenges, the report notes that there are also policy challenges that vary from country to country, the need for reliable geoscience data for conducting proper resource assessment, complicated permitting processes that can delay projects, thus adding to the cost, and challenges with social acceptance and community engagement for commercial utilization of these resources. Funding for these projects can also be problematic, as geothermal exploration and development projects have inherent technical and economic risks associated with them. Funding is also required to support the research and innovation that is needed to provide the technical advances needed to make next-generation geothermal commercially and technically viable. All of these efforts also require a trained workforce that can carry out these projects.

3.7 Cross-cutting themes of these roadmapping efforts that could be applied to Indonesia

These reports highlight many of the same technology needs to accelerate geothermal deployment. The cross-cutting themes identified by these studies can be summarized by the following general categories:

3.7.1 *Resource assessment*

- Development of publicly available geothermal database containing comprehensive geologic, geochemical, and geophysical information related to geothermal systems, organized using GIS platform
- Improved subsurface characterization using integrated approach
- Improved synthesis of subsurface information using 3D modeling methods.

3.7.2 *Resource access*

- Improved drilling methods to lower costs and increase speed
- Improved well completion methods
- Development of high temperature measurement while drilling (MWD) tools.

3.7.3 *Reservoir management*

- Improved well stimulation methods (especially for EGS)
- Improved numerical simulators for reservoir modeling
- Development of mitigation methods to address induced seismicity
- Development of approaches to manage scaling and corrosion
- Improved downhole pumps.

3.7.4 *Resource utilization*

- Improved power plant efficiencies
- Cascaded and hybrid uses, such as direct mineral recovery from geothermal brines
- Expansion of geothermal resources to include moderate and low-temperature systems, EGS, AGS, and superhot geothermal resource.

3.7.5 *Technology development and transfer*

- Investment in research and development activities to develop improved drilling, well completion, and downhole measurement tools
- Technology transfer from the oil and gas industry.

These studies also indicate the need for improved community outreach efforts and the development of best practices to protect the environment and local communities, as social acceptance and support are needed if increased deployment of geothermal resources is to occur.

4 Current status of geothermal exploration and development in Indonesia and geothermal's role in achieving the national net zero emission target

As the fourth most populous country in the world, Indonesia has become the major energy player in the Southeast Asia region. The energy sector has an essential role to be a catalyst for Indonesia's national economic growth and provide prosperity for more than 270 million people. In 2020, the national energy demand reached 142 MTOE, and it is projected to reach 310 MTOE by 2060. This enormous energy demand will tend to bring massive carbon emissions if there is not enough commitment towards the clean energy transition. Therefore, the government of Indonesia has launched several policies and commitments to ensure its energy security as well as to mitigate greenhouse gas emissions significantly.

Indonesia has many energy resources, including both fossil fuels and renewables. Most Indonesian energy supply comes from fossil fuel sources. Currently, most of Indonesia's energy is supplied by fossil fuel sources. However, to reduce greenhouse gas emissions and achieve energy security, the Government of Indonesia has committed to diversifying the primary energy sources and developing geothermal energy up to 22.7 GW by 2060 to achieve the national Net Zero Emission target.

4.1 Current status of geothermal development in Indonesia

According to the Indonesian Geological Agency (2024), Indonesia has 368 geothermal prospect areas with total resources of 23,690 MW that are scattered throughout the country (Fig. 16). Furthermore, the Government has set 63 geothermal working area/Wilayah Kerja Panas Bumi (WKP) and 15 preliminary survey and exploration assignment area/Wilayah Penugasan Survei Pendahuluan dan Eksplorasi Panas Bumi (PSPE), which are ready to be developed.

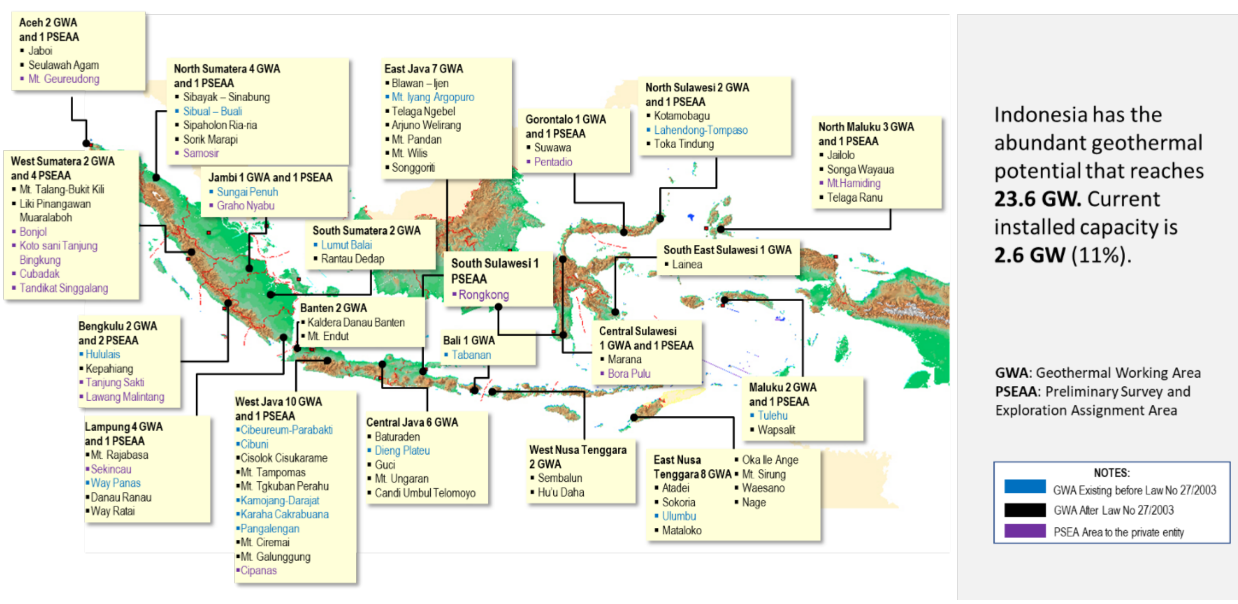


Figure 16. Map of existing geothermal developments within Indonesia (MEMR)

Indonesia began developing geothermal power plant projects in the 1980s. Since then, the installed capacity of geothermal has gradually increased. Figure 17 shows the increase of geothermal installed capacity over the last decade. Compared to the ambitious goals for expanding the development of geothermal resources to be 22.7 GW by 2060, the current actual rate of growth has been rather slow. Therefore, the Government needs to consider significant technological development to develop non-high temperature fields and extract more heat energy in a more sustainable way.

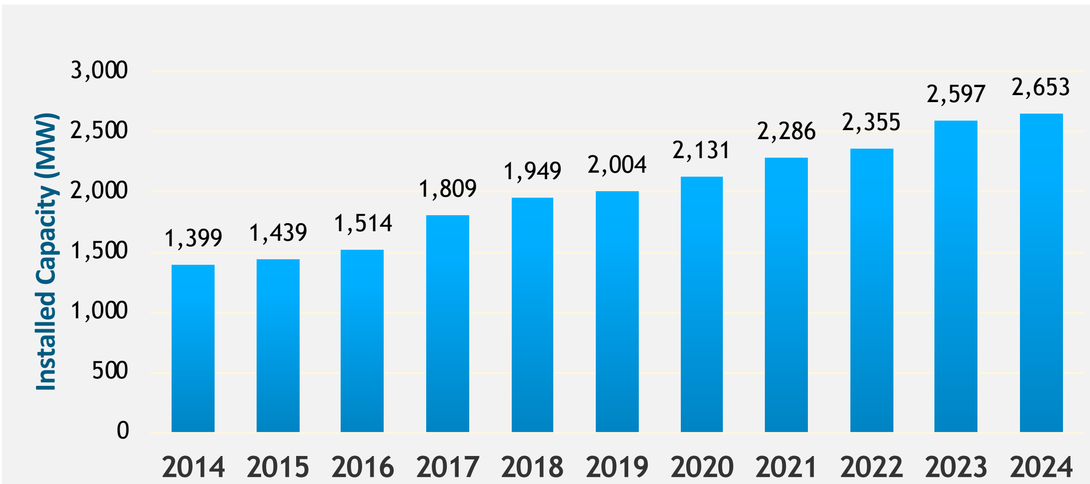


Figure 17. Installed geothermal capacity in Indonesia between 2014 and 2024 (MEMR)

Table 1 provides a list of existing geothermal fields with their installed capacities and planned expansion; Fig. 18 depicts their locations.

Table 1. Existing geothermal fields in Indonesia and their capacity (MEMR)

Field name	Location	# Current Units	Installed capacity (MW)	Planned expansion (MW)
Java				
Gunung Salak	West Java	7	396.51	40
Kamojang	West Java	5	239	30
Darajat	West Java	3	270	
Wayang Windu	West Java	2	227	60
Patuha	West Java	1	59.88	165
Karaha Bodas	West Java	1	30	
Dieng	Central Java	2	72.8	245
Sumatra				
Sarulla	North Sumatra	3	418.13	
Sibayak	North Sumatra	3	13.3[a]	40
Sorik Marapi	North Sumatra	5	279.1	
Muara Laboh	West Sumatra	1	89.25	145

Lumut Balai	South Sumatra	1	59.9	60
Rantau Dedap	South Sumatra	1	98.4	134
Ulubalu	Lampung	3	229	20 (including 0.5 MW for green H_2 plant
East Nusa Tenggara				
Mataloko	East Nusa Tenggara	1	2.5[a]	20
Ulumbu	East Nusa Tenggara	4	10	40
Sokoria	East Nusa Tenggara	3	11.58	19
Sulawesi				
Lahendong	North Sulawesi	7	123.72	35

[a] – The plants at Sibayak and Mataloko are currently not in operation.

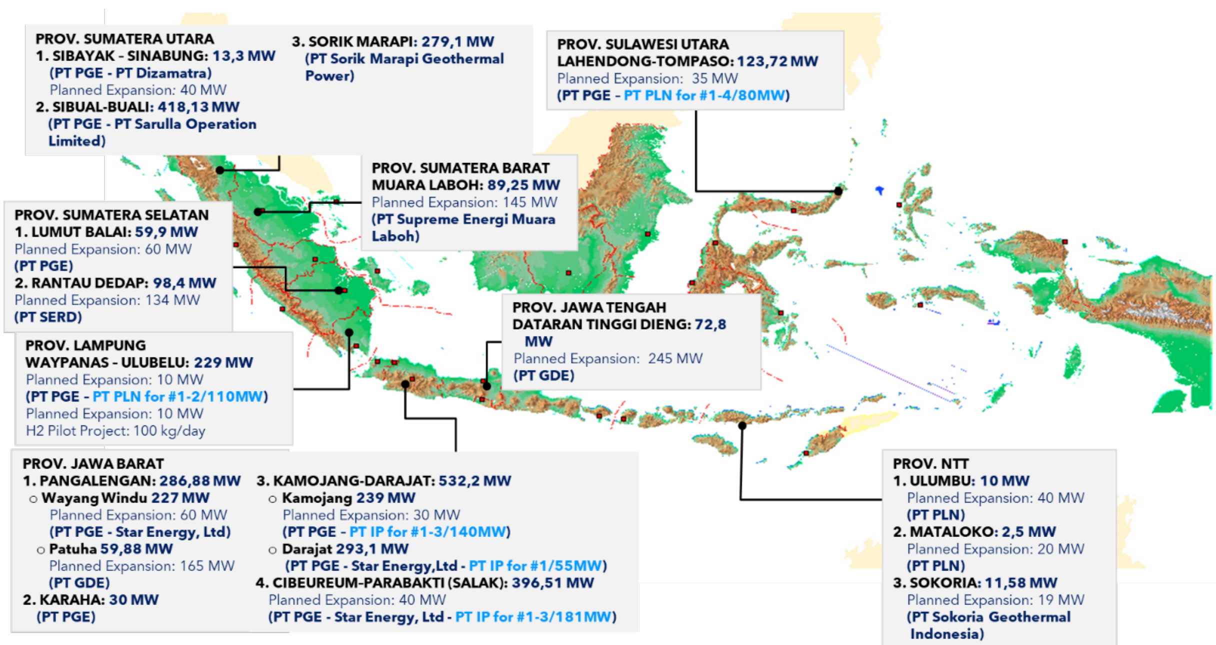


Figure 18. Map of producing geothermal power plants in Indonesia (MEMR)

4.2 Quick wins for geothermal development and regulation improvement in Indonesia

In the next 5 years, Indonesia aims to develop another 1,190 MW from the development of co-generation, retrofitted, brownfield, and some priority projects in eastern Indonesia (Fig. 19) –. As the biggest geothermal state-owned enterprise, Pertamina Geothermal Energy aims to collaborate with PLN for the development of co-generation projects with the total expansion capacity up to 225 MW. The projects will utilize the current excess steam/heat so that projects are considered to be low risk and can be developed faster. Star Energy Geothermal also aims to optimize their current existing plants and expects to have additional capacity up to 32.6 MW. Additionally, the

Indonesian government encourages the acceleration of geothermal development in eastern Indonesia as the electricity supply is urgently needed to replace expensive diesel power plants.

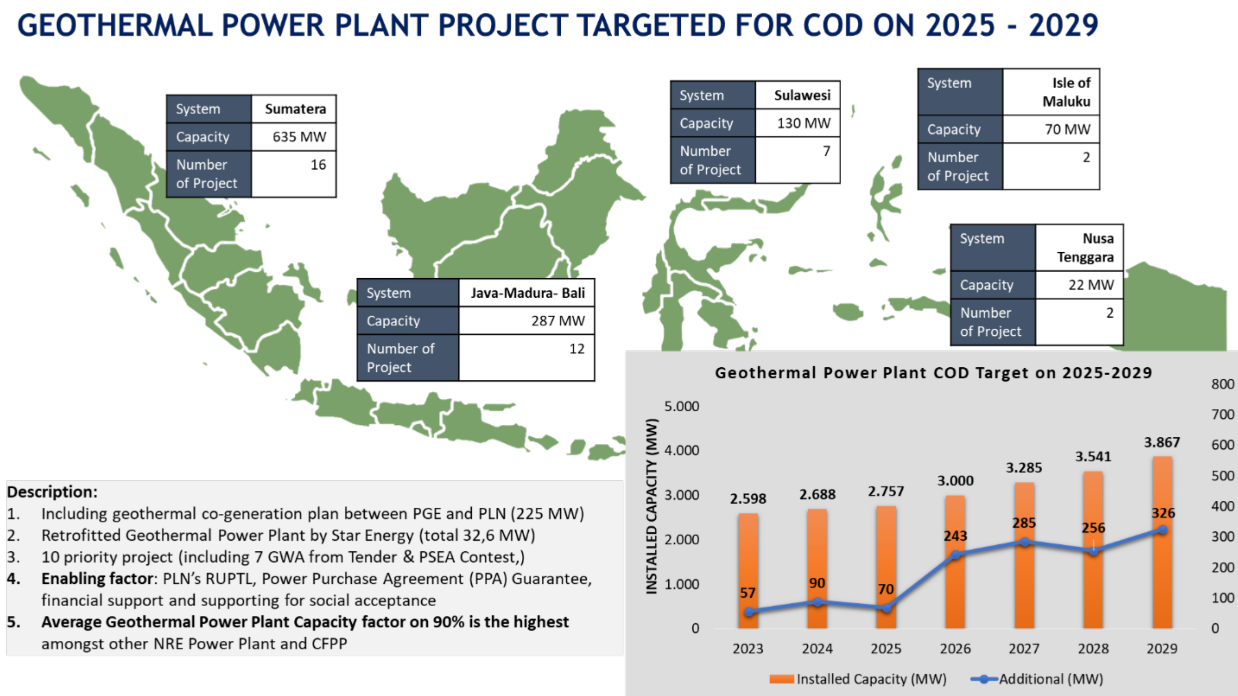


Figure 19. Geothermal power plant development planned for 2025-2029 in Indonesia (MEMR)

In order to accelerate the geothermal development through improving business certainty and solving the local content issues, the Government of Indonesia has stipulated Presidential Regulation No.112/2022 related to tariff setting for renewable projects and Ministerial Regulation No. 11/2024, which provides more flexibility for electricity infrastructure projects in the procurement process (Fig. 20).

REGULATION'S BREAKTHROUGH TO ACCELERATE GEOTHERMAL INVESTMENT

PRESIDENTIAL REGULATION NO 112/2022

Renewable Energy Development is carried out based on the RUPTL, which takes into account the target of the renewable energy mix, supply-demand balance, and the economic value of power plants

Ceiling Price (HPT) for 2-stage staging with location factors applies to stage 1, for each type of renewables:

Type	*Stage* 1 (cUSD/kWh)	*Stage* 2 (cUSD/kWh)
Geothermal	7.65 – 9.76 x F	6.5 – 8.30
Hydro	6.74 – 11.23 x n x F	4.21 – 7.02
Excess Power Hydro	5.80 x 0.7	
Solar PV	6.95 – 11.47 x n x F	4.17 – 6.88
Wind	9.54 – 11.22 x n x F	5.73 – 6.73
Biogas	7.44 – 10.18 x n x F	4.46 – 6.11 x n
Biomass	9.29 – 11.55 x n x F	7.43 – 9.24 x n

n: Technical Factor (0.7 – 1.0) F: Location Factor (1 – 1.5)

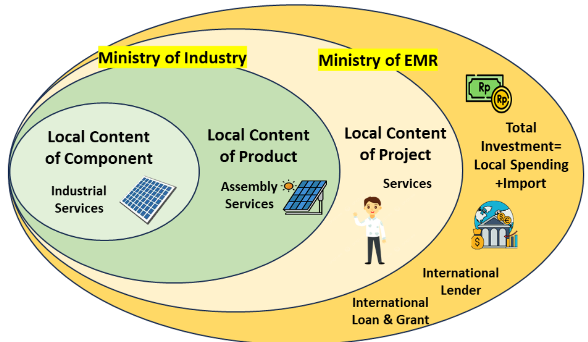
B to B (requires MEMR approval): Peaker Hydro; Biofuel PP; Ocean PP

Presidential Regulation 112/2022 also mandates the Government c.q. The MEMR to prepare a roadmap to accelerate the retirement of the CFPP's operational life and limit the development of new CFPPs, except for those CFPPs that have been listed in the RUPTL and which are integrated with industry.

Muaralaboh Unit 2 (80 MW) and Unit 3 (60 MW) are the first geothermal projects funded under the Asia Zero Community (AZEC), with total investment for 638.7 million USD

MEMR REGULATION NO 11/2024 – Debottlenecking on Local Content Regulation

*"To **accelerate the development of electricity infrastructure while still prioritizing the use of domestic products,** it is necessary to regulate the use of domestic products for the development of electricity infrastructure"*



Project Name	Dieng #2	Patuha #2	Hululais
Capacity (MW)	55	55	2 x 55
Investment (million USD)	108	135	204
COD (Year)	2027	2027	2028

Figure 20. Details of Presidential Regulation No. 112/2022 to accelerate geothermal investment (MEMR)

4.3 The role of geothermal energy in achieving net zero emissions in Indonesia by 2060

The government of Indonesia has stipulated the MEMR Decree on the National General Electricity Plan for 2024-2060. The planning document provides the electricity demand projections, the targets for each of the clean energy projects to be developed, and the plans for major grid integration development. It is projected that the national energy demand (Fig. 21) will rise from 482 TWh (1713 kWh/capita) in 2024 to 1813 TWh (5038 kWh/capita) by 2060. The demand will be dominated by the industrial sector (774 TWh), followed by the residential sector (502 TWh), commercial buildings (245 TWh), electric vehicles (198 TWh), and the public sector (94 TWh).

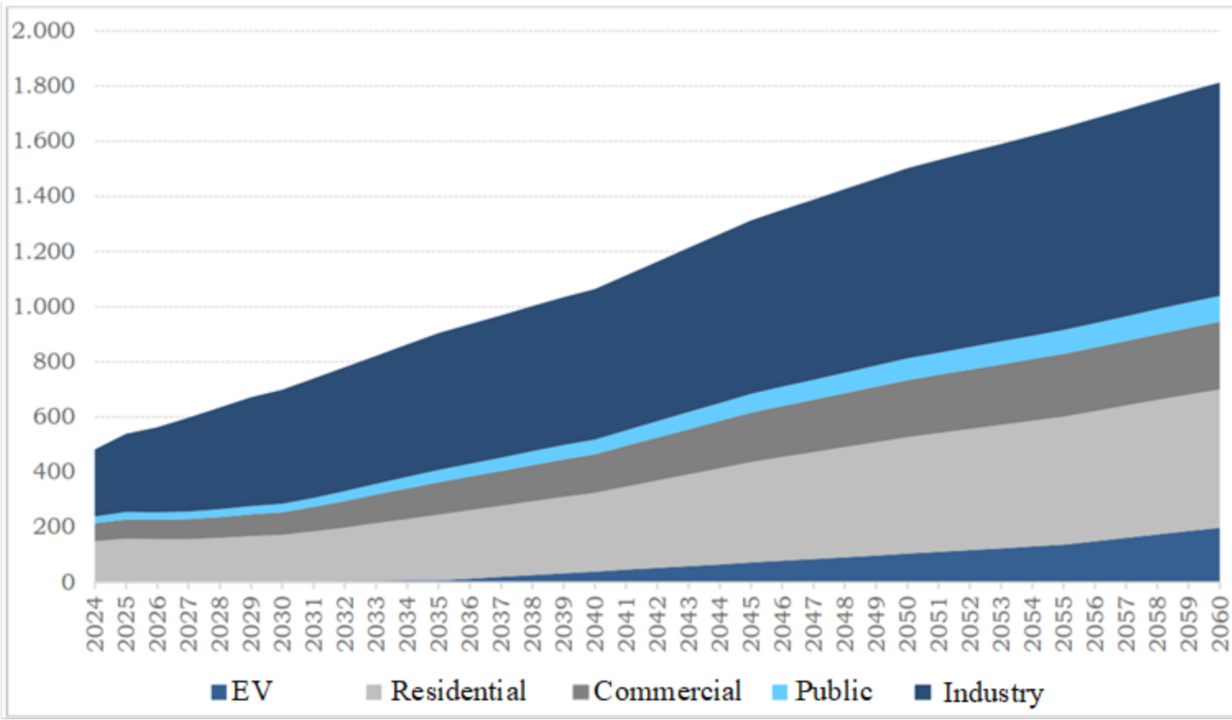


Figure 21. Indonesia's national electricity demand projection (in TWh)

On the supply side, the government aims to develop various clean energy projects with up to 443 GW of installed capacity by 2060 (Fig. 22). As one of the abundant renewable energy sources in Indonesia, geothermal energy will play an important role in achieving the net zero emission target. Geothermal power plants are expected to provide baseload generation that can serve as the backbone of the national grid. Moreover, massive geothermal projects are also expected to be entering the grid around 2040 so that they can replace existing coal thermal power plants that will be retiring. In summary, geothermal project are expected to contribute around 178 TWh (9.2 % of the energy mix) by 2060 with a total installed capacity of 22.7 GW (Fig. 23).

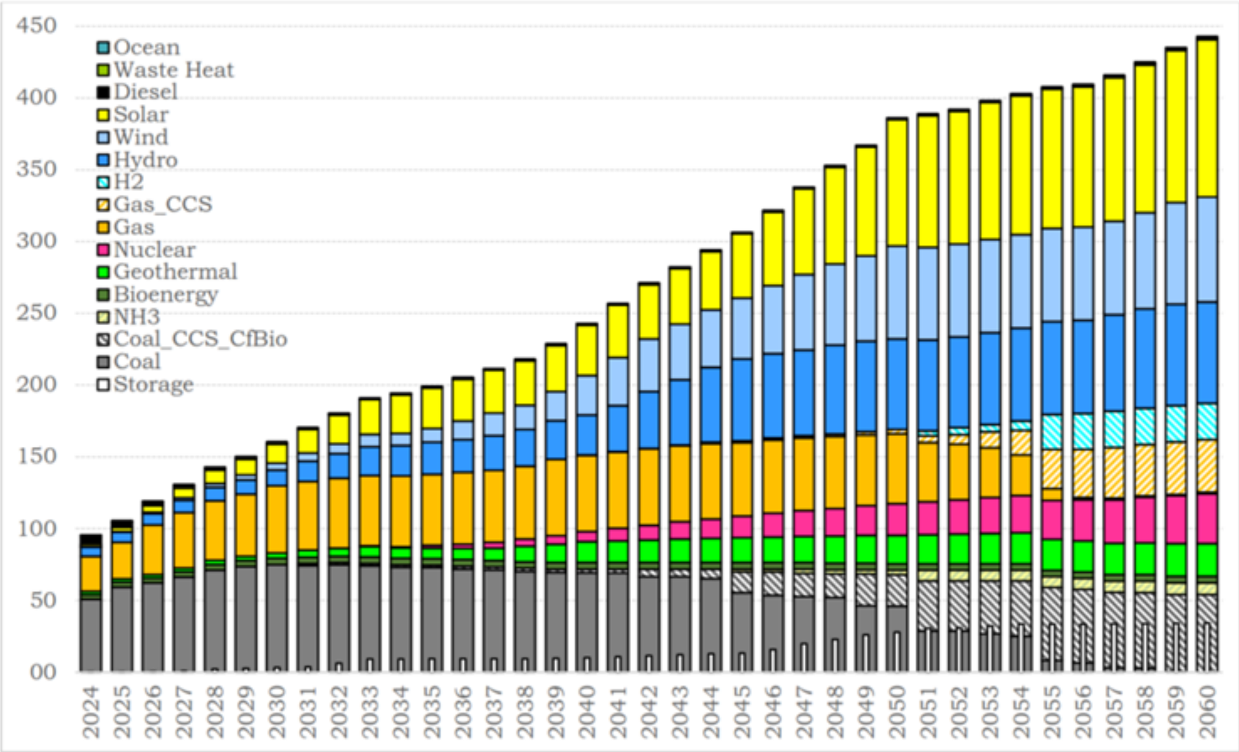


Figure 22. Indonesia's national power plant development target (in GW installed capacity)

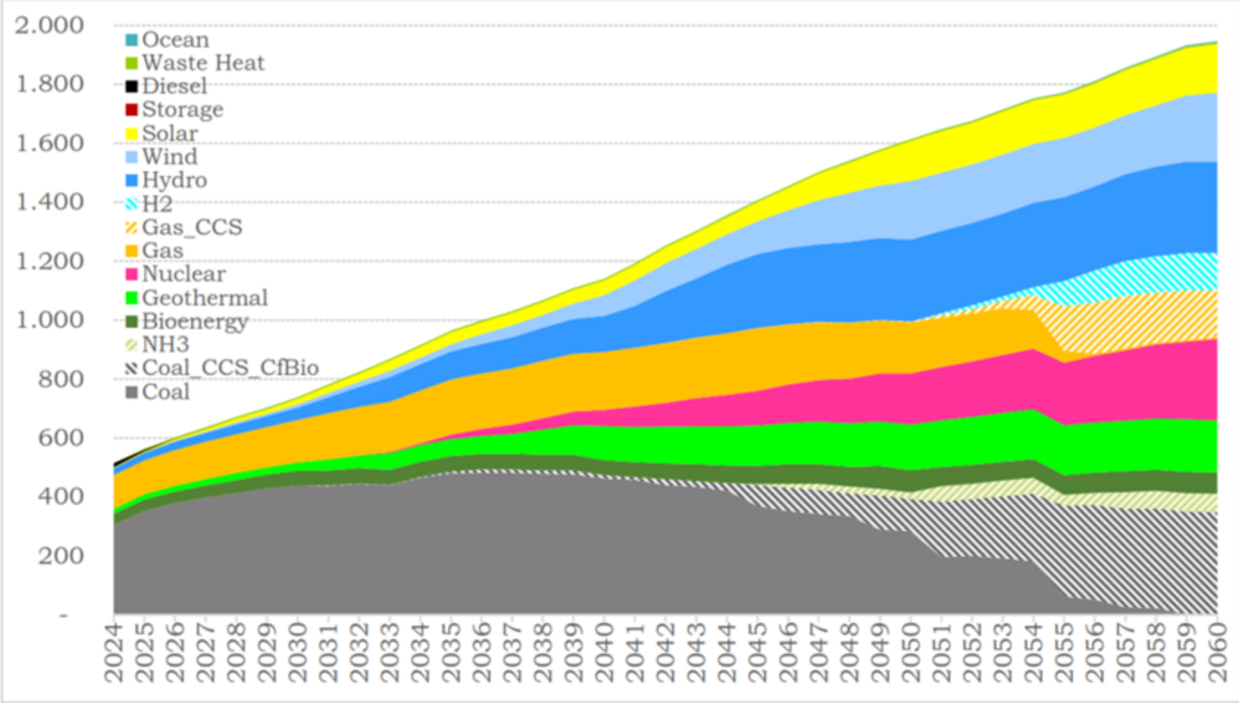


Figure 23. Indonesia's national electricity mix projection (in TWh)

In the near term (2024-2033), the development of geothermal brownfield and expansion projects are encouraged by the Indonesian government. These projects are expected to be developed relatively fast and immediately can fulfill the growing demand. Technologies like closed-loop geothermal will be tested to see if they can recover more heat from existing geothermal fields. The Indonesian government is also opening working area tenders for greenfields and conducting several government drilling programs. The Geological Agency is also initiating exploration of low to medium enthalpy systems for both electricity generation and direct use applications. Hence, the technology of wellbore pumps and generators will be needed to extract energy from these lower enthalpy systems.

As the coal thermal power plants start retiring in 2034-2040, the national grid will need replacements to maintain a reliable electricity supply. Here, the results of the current working area tender and government drilling are expected to ramp up. Currently, while the coal plants are still in operation, it will be important to begin pilot projects involving unconventional geothermal technologies such as enhanced geothermal systems (EGS), advanced geothermal systems (AGS), and supercritical geothermal systems, which have the potential to provide significant contributions to energy supplies to the grid.

After 2040, these unconventional geothermal systems are expected to be commercially viable and can help achieve the goal of attaining the installed geothermal capacity of 22.7 GW. To be able to replace all of the retired coal power generation, the Indonesian government is also expecting significant contributions from other clean energy technologies, such as nuclear, carbon capture and storage, and clean ammonia and hydrogen.

The following key challenges to geothermal development, along with possible solutions, have been identified as part of this effort (Table 2).

Table 2. Challenges, opportunities, and solutions for geothermal development in Indonesia identified by MEMR

Challenges/Opportunities	Solutions
Excess heat from brine	Cogeneration
Subsurface uncertainty and risk due to lack of subsurface data	Government exploration drilling
Idle wells/Non-productive wells	Closed loop / ESP
No more gigantic resources	Low-medium enthalpy system using EGS and Organic Rankine Cycle (ORC) plants
Drilling risks	Integrated drilling solutions

In response to the world climate crisis, Indonesia has pledged to invest $20 billion to finance the energy transition of the electricity sector as part of the Just Energy Transition Partnership during the G20 Summit in Bali. The Bali roadmap outlines concrete actions to address energy transition effort among members by realizing three priorities **(energy accessibility, technology scale-up, and financing)** through active involvement and collaboration of G20 countries. One of the long-term goals of this effort is to develop 22.7 GW of geothermal power production in Indonesia by

2060. Given that the current level of installed capacity is at 2.6 GW, the rate of geothermal deployment will need to be accelerated significantly over its current level.

5 Stakeholder feedback on technical challenges and research needs

5.1 Initial stakeholder feedback from 2024

Based on Zoom discussions with various members of the Indonesian geothermal community and participation in the U.S.-Indonesia geothermal workshop and IIGCE meeting (see details in Appendix A), the following technical areas were highlighted as being of particular interest.

5.1.1 Geoscience and Upstream Geothermal Technologies

- New approaches for geothermal exploration and well targeting
- Potential exploration & development strategies for utilizing low-med enthalpy geothermal resource
- New innovations in subsurface characterization to reduce risk.

5.1.2 Drilling, Well Completion, and Subsurface Technologies

- Drilling rig new technology for geothermal game changer
- Apply new technologies and innovations to geothermal drilling and improved monitoring of drilling operations
- Look at different drilling and well completion strategies, including horizontal wells and closed loop systems
- Oil and gas downhole tools technology conversion to be applicable for geothermal applications, which has higher temperature, abrasiveness, sour services, and excessive losses.

5.1.3 Downstream and Power Plant Technologies

- Evaluate new innovations in geothermal power plant system (modular designs, improved cooling tower systems, etc.)
- Innovative business scheme (for additional revenue streams)
- Cascaded use of produced geothermal fluids
- Baseload vs. load-following power production
- Well head power plant vs. centralized power plant
- Downhole pump for non-artesian geothermal production wells.

5.2 Stakeholder feedback from 2025 focus group discussions

A focus group discussion was conducted at the Ministry of Energy and Mineral Resources office in Jakarta on January 8, 2025, with over 100 stakeholders from Indonesia's geothermal community in attendance. Additional details from this workshop can be found in Appendix B. Four different breakout groups made up of participants from the meeting focused on identifying additional ideas that could address some of the challenges faced by geothermal operations in Indonesia. Each of the groups addressed one of the following topic areas:

- Reducing resource risk
- Reducing drilling costs and risks
- Expanding uses of geothermal resources

- Workforce development, community outreach, and social acceptance.

A summary of the feedback provided by each group is provided in the sections below.

5.2.1 Reducing Resource Risk

- Incorporate interpretations of data from SMEs into the Genesis database
- Include data analysis tools
- Retain traditional resource estimate tools (stored heat, power density) in addition to new methods
- Use United Nations Framework Classification (UNFC-2009) for geothermal resources and NREL GeoRePORT tools to assess project readiness.

5.2.2 Reducing Drilling Costs and Risks

- Create intercompany collaboration on drill rig procurement
- Share drilling success and failure stories
- Improve methods to deal with stuck pipe using geologic hazard identification and real-time early warning system
- Develop improved methods to identify location of clay cap and permeable regions of reservoir.

5.2.3 Expanding Uses of Geothermal Resources

- Share best practices for hazard mitigation (such as induced seismicity) for EGS
- Locate early EGS project sites in remote locations and avoid major active faults (such as Great Sumatra Fault)
- Create dedicated field test site for evaluating unconventional geothermal resources
- Use closed loop on new but tight hydrothermal wells (better well conditions)
- Make sure that multiple companies are involved to avoid issues with single provider monopoly.

5.2.4 Workforce Development, Community Engagement, and Social Acceptance

- Increase accountability to ensure that "bonus production" distribution actually benefits local community
- Consider NZ model for including community as partners in projects (Māori as business partners for projects on tribal lands)
- Provide scholarships for local students
- Develop geothermal teaching materials to be used for local schools
- Educate government regulators about geothermal.

6 Potential technologies that could be applied to Indonesia

Here is a brief description of some approaches that could be applied to Indonesian geothermal projects with the objective of expanding the resource base, reducing the risk of geothermal exploration and development, and reducing the cost, making geothermal more competitive with other energy options. These topics are described in more detail below.

- Database development and sharing
- Resource assessment methods
- Geochemical modeling
- Well targeting
- Drilling
- Utilization of geothermal resources beyond conventional high temperature hydrothermal systems
- Technology transfer and development
- Community outreach and social acceptance.

This list of topics can be expanded based on additional feedback from Indonesia's geothermal stakeholders – it is only meant to serve as a starting point.

6.1 Database development and sharing

Reliable geoscience data is required to build accurate models and develop realistic assessments of geothermal resources. To reduce exploration risk, there is a real need for a unified geothermal database that contains relevant geologic, geophysical, and geochemical data for Indonesia. The database could be linked to existing sites where some of this information is already available. This information could consist of a wide variety of information that might be available on national, regional, and/or local scales. These data could be used as inputs for geothermal play fairway models that could help identify prospective geothermal areas and help evaluate geothermal prospects. The data could consist of the following types of information:

1. Remote sensing
    - Digital elevation models
    - LiDAR
    - Thermal infrared
    - Hyperspectral
2. Geophysical data
    - Heat flow
    - Gravity
    - Magnetics
    - Electrical methods
    - Seismic

- Location of historical earthquakes (earthquake catalog)/passive seismic
- Thermal gradient data
- Regional stress data

3. Geological data
    - Geologic maps and cross sections
    - Quaternary faults
    - Location, ages, and compositions of volcanoes
4. Geochemical data
    - Location, temperature, and chemistry of geothermal features (hot springs, fumaroles, etc.)
    - Chemistry of geothermal well fluids
    - Alteration mineralogy
5. Well data
    - Locations, depths, temperatures of wells
    - Flow rates, fluid compositions, injectivity/productivity
    - Well completion information and well status.

The U.S. Department of Energy (DOE) has developed an extensive geothermal data repository (GDR) (e.g., Weers et al., 2022; https://gdr.openei.org/); this could serve as a model for a similar geothermal database for Indonesia. The GDR was launched just over 10 years ago and provides universal access to over 1250 datasets consisting of over 287 terabytes; over 15 million downloads have been made from this system. The dataset entries are accompanied by metadata, which provide important information such as how the data were collected, how data were processed, and associated errors in measurements. New datasets are continually being uploaded to this system, as all DOE-funded projects are required to archive their data in this system. The GDR is supplemented by the National Geothermal Data System (NGDS), which is a distributed, interoperable network of data from state geological surveys across the U.S. and the nation's leading academic geothermal centers (https://data.geothermaldata.org). These datasets are linked as part of the Open Energy Data Initiative (OEDI), a partnership between the National Renewable Energy Laboratory (NREL), DOE, Amazon, Microsoft, and Google. The network of data sharing partners is depicted in Fig. 24 below.

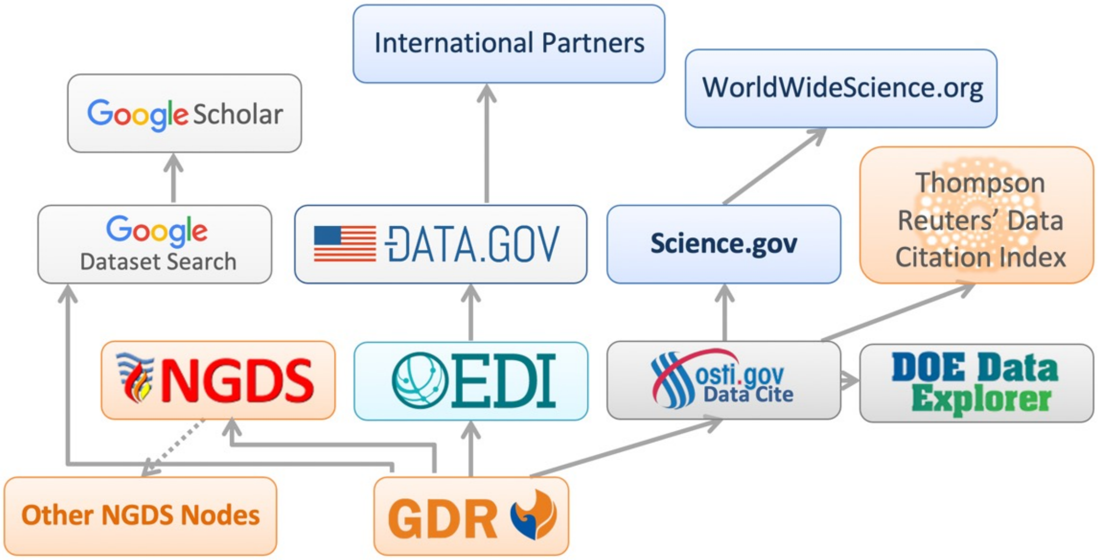


Figure 24. The DOE's Geothermal Data Repository's network of data sharing partners through the OEDI

6.1.1 *Recent progress on database development and data sharing in Indonesia*

MEMR recently launched the new Genesis geothermal database system (https://genesis.ebtke.esdm.go.id/gdr/) at the recent IIGCE meeting. This system provides a map-based array of geothermal resources throughout Indonesia (Fig. 25) that have linked digital data resources relating to geological, geophysical, and geochemical datasets. Hopefully it will connect to other existing geothermal relevant datasets (see list below) so that this one site can provide all available geoscientific information that is relevant to geothermal resource evaluation.

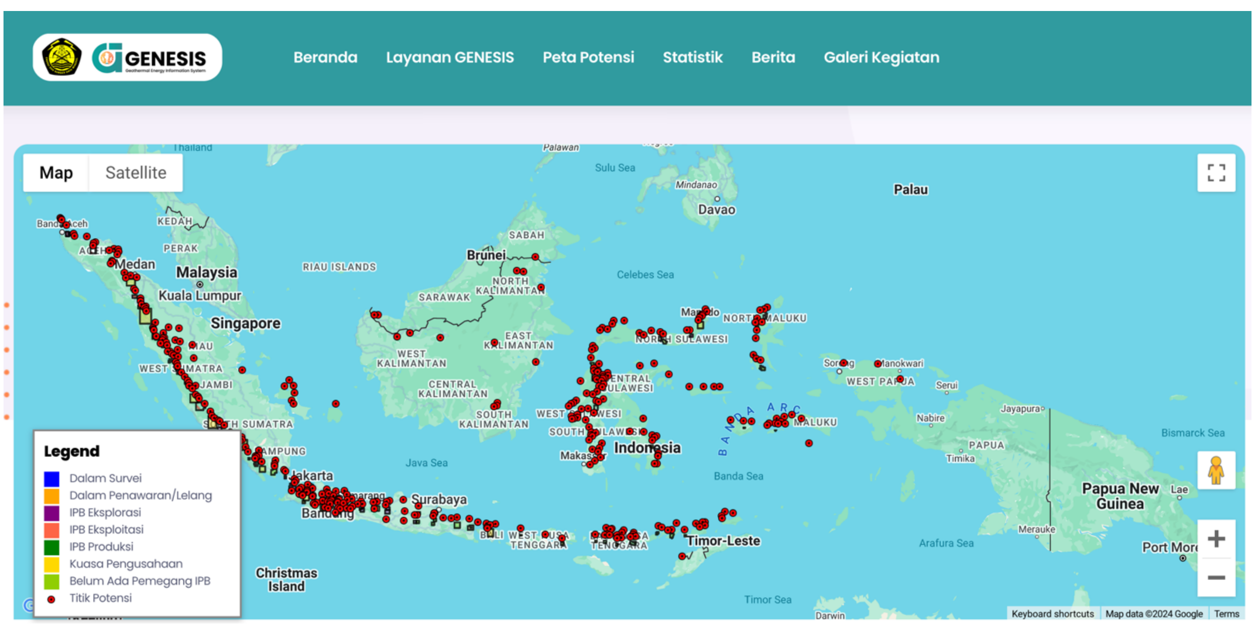


Figure 25. Screenshot of the MEMR Genesis database display, with red dots indicating potential geothermal resources

Publicly available data (other datasets likely exist – not complete)

- Compendium of active volcanoes
    - Smithsonian Institution (https://volcano.si.edu/volcanolist_countries.cfm?country=Indonesia)
    - Pusat Vulkanologi dan Mitigasi Bencana Geologi (VSI) (https://vsi.esdm.go.id/)
- Satellite imagery and hyperspectral data
    - Landsat: https://www.usgs.gov/landsat-missions/landsat-data-access
    - SPOT: https://earth.esa.int/eogateway/missions/spot
    - Google Earth: https://earth.google.com
    - Other NASA satellite imagery: https://worldview.earthdata.nasa.gov/
- Geologic maps and surveys
    - Center for Geological Survey, Geological Agency, Ministry of ESDM (https://geologi.esdm.go.id/geomap)
    - Pusat Vulkanologi dan Mitigasi Bencana Geologi (VSI) (https://vsi.esdm.go.id/portalmbg/)
    - JICA
    - British Geological Survey (Sumatra) https://www.bgs.ac.uk/geology-projects/applied-geochemistry/international-geochemistry-cd-rom/sumatra-regional-geochemical-survey/
- GIS geologic data
    - https://vsi.esdm.go.id/portalmbg/
    - https://magma.esdm.go.id/
    - https://geologi.esdm.go.id/geomap
- Digital Elevation Model (DEM) data
    - DEMNas (Indonesian National Digital Elevation Model) https://tanahair.indonesia.go.id/demnas/#/
- Location of and information on geothermal features
    - MEMR Geological Agency https://georima.esdm.go.id/
- Historical seismic catalog for Indonesia
    - Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) https://inatews.bmkg.go.id/eng/
    - https://repogempa.bmkg.go.id/
    - U.S. Geological Survey catalog https://earthquake.usgs.gov/earthquakes/search/
- Heat flow

- International Heat Flow Commission
    - https://ihfc-iugg.org/products/global-heat-flow-database/data
    - https://ihfc-iugg.org/viewer/ (interactive map)

- Stress map
  - Heidbach, O., M. Rajabi, X. Cui, K. Fuchs, B. Müller, J. Reinecker, K. Reiter, M. Tingay, F. Wenzel, F. Xie, M. O. Ziegler, M.-L. Zoback, and M. D. Zoback (2018): The World Stress Map database release 2016: Crustal stress pattern across scales. Tectonophysics, 744, 484-498, doi:10.1016/j.tecto.2018.07.007
  - https://www.world-stress-map.org/download.

6.1.2 Other relevant geothermal datasets and analysis tools for Indonesia

Project InnerSpace, in partnership with Google, has recently launched a beta version of a geothermal exploration opportunities map project (GeoMap™) for many parts of the world (https://geomap.projectinnerspace.org/geomap/). It consists of surface and subsurface modules and several analytical tools that address user questions relating to geothermal resource potential. This model utilizes global heat flow data to evaluate the potential for EGS resource development as well as direct use applications. The model uses a heat-in-place energy calculation for different depths (see IEA (2024) for more details). The example below (Fig. 26) represents the amount of thermal energy (above a cutoff temperature of 150°C) between 500 m and 4000 m depth and indicates the elevated geothermal resource potential for much of Indonesia. The GeoMap™ system also uses a weighted overlay analysis tool where different Geographic Information System (GIS)-based geospatial data layers, such as faults, seismicity, temperature, volcanism, and thermal springs, are used to create a weighted assessment of the geothermal resource potential, where warmer colors indicate a higher geothermal potential (Fig 27). A techno-economic tool is also available within the suite of analytical tools to assess the levelized cost of electricity (LCOE) and the levelized cost of heat (LCOH) of the resource based on surface conditions as well as current technologies and future technology advances, as described in the IEA (2024) report.

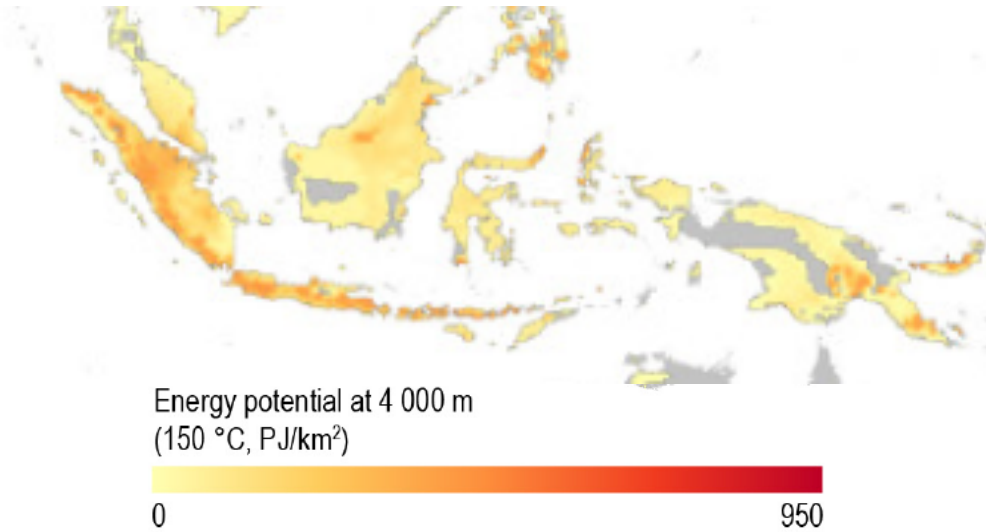


Figure 26. EGS potential for depths to 4 km using Project InnerSpace calculations for EGSs based on GeoMap™ data (IEA, 2024)

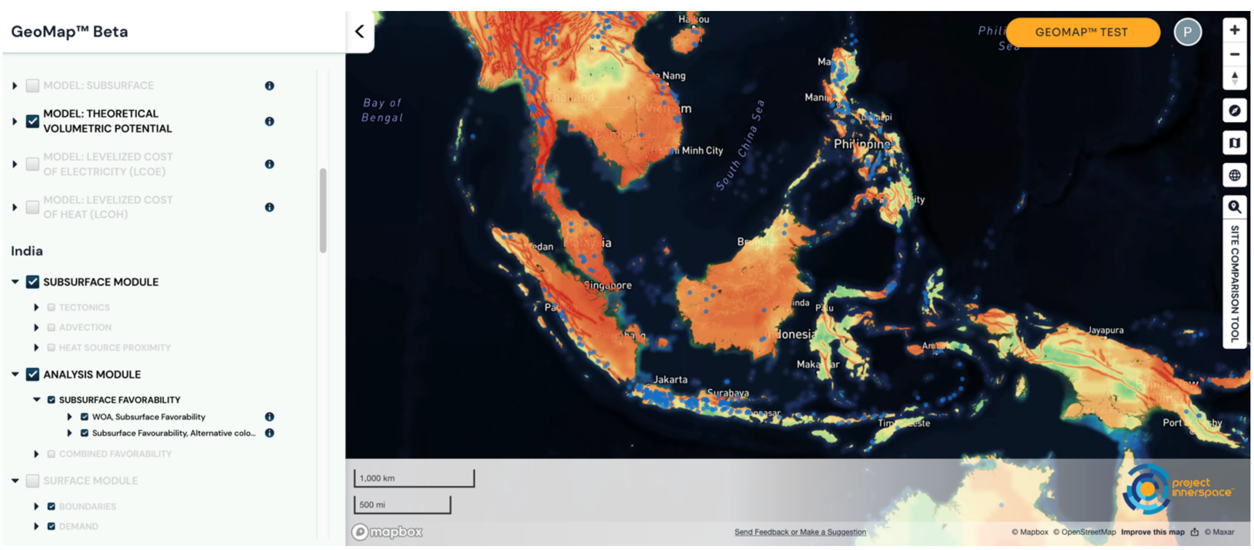


Figure 27. Subsurface favorability assessment (warmer colors are more prospective) for Indonesia along with the location of thermal springs (blue dots) and active faults (red lines) using Project Innerspace's GeoMap™

6.2 Resource assessment methods

One of the fundamental needs for geothermal exploration and development is developing an understanding of where geothermal resources are located, what their key characteristics are (such as reservoir temperature, resource depth, resource size, location and distribution of permeability, and fluid chemistry), and what the uncertainties of these properties are. The typical geothermal exploration workflow involves an integrated, multi-disciplinary, iterative approach, as illustrated below in Fig. 28.

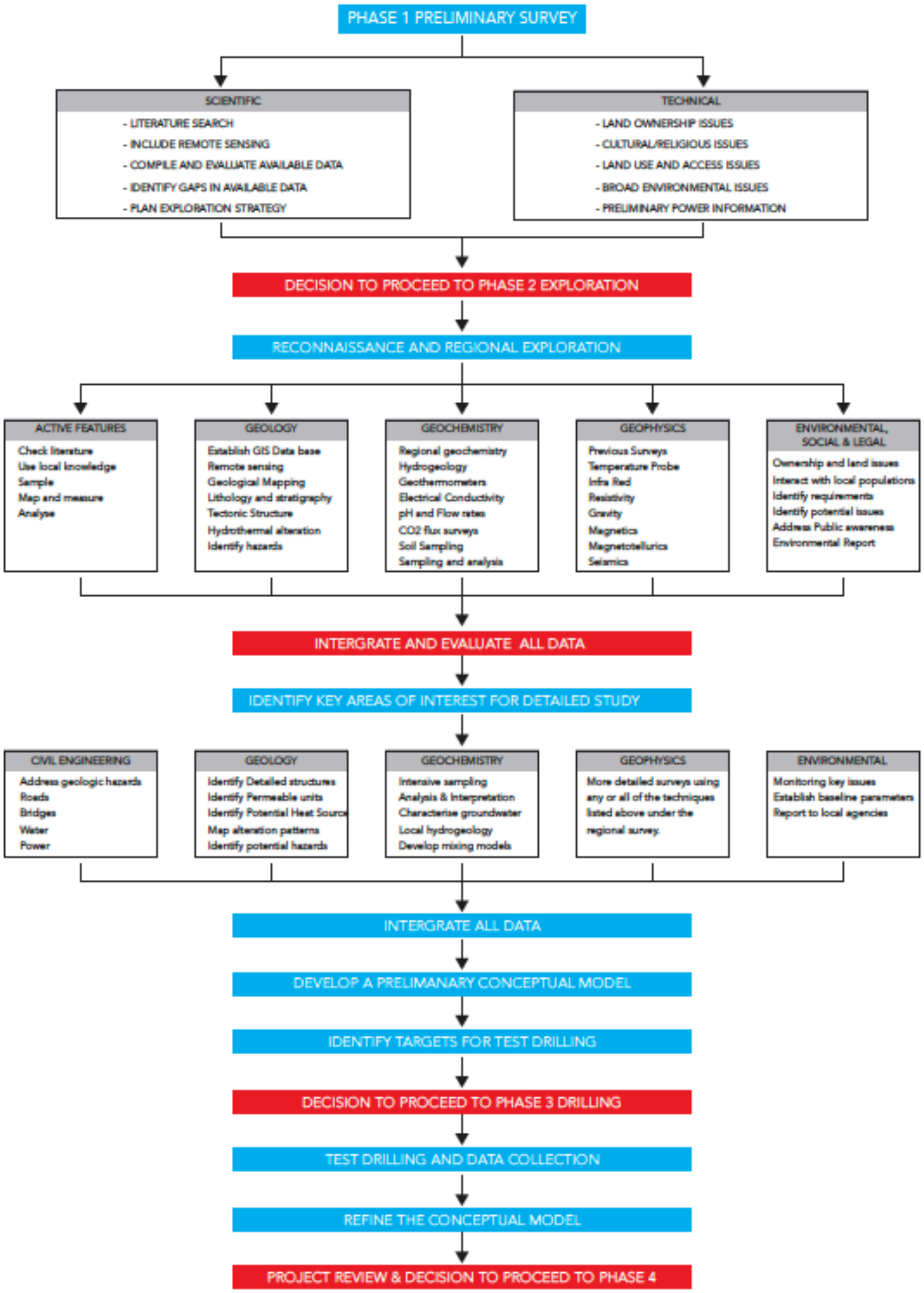


Figure 28. Typical workflow for geothermal exploration and development project (Harvey et al., 2016)

6.2.1 Geothermal Play Fairway Analysis method

One of the methodologies that DOE's Geothermal Technologies Office has championed to be developed and implemented to improve exploration efforts to identify and characterize geothermal resources is the adaptation of the play fairway analysis (PFA) approach that was originally developed by the oil and gas industry. This approach uses a range of evidence layers (Fig. 29) to help identify the presence of key features of geothermal systems. In the case of conventional hydrothermal resources, these would be a heat source, reservoir permeability, fluid, and potentially a reservoir seal (e.g., Lautze et al., 2017; Faulds et al., 2017; DeAngelo et al., 2024). The goal is to use a range of data types to create different evidence layers, which in turn can be combined to create a geothermal probability map (Fig. 30), as well as an evaluation of the uncertainty, helping to identify key data gaps. This methodology is typically employed using a GIS-based platform with data projected onto a 2D surface but can also be adapted to capture the 3D nature of geologic data (e.g., Poux and O'Brien, 2020).

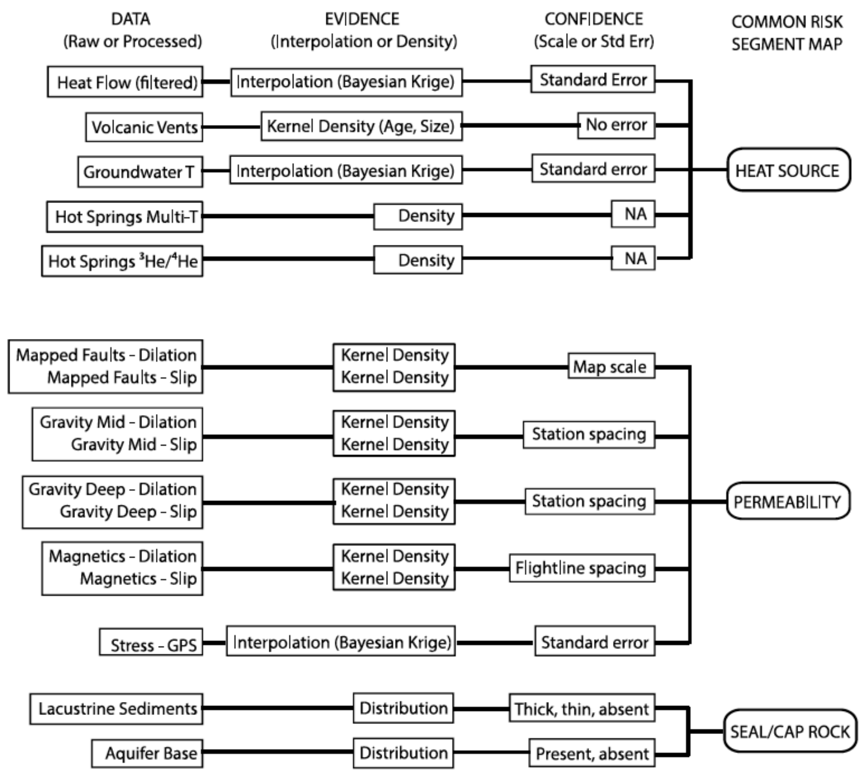


Figure 29. Flow chart showing the input data sets and workflow for developing common risk segment maps for geothermal play fairway analysis of the Snake River Plain region, southern Idaho (Shervais et al., 2024)

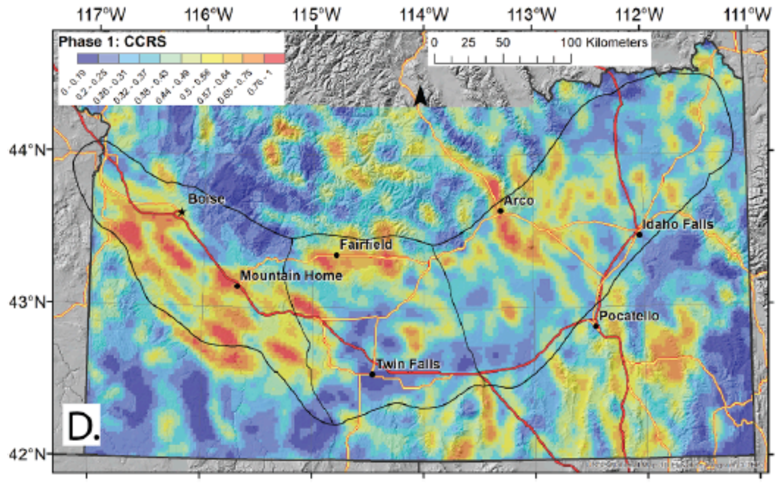


Figure 30. Composite common risk segment map using input from heat, permeability, and seal risk maps for the Snake River Plain, southern Idaho (Shervais et al., 2024)

Geothermal PFA can also be adopted to evaluate EGS and superhot geothermal resource potential (e.g., Beardsmore and Cooper, 2009; Kolker et al., 2022; Taverna et al., 2024). Machine learning methods can be applied to geothermal PFA (e.g., Faulds et al., 2020; Siler et al., 2021; Mudunuru et al., 2023). However, care must be used when using AI tools, making sure that sufficient data are available to serve as training data for any ML models (e.g., Mordensky et al., 2023).

6.2.2 Resource assessment method using geothermal modeling tools and cloud computing methods

Many initial geothermal resource assessments are made using the traditional heat-in-place method, which utilizes estimates of the reservoir volume, reservoir temperature, and a heat recovery factor to come up with a resource estimate. However, this method depends on assuming an energy recovery factor, which can lead to significant errors in resource estimates (e.g., Grant, 2014). A modified approach to this method was developed by Wilmarth et al. (2021) (power density method), where well characterized geothermal fields plotted by power density and reservoir temperature appear to be grouped based on their tectonic setting (fault-based systems, arc-based systems, rift systems, and hot arcs).

Researchers at the Geothermal Institute at the University of Auckland have developed a new approach for assessing geothermal resource potential (Dekkers et al., 2022). This workflow begins with developing digital geological conceptual models using available data and then creating a large number of corresponding numerical reservoir models that capture reservoir and wellbore physics and realistic energy extraction scenarios using cloud computing (Fig. 31). This approach provides a more rigorous method that results in less uncertain resource estimates. This approach has been applied by a team of researchers at the University of Auckland, the Geothermal Directorate at the Ministry of Energy and Mineral Resources, and the Center of Mineral, Coal, and Geothermal Resources at the Geological Agency to assess the resource potential of six geothermal systems in Indonesia (O'Sullivan et al., 2024).

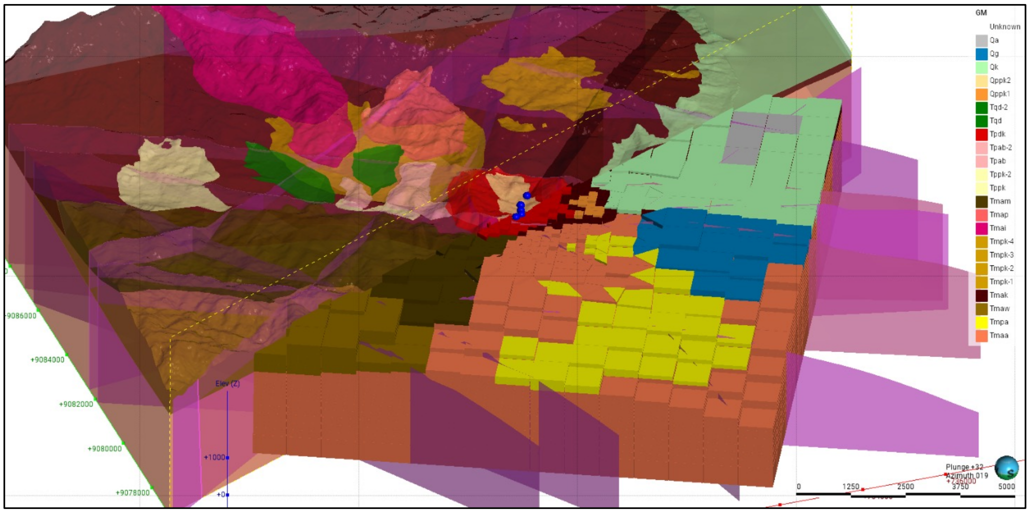


Figure 31. Maritaing geological model alongside numerical model used to estimate resource potential (O'Sullivan et al., 2024)

6.3 Geochemical modeling

Geochemical modeling can be used for both exploration and field management processes. One of the key inputs for resource assessment is an estimate of the reservoir temperature, which commonly is determined using chemical geothermometers prior to drilling deep wells. Many different liquid, gas, and isotopic geothermometers have been used for this purpose (e.g., Powell and Cumming, 2010), but multicomponent geothermometers provide an additional way to estimate reservoir temperatures by using all of the geochemical information contained in geothermal fluid analyses (e.g., Spycher et al., 2014; Olguín-Martínez et al., 2022; Ystroem et al., 2022; 2023; Palmer et al., 2024). This approach is especially helpful in dealing with lower enthalpy systems or with boiled, cooled, or mixed fluids.

Scaling is another issue that can be addressed through geochemical modeling. The two main types of scaling for geothermal wells are silica scaling, which can occur in cooled, supersaturated reinjected brine, as has occurred at Dieng (e.g., Pambudi et al., 2015), and carbonate scaling, which is problematic for geothermal reservoirs with significant amounts of carbonate. Geochemical modeling that considers both thermodynamic and kinetic effects can be used to develop approaches to mitigate scaling (e.g., Xu et al. 2004; Brown, 2011; Mendoza and Camba, 2021; Přikryl and Alexandersson, 2021; Lichti et al., 2021).

Geochemical modeling can also be used to evaluate and design mitigation measures for acidic geothermal fluids. Such low-pH fluids have been encountered at several geothermal fields in Indonesia, especially at Namora-I-Langit (e.g., von Hirtz et al., 2018) and require special attention to avoid significant issues with corrosion.

6.4 Well targeting

One of the most challenging and important aspects of geothermal exploration is the targeting of exploration wells. Given the high costs and inherent risks of drilling, it is critical that all available geologic, geochemical, and geophysical data be utilized to develop a 3D conceptual model of the geothermal system to help derisk this process. The conceptual model (along with alternative scenarios) can be used to identify data gaps along with finding potential sites and subsurface targets for drilling exploration wells to confirm the presence of a geothermal system and constrain its extent (e.g., Cumming, 2009; 2016). This approach can be an extension of the play fairway analysis, with a focus on a specific geothermal system. For conventional hydrothermal systems, the challenge is to identify a drilling target that will encounter elevated temperatures and permeability. While fault models have been used extensively to target geothermal wells, their success has been sporadic in nature (e.g., White et al., 2021; Stark et al., 2022). The Philippine Geothermal Production Company has developed the quantitative evaluation of drilling targets (QED Targets) method to statistically evaluate the effectiveness of "targets", such as mapped and interpreted fault zones, by registering the frequency that permeable zones are intersected inside and outside of these targets (Fig. 32).

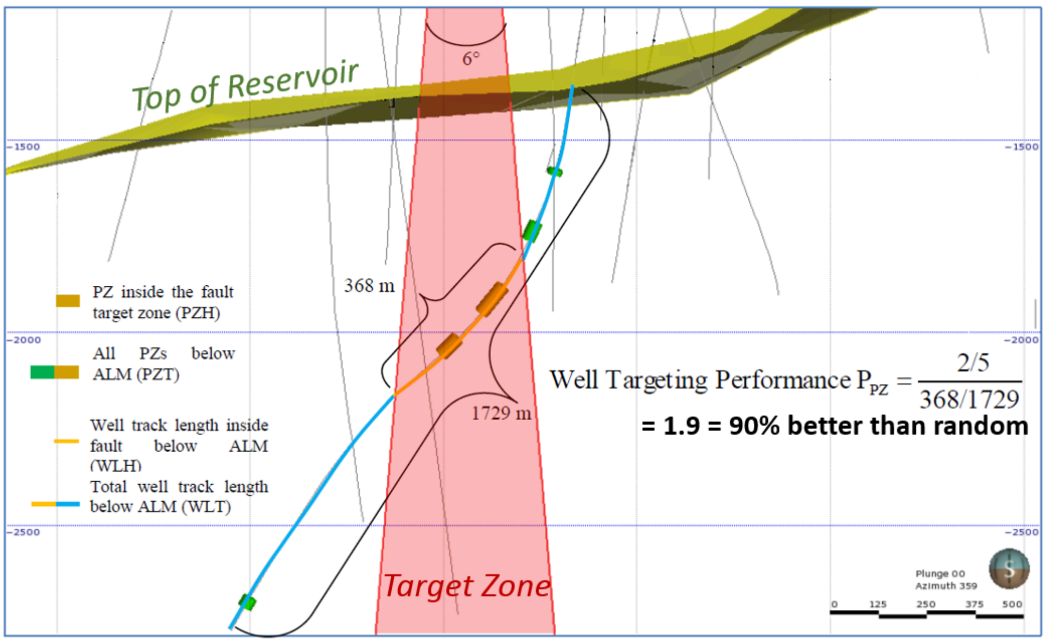


Figure 32. Illustration of distribution of permeable zones inside and outside of presumed "target zones" (Stark et al., 2022)

Developing an adaptive approach that enables learnings from early wells to inform how future wells will be sited and targeted could help in improving the success rate of geothermal wells (e.g., Sanyal and Morrow, 2012). Such an approach could utilize 3D modeling software that can integrate a wide range of geologic and geophysical inputs and be easily updated as new information becomes available (e.g., Poux et al., 2021; Poux and Banks, 2022). Such models can then be used to provide information on the 3D distribution of rock properties and key structural features needed as input for reservoir models. It is also important to consider the fault geometry and intersections as well as the stress orientations when evaluating which structures are likely to represent permeable features (e.g., Siler et al., 2018).

6.4.1 Recent improvements in well targeting in Indonesia

Much of the focus on targeting geothermal wells in Indonesia has been on intersecting potential structural targets within the geothermal reservoir. Mapping of faults at the surface in Indonesia is challenging due to the tropical climate, which results in rapid weathering of outcrops, and the densely forested nature, which also obscures structural features. One of the important technical developments that has been widely deployed in Indonesia in recent years is LiDAR (light detection and ranging), which enables the identification of faults. LiDAR surveys conducted in several geothermal fields, such as Sarulla (Fig. 33), Darajat, and Bukit Daun (e.g., White et al., 2021; Itani et al., 2021; Ikhwan et al., 2021). These surveys permitted improved mapping of the surface geology and structural features. In addition, the use of borehole televiewer logs provided additional information as to the location and orientation of permeable zones within wellbores, providing additional constraints on the nature of permeable structures within the reservoir. The integration of these two new techniques (LiDAR and borehole image logs) into resource structural models has greatly improved the identification of key structural features that should improve targeting of future wells.

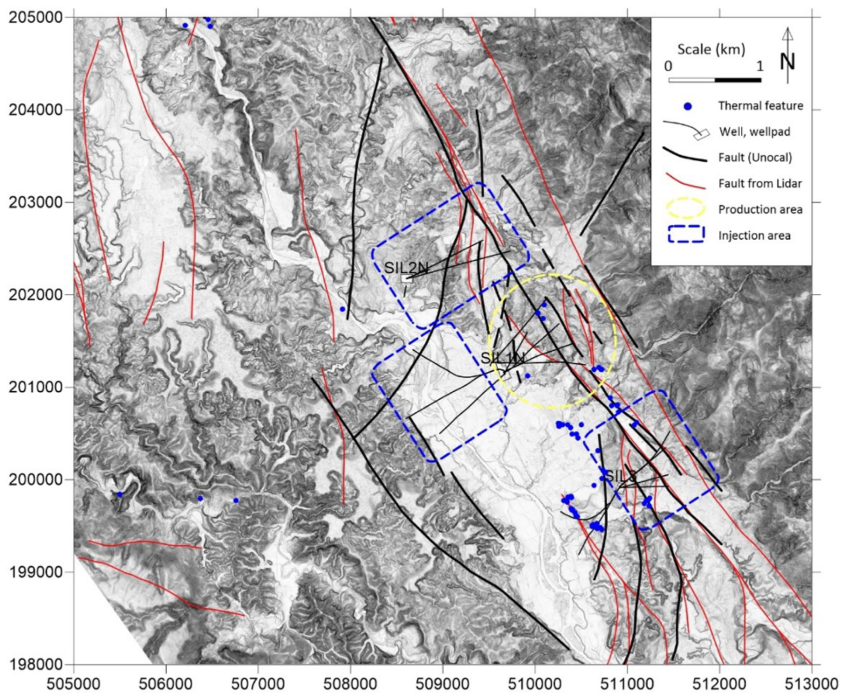


Figure 33. LiDAR image of Silangkitang area of the Sarulla geothermal field, North Sumatra, with faults identified from Unocal mapping and LiDAR interpretation (White et al., 2021)

6.5 Drilling

One of the primary objectives of the DOE's EGS Earthshot is to dramatically reduce the cost of drilling and completing geothermal wells. Geothermal wells constitute almost half the cost of a geothermal project, so the reduction of drilling costs would help reduce the overall costs of all forms of geothermal energy, thus improving its competitiveness. Two major improvements have been recently demonstrated at the Utah FORGE site (Fig. 34) (Dupriest and Noynaert, 2022; 2024), and also by Fervo Energy at their Cape Modern geothermal field (Figs. 35 & 36), which is located adjacent to the Utah FORGE testbed. Implementation of a physics-based limiter redesign workflow facilitated by the use of real time surveillance of mechanical specific energy (MSE), along with utilization of polycrystalline diamond compact (PDC) bits customized for the rock being drilled, has resulted in dramatic reductions in the time needed to drill, and has also led to significant cost reductions. Figs. 33-36 illustrate how implementation of this drilling approach along with use of the PDC bit have resulted in major improvements in drilling operations. The details associated with these drilling improvements can be found in the references listed above. Although these wells were drilled for EGS, adoption of this approach by the Indonesian geothermal drilling community could provide immediate benefits through reduced drilling times and lower drilling costs.

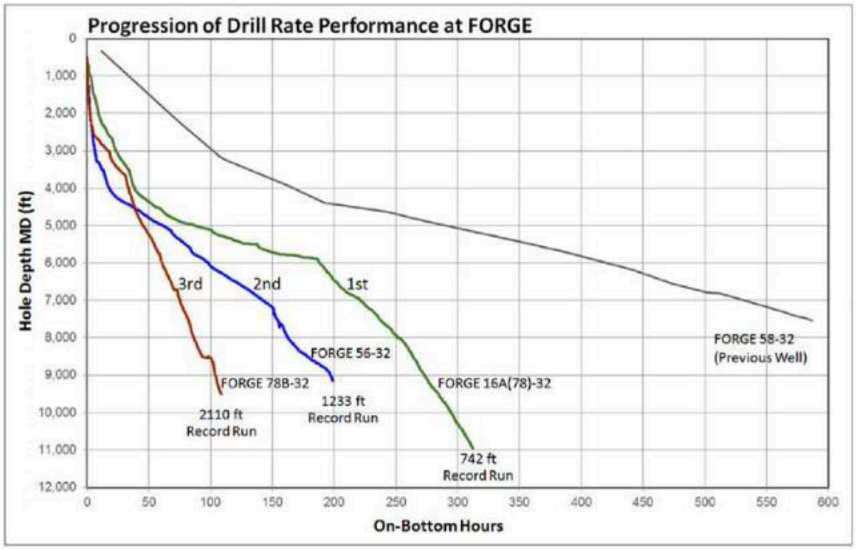


Figure 34. On-bottom drilling hours vs. depth for four wells drilled at Utah FORGE site (Moore et al., 2023)

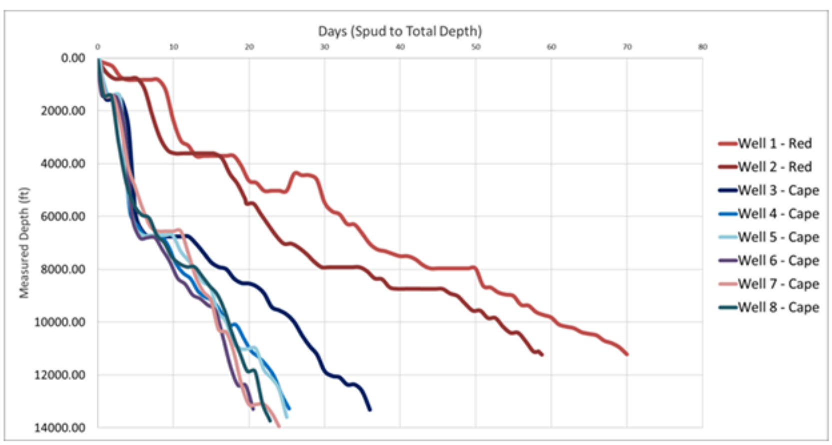


Figure 35. Spud to total depth (TD) results for Fervo EGS wells at Cape Modern, Utah (El-Sadi et al., 2024)

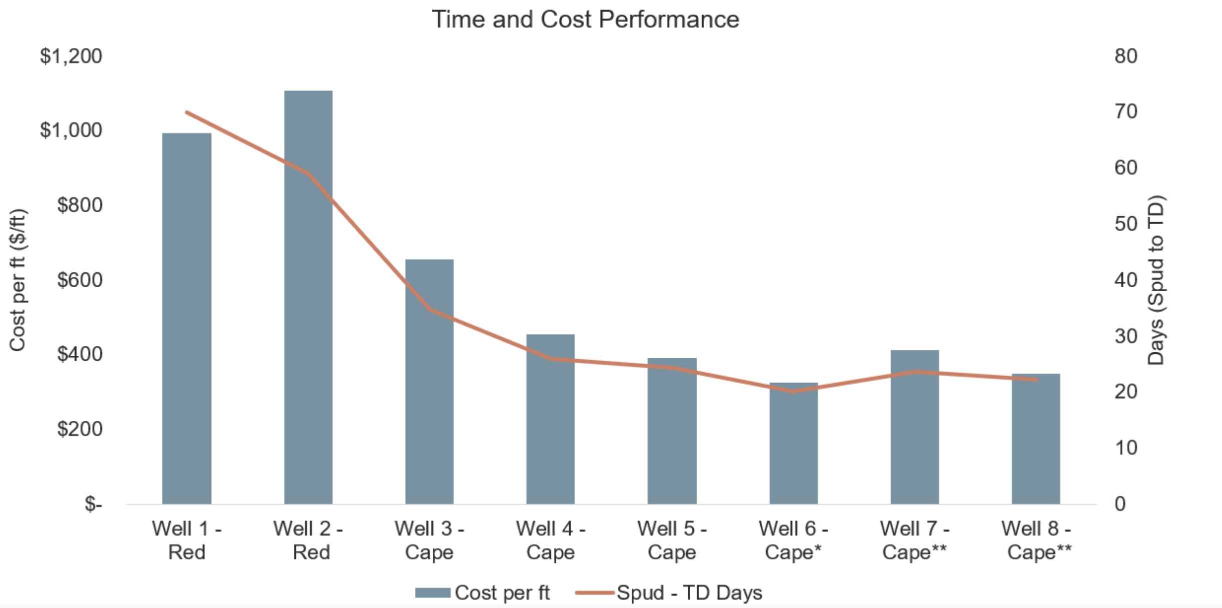


Figure 36. Fervo horizontal well cost per ft. and spud to TD trends (El-Sadi et al., 2024)

DOE's Next Generation Geothermal Power study (Blankenship et al., 2024) highlights these drilling advancements, and suggests that further improvements are possible based on the drilling performance achieved by the oil and gas industry (Fig. 37).

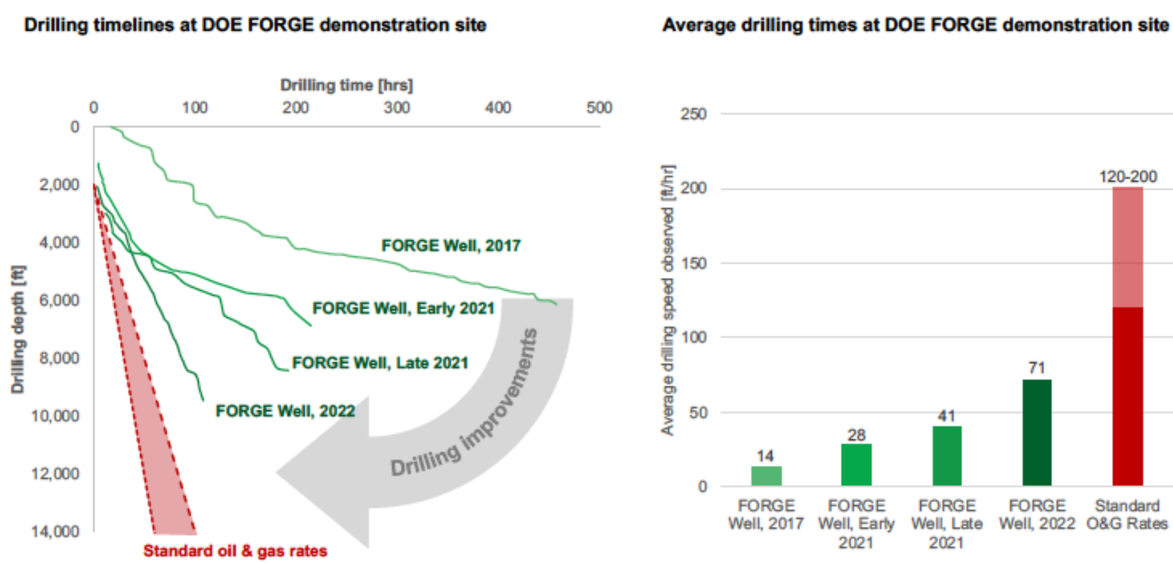


Figure 37. Recent improvements in geothermal drilling rates compared with oil and gas drilling rates (Blankenship et al., 2024)

6.5.1 Recent geothermal drilling improvements in Indonesia

Two of the major international geothermal service companies, Baker Hughes and Schlumberger, are heavily involved in the geothermal drilling efforts described above at Utah FORGE and the Fervo Energy Cape project in Utah. Thus, these companies are very much aware of the potential of exporting this approach to other geothermal drilling operations around the globe, including

Indonesia. Yustisia et al. (2024) describe how the use of innovative hybrid PDC bits at the Sorik Marapi field in North Sumatra through a partnership between Baker Hughes, KS Orka, and PT Sorik Marapi Geothermal Power, has resulted in higher rates of penetration (ROP) and longer bit runs, resulting in a reduction in the number of days needed to drill wells. This approach begins by using drilling simulation software to design and manufacture the appropriate hybrid drill bit design for the rock section (Fig. 38). The hybrid bit design that combines elements of the PDC and roller cone bits helps to improve bit durability and increase the ROP. Data obtained from over 40 wells were used to compare the performance of the new hybrid PDC bits with that of traditional roller cone bits. For the 17.5” sections, a 27% improvement in the distance drilled was observed, and a 74% improvement in ROP was obtained using the new hybrid bits. For the 12.25” sections, a 105% improvement in the distance drilled was observed, along with a 45% improvement in ROP for the hybrid bit (Fig. 39).

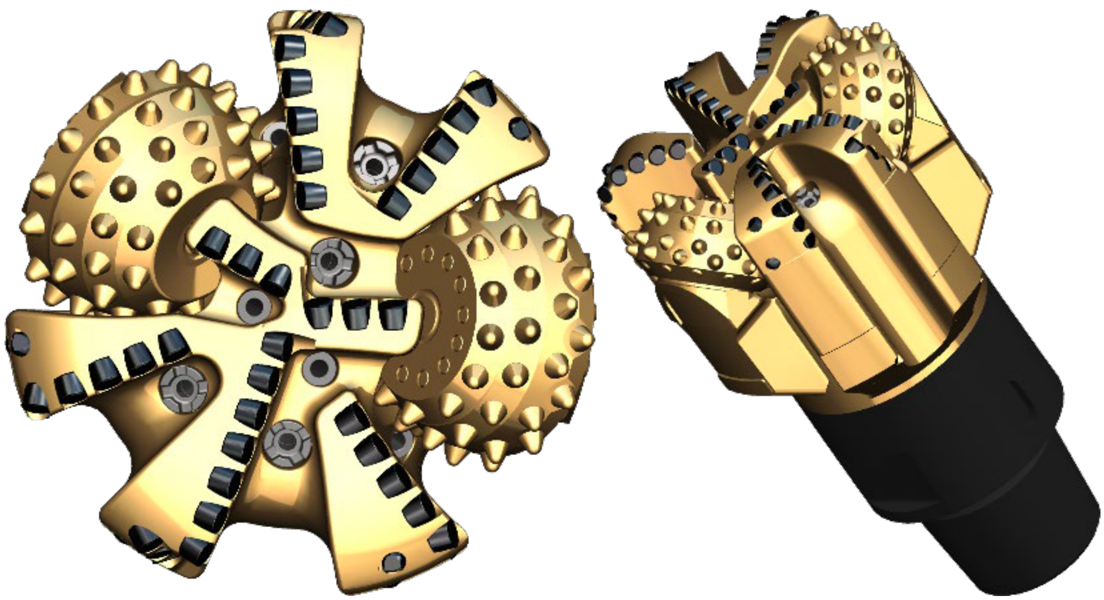


Figure 38. Examples of 12.25-inch hybrid bits with 5 blades, 2 cones, and 5/8” cutters used at Sorik Marapi (Yustisia et al., 2024)

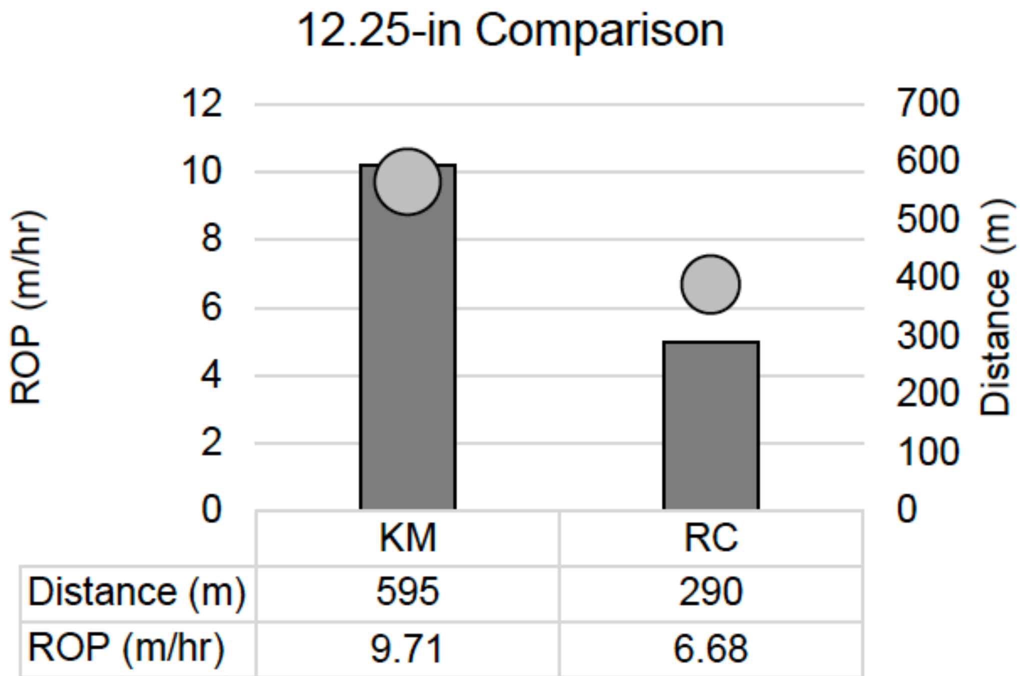


Figure 39. Comparison between the hybrid bit (KM) and roller cone (RC) performance in terms of rate of penetration (circles) and distance drilled (bars) (Yustisia et al., 2024)

Drilling costs are also heavily influenced by rig availability, which is impacted by the oil and gas market in Indonesia (Al Asy'ari et al., 2024). Rig procurement is impacted by the volatility in oil prices, the limited number of contractors and suppliers that have geothermal experience, and local content requirements imposed by the government of Indonesia. Finally, companies have also focused on all aspects of drilling, such as bit selection, to address slow penetration rates due to hard and abrasive formations, reducing non-productive time associated with stuck pipe and lost circulation issues, and shortening the duration of flat time activities such as tripping, installing casing and liner, cementing, and well completion. Detailed planning and review of fully integrated drilling and well completion operations can result in significant reduction in drilling and well completion costs and time (Kusuma et al., 2024).

6.6 Utilization of geothermal resources beyond conventional high temperature hydrothermal systems

DOE's GeoVision study (DOE, 2019) contains a much more expansive view of the potential uses of geothermal resources beyond just high temperature hydrothermal systems for power generation. The following cartoon (Fig. 40) from the DOE study provides an illustration of some of the many uses that are available.

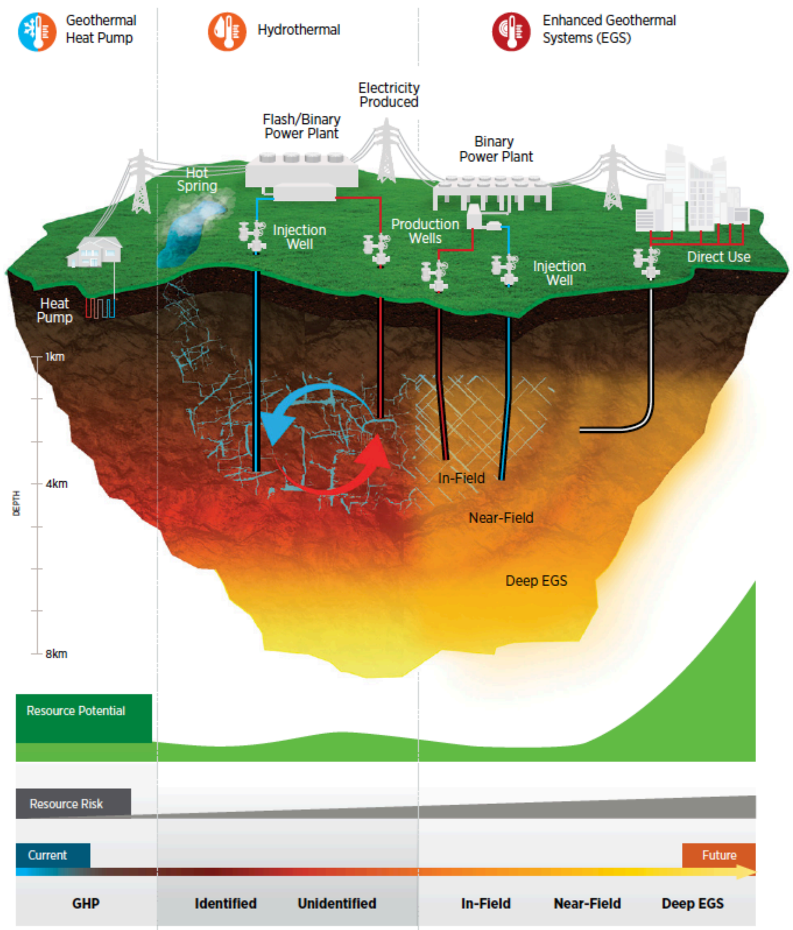


Figure 40. Illustration of the range of geothermal resources (heat pumps, hydrothermal, and EGS) available for utilization (DOE, 2019), greatly expanding the distribution, abundance, and potential application of geothermal resources around the globe

6.6.1 Moderate and low enthalpy resource potential in Indonesia

Indonesia has an abundance of moderate and low temperature geothermal resources, but most geothermal power development projects in Indonesia have focused on the development of high temperature hydrothermal resources. Binary systems can be used as bottoming cycles for high temperature geothermal fields as well as for producing electricity from moderate temperature geothermal resources – reservoirs with temperatures as low as 130°C can serve as commercially viable geothermal systems, such as the Don A. Campbell field in Nevada (Orenstein et al., 2015). Issues with scaling resulting from injection of cooled geothermal brines will need to be overcome to stimulate the utilization of ORC plants to take advantage of these lower temperature geothermal resources.

6.6.2 EGS and AGS resource potential in Indonesia

Unconventional geothermal resources may significantly expand the potential for geothermal resource development in Indonesia (e.g., Mustika et al., 2023). Based on the much larger resource potential represented by Enhanced Geothermal Systems (EGS), DOE's Geothermal Technologies Office has focused most of its considerable resources on developing and improving technologies that would allow for widespread commercial deployment of this resource. DOE launched the EGS Earthshot in 2022, with the goal of reducing the cost of EGS by 90% to $45 per MWh by 2035 (Augustine et al., 2023). It has also invested hundreds of millions of dollars in EGS research and development efforts conducted at the Utah FORGE field laboratory and has recently announced the funding of three EGS demonstration sites, with a fourth planned for the eastern U.S.

The U.S. Geological Survey (USGS) estimated that the potential EGS resource for the western U.S. is more than 12 times that of the identified and undiscovered hydrothermal resources for that area (Williams et al., 2008); it is likely that extensive EGS resources are also present in Indonesia. Some EGS testing has been conducted at Salak (e.g., Yoshioka et al., 2019) and Patuha (Lee et al., 2023) to use hydraulic stimulation to improve the performance of low permeability wells. Some preliminary estimates of EGS potential have been made for some Indonesian sedimentary basins (e.g., Hendrawan and Draniswari, 2016; Sihotang and Alam, 2019), and as noted earlier, the GeoMap™ tool suggests that Indonesia has a wealth of EGS potential. However, as of now, there has been no attempt to develop commercial EGS resources in Indonesia. There have been significant developments in closed-loop geothermal systems and downhole energy recovery systems, and GreenFire Energy is planning to test their technology using underperforming wells (e.g., Adityatama et al., 2023).

6.6.3 Superhot resource potential in Indonesia

Another geothermal resource type that likely is present in Indonesia is superhot geothermal, which has the potential of having much higher energy content per well; such resources likely underlie much of the existing hydrothermal systems (e.g., Reinsch et al., 2017; Cladouhos and Callahan, 2024). The Clean Air Task Force (CATF) has been leading an effort to evaluate the resource potential and challenges associated with this type of resource (Hill, 2022). Using the depth from the ground surface to formation temperatures ≥450°C, with subsurface temperatures estimated using the LithoRef18 model of Afonso et al. (2019), the portions of Indonesia shaded in pink in Fig. 41 were estimated to have these elevated subsurface temperatures at depths between 5 and 7.5 km depth. These areas are mostly located in volcanically active regions where heat flow is expected to be elevated.

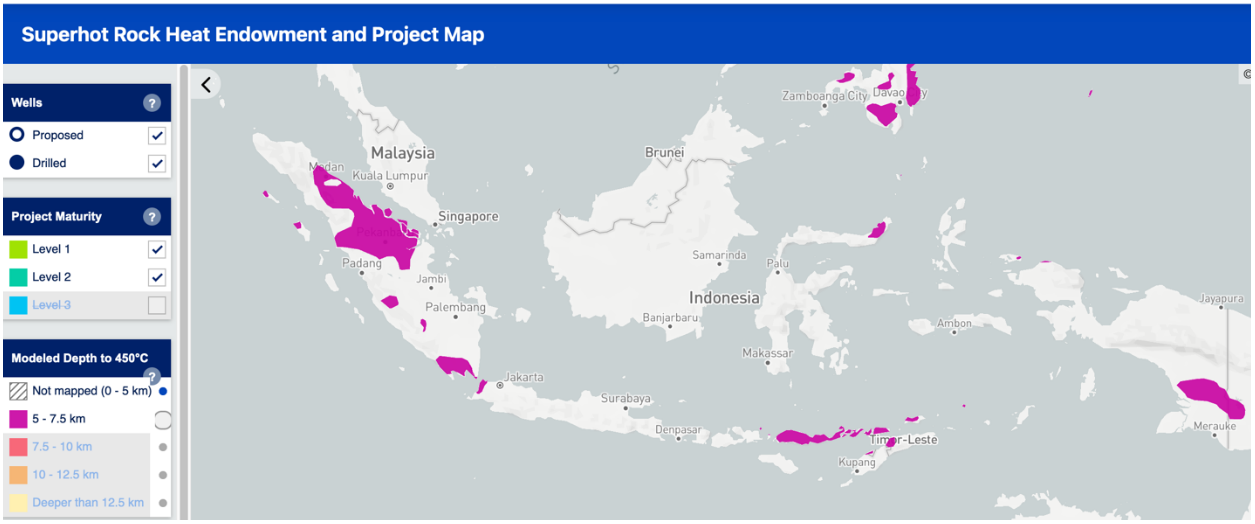


Figure 41. Superhot resource map created using CATF mapping tool, with areas shaded in pink predicted to have subsurface temperatures ≥ 450°C at depths of 5-7.5 km (https://www.catf.us/shr-map/)

6.6.4 Direct use potential in Indonesia

Direct use applications of geothermal energy for heating and cooling are growing and could help reduce the burden placed on the electricity and transmission systems. Ground source heat pumps can be deployed almost anywhere and can be used for heating and cooling buildings. Given that Indonesia is in a tropical setting, building cooling needs would likely outweigh heating demands. Other potential direct use applications could include timber, coffee and tea drying, greenhouses, fish farms, and tourism.

6.6.5 Mineral recovery potential in Indonesia

An additional type of added value to geothermal brines is the dissolved constituents. There are several projects underway in New Zealand and Japan that look to recover high purity silica and other constituents from geothermal brines (e.g., Climo et al., 2021; Sato et al., 2021). Some geothermal brines also have elevated (~200 ppm) lithium contents, and there are efforts underway in the U.S. and Europe to commercially recover the lithium from geothermal brines; such a process could add significant economic value to these projects (e.g., Sanjuan et al., 2022; Dobson et al., 2023). Some initial studies have been conducted to evaluate the viability of lithium recovery from brines in geothermal fields in Indonesia (Suud et al., 2023; 2024).

6.7 Technology transfer and development

All of the recent review studies on next-generation geothermal discussed in Section 3 have stressed the need for technology advances to help make geothermal more cost competitive with other energy sources and to reduce risk and shorten timelines. There are numerous ways to accelerate these advances, as described in the following sections.

6.7.1 Technology transfer from other industries

The oil and gas industry has developed many new technologies related to subsurface characterization, reservoir modeling, drilling, well completion, and reservoir stimulation that could be adopted for geothermal systems. Pertamina's oil and gas operations thus may be able to assist Pertamina geothermal in adopting relevant oil and gas technologies. Both the oil and gas industry and the minerals industry also are good sources of subsurface geoscientific data that can be used to improve geologic models for geothermal systems. The DOE GTO has instituted the Geothermal Energy Oil and Gas Demonstrated Engineering (GEODE) initiative (https://www.geode.energy/), which seeks to facilitate the transfer of knowledge and technology from the oil and gas industry to the geothermal community. The initial phase of this project is focused on developing a roadmap to transfer oil and gas technologies, best practices, and methodologies.

6.7.2 Technology transfer from multinational service companies

Multinational service companies that support oil and gas as well as geothermal operations, such as Schlumberger, Baker Hughes, and Halliburton, also provide access to new technologies that have been developed in the oil and gas industry as well as geothermal technology advances that have been employed in other fields around the world. Utilizing these companies could help accelerate the deployment of these approaches in Indonesia.

6.7.3 Technology transfer through international collaboration

International collaboration with other countries with geothermal experience through programs such as NZW also provide opportunities for technology and knowledge transfer. The Indonesian and New Zealand governments signed an agreement during the 2024 IIGCE (PINZ) related to geothermal energy, creating a five-year partnership that will focus on: 1) sector policy, regulation, and planning support; 2) planning, executing, and recalibrating exploration drilling for the Government of Indonesia-led geothermal exploration and project preparation; and 3) increasing geothermal workforce skills and capacity. More information on this program can be found at https://events.tetratech.com/pinz-indonesia-geothermal?hs_preview=zNLIaMLr-177165473830. This collaboration builds on many years of interaction between the Geothermal Institute at the University of Auckland and the Indonesian geothermal community.

6.7.4 Technology development through start-up ventures

Two of the new innovative geothermal companies in the U.S., Fervo Energy (https://fervoenergy.com/), and Zanskar (https://www.zanskar.com/), began as start-up companies at Lawrence Berkeley National Laboratory's Cyclotron Road (https://cyclotronroad.lbl.gov/), one of DOE's Lab-Embedded Entrepreneurship Programs (https://www.energy.gov/eere/ammto/lab-embedded-entrepreneurship-program). Fellows selected for the Cyclotron Road program receive a two-year stipend, entrepreneurial training, and access to Berkeley Lab's expertise and facilities. Their development of new technologies and workflows for improved geothermal resource development has attracted capital venture investment in their companies.

6.7.5 Technology development through government-funded research

Many of the technology advances made in geothermal energy around the world have been funded through government investments in research and development (R&D). Significant funding has been provided by the U.S. Department of Energy's Geothermal Technology Office (GTO) since the 1970s to advance geothermal resource development and expand resource utilization (geothermal.energy.gov). The GTO sponsors research in EGS, hydrothermal resources, low temperature and coproduced resources, and data modeling and analysis. Fig. 42

highlights how the GTO budget is used to fund projects that advance geothermal resource development.

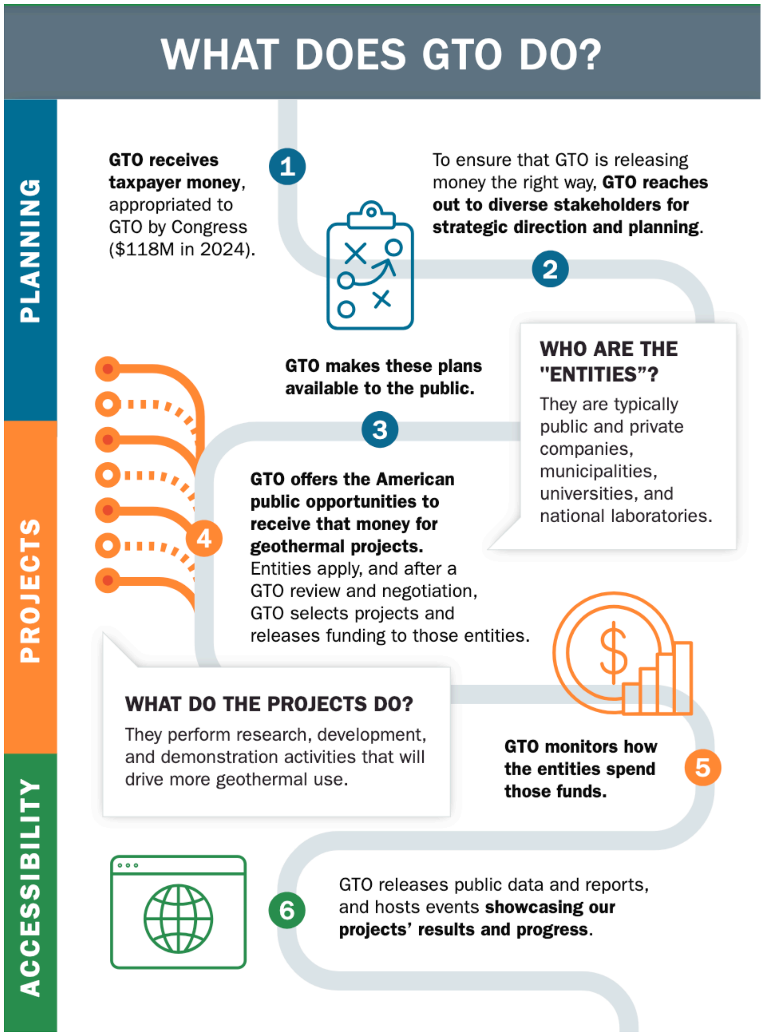


Figure 42. Pathway illustrating what DOE's Geothermal Technologies Office does to advance geothermal energy (https://www.energy.gov/eere/geothermal/about)

Many other countries, such as Iceland, New Zealand, Japan, and the countries of the European Union, have made significant R&D investments in geothermal energy. Government agencies and academic institutions in Indonesia, such as MEMR and ITB, have also made important contributions to the advancement of geothermal knowledge. Continued investment in research is needed to help reduce the costs and risks associated with geothermal energy.

6.8 Community outreach and social acceptance

It is critical that geothermal companies develop and maintain open communications with the local community throughout all phases of geothermal projects. The book "Geothermal Energy and Society" (Manzella et al., 2019), provides an excellent overview on this topic, along with case studies of eleven different countries, with a focus on societal dialogue, effective communication between parties, and public engagement activities. Providing accurate information on the impacts (positive and negative) of these projects is very important, as well as listening to the community about their priorities and concerns about the geothermal projects. Conflicts in land and water use can arise, as well as issues regarding seismicity, noise, gas, and fluid emissions that could negatively impact local residents and the surrounding environment. It is vital that mitigation measures be taken by companies to reduce or eliminate these impacts, if possible. It is also important to demonstrate the potential benefits (such as jobs, improved roads and infrastructure, reliable power, tax revenues, etc.) for the community. Data from environmental monitoring networks should be provided to community groups so that they develop confidence in reporting. Outreach efforts could include holding regular tours of the field to community groups, developing a visitor center with educational displays, hosting regular question and answer sessions, and having ways for community members to post questions and concerns regarding geothermal operations.

For example, at the Geysers geothermal field in California, Calpine has developed a geothermal visitor center (Dobson et al., 2012) that has interactive displays (Fig. 43) on the history of the area, the global context of geothermal energy, the local geology, how geothermal energy is produced, water use and reinjection, induced seismicity, and enhanced geothermal systems. They also have a very informative website (www.geysers.com), and host regular tours of the field. The local county government created a Seismic Monitoring Advisory Committee that meets twice a year to address questions and concerns related to induced seismicity, with representatives from the geothermal companies (Calpine and Northern California Power Authority (NCPA)), the county government, the local community, the Department of Conservation's California Geologic Energy Management Division, with occasional participation from outside seismic experts from the U.S. Geological Survey and Lawrence Berkeley National Laboratory.

Figure 43. Part of the displays at the Calpine geothermal visitor center (Dobson et al., 2012), including a real-time display of seismicity at the Geysers

The U.S. Department of Energy's Geothermal Technologies Office has developed a comprehensive website (geothermal.energy.gov) that provides access to many technical resources and geothermal publications, as well as upcoming funding opportunities. It also contains a summary of geothermal basics, with fact sheets on what is geothermal energy, what are geothermal heat pumps, a list of frequently asked questions, and a compendium of geothermal success stories (https://www.energy.gov/eere/geothermal/geothermal-basics). Similar informative geothermal websites have been developed by organizations such as Geothermal Rising (https://geothermal.org/resources), the International Geothermal Association (https://www.lovegeothermal.org/explore/what-is-geothermal/), the New Zealand Geothermal Association (https://www.nzgeothermal.org.nz/geothermal-in-nz/what-is-geothermal/), and the Indonesian Geothermal Association (https://www.inaga-api.or.id/home/).

It is always advantageous that outreach materials be written using language and images that communicate effectively with the public. One example is a series of comic books developed by Energía Andina, a geothermal company in Chile, which helps to demystify the geothermal activities, and put geothermal resources into a local context (Fig. 44).

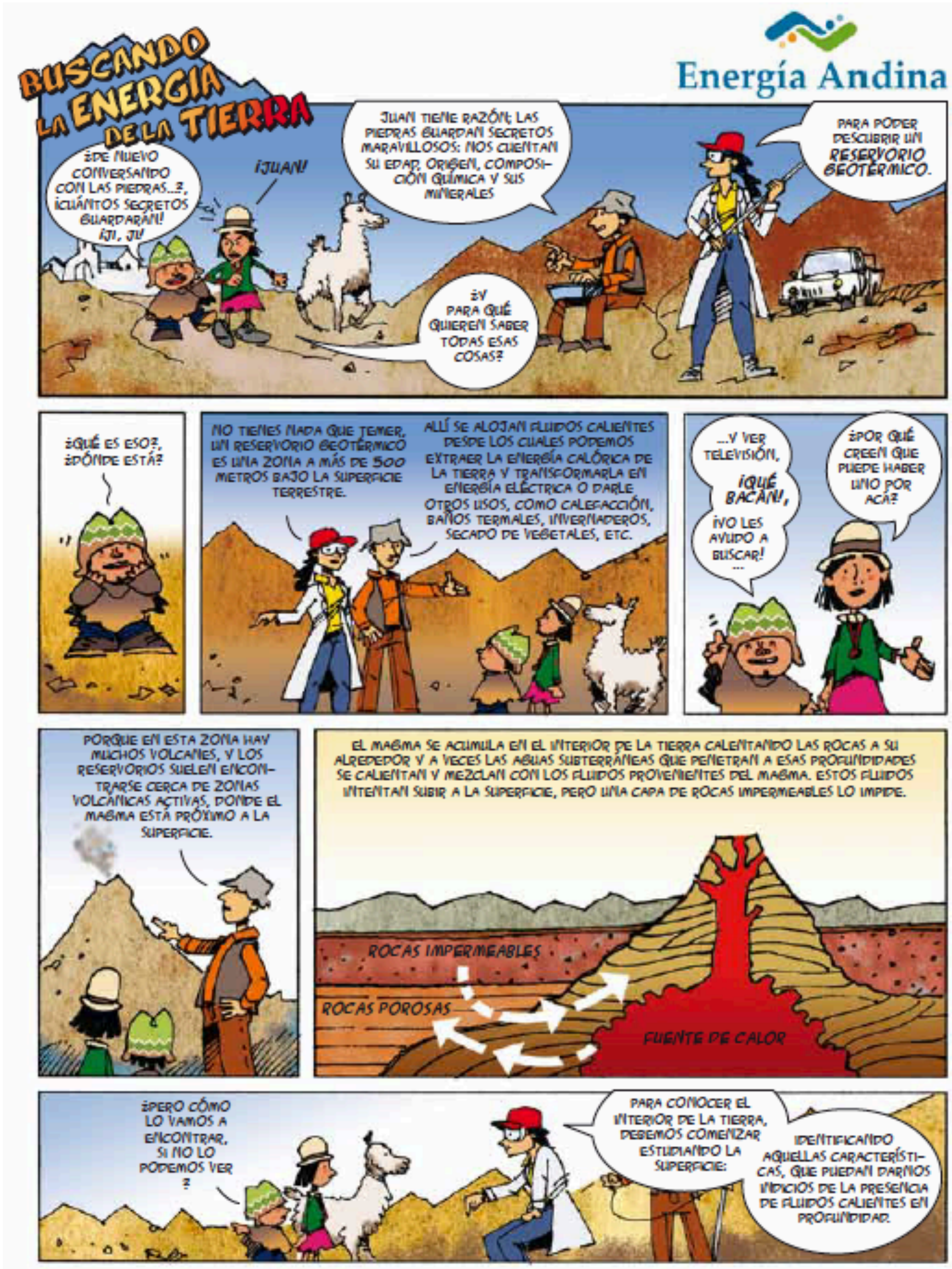


Figure 44. Extract from geothermal community outreach comic book produced by Energía Andina

Community consent is critical for geothermal projects to proceed. A recent Associated Press article (Milko, 2024) noted that for several locations in Indonesia, local communities have protested geothermal development due to safety and environmental concerns. Thus, it is critical that companies develop and maintain extensive community outreach programs that educate local communities about geothermal developments and provide an opportunity for residents to voice their concerns.

7 Next steps – potential ways to spur geothermal technology advances in Indonesia

Based on the main areas described in the previous section, here is an initial list of potential actions that could be taken to help accelerate geothermal development in Indonesia with a focus on technical issues. **Suggestions from the focus group meeting participants are highlighted in *italics*.**

7.1 Database development and data sharing

MEMR has taken an important step in this area through the establishment of their publicly accessible Genesis geothermal database. Future steps could include:

- Adding links to other relevant data sources
- Digitizing and uploading relevant maps and reports
- Identifying key data gaps that could help direct new field data collection
- Including metadata annotations to provide information on datasets
- Continued additions to the database as new data become available
- Sharing of relevant geoscience data from the oil and gas and minerals industries
- Developing training data sets and analytical tools for artificial intelligence (AI) and machine learning (ML) methods
- Collaborating with current international geothermal data mapping efforts (e.g., Project InnerSpace's GeoMap™) that include Indonesia
- Government funded data collection and exploration drilling of new prospects can help derisk geothermal development
- *Including data analysis tools and data interpretations from subject matter experts*
- *Using United Nations Framework Classification (UNFC-2009) for geothermal resources and NREL GeoRePORT tools (e.g., Young and Levine, 2018) to assess project readiness – the UNFC-2009 approach has already been applied to the Mataloko geothermal field (IRENA & IGA, 2021).*

7.2 Resource assessment methods

The partnership between the University of Auckland, MEMR, and the Geological Agency in Indonesia has resulted in a new set of resource assessment tools that can provide more reliable resource estimates. The following actions could help expand this effort:

- Application of the new resource assessment method to more geothermal systems in Indonesia to develop improved resource estimates*, along with conventional heat-in-place and power density methods*
- Evaluation of the resource potential of other types of geothermal resources, such as EGS, AGS, and moderate- and low-enthalpy geothermal systems
- Application of geothermal play fairway analysis methods for highlighting additional prospective geothermal areas over a regional scale in Indonesia
- Connect MEMR with the Project InnerSpace (EGS resource assessment using GeoMap™) and CATF (superhot resource assessment) teams to learn more about their data sources and resource assessment methods

7.3 Geochemical modeling

New geochemical modeling tools can be used to estimate reservoir temperatures and deal with issues such as scaling and corrosion. The following actions could be adopted:

- Adoption of multicomponent geothermometry, especially when dealing with mixed thermal fluid chemistry
- Use of thermodynamic and kinetic geochemical modeling tools to evaluate scaling and corrosion problems and identify potential solutions

7.4 Well targeting

One key way to reduce project drilling costs is to avoid drilling bad (unproductive) wells. Here are some suggestions on how to achieve this:

- Better integration of all available geologic, geophysical, hydrologic, and geochemical data into a 3D model
- Utilization of LiDAR and borehole image logs to better constrain structural features
- Joint inversion of geophysical datasets to improve model resolution
- *Develop improved methods to identify location of clay cap and permeable regions of the reservoir*
- Continuous review of "target" success from drilling operations, with regular conceptual model updates as new data become available.

7.5 Drilling

Drilling costs represent a significant component of geothermal project costs, especially during the early phases of resource exploration and confirmation. The following activities could contribute to lowering costs and reducing drilling times:

- Application of a physics-based limiter redesign workflow facilitated by the use of real time surveillance of mechanical specific energy (MSE), along with utilization of polycrystalline diamond compact (PDC) bits customized for the rock being drilled
- Improved rig procurement methods *involving intercompany collaboration*
- *Share drilling success and failure stories*
- *Improve methods to deal with stuck pipe using geologic hazard identification and real-time early warning system*
- Focus on integrated drilling activities with learnings applied for continual process improvement
- Utilization of multinational service companies with experience in improved drilling technologies to facilitate knowledge transfer
- Visits of Indonesian drilling crews to geothermal drilling operations in U.S. employing the new drilling workflow to learn firsthand how these methods are being implemented.

7.6 Utilization of geothermal resources beyond conventional high temperature hydrothermal systems

Indonesia has tremendous untapped unconventional geothermal resource potential that could be harnessed for power generation, direct use applications, and mineral recovery. Some of the actions that could be taken to advance this effort include:

- Evaluation of resource potential in Indonesia for unconventional geothermal resources (EGS, AGS, superhot, moderate and low-temperature resources, mineral recovery, and direct use applications)
- Look at proximity of companies who might be able to use heat for industrial processes (such as crop and timber drying) to both developed and undeveloped geothermal resources
- Encourage companies who are commercially developing unconventional geothermal resources in other countries to visit and consider doing business in Indonesia
- *Share best practices for hazard mitigation (such as induced seismicity) for EGS*
- *Locate early EGS project sites in remote locations and avoid major active faults (such as Great Sumatra Fault)*
- *Create dedicated field test site for evaluating unconventional geothermal resources*
- *Use closed loop on new but tight hydrothermal wells (better well conditions)*
- *Make sure that multiple companies are involved to avoid issues with single provider monopoly.*

7.7 Technology transfer and development

Technology transfer and development has been as a critical step in accelerating geothermal development around the world by lowering costs, reducing risk, and expanding the geothermal resource base. Here are a few actions that could help spur tech transfer and development in Indonesia:

- Look for the potential for technology transfer between the oil and gas industry and the geothermal community – this may be most expedient between Pertamina and Pertamina Geothermal.
- Numerous universities in the United States have created industry technical consortia, especially in the oil and gas sector, to sponsor directed research. It might be useful for universities in Indonesia to consider developing a similar approach with geothermal companies, which could enable them to use industry data to address key technical challenges.
- Use of multinational service companies that work in both the oil and gas and geothermal industries can help accelerate technology adoption.
- International collaboration can foster technology transfer between countries – Indonesia might consider joining the International Energy Agency's Technology Collaboration Programme on geothermal energy (https://www.iea-gia.org/).
- Development of geothermal start-up incubators can help create new technologies.
- Continued government investment in geothermal R&D is important.

7.8 Workforce development, community outreach, and social acceptance

Geothermal development cannot proceed without a trained workforce and social acceptance. The following actions could help address some of the challenges faced:

- Develop geothermal drilling training capabilities involving the MEMR training center and the Jakarta Drilling Society
- Create educational materials geared to a public audience on geothermal energy
- Promote outreach activities to local communities and schools
- Provide job training and employment to the local community
- Improve infrastructure (roads, water, sewage systems, power, internet, etc.) for the local community
- Develop and implement corporate best practices relating to environmental and community issues
- Promote transparent and constant communication between geothermal companies and local communities
- Make sure that communities benefit rather than are harmed by geothermal development projects
- *Increase accountability to ensure that "bonus production" distribution actually benefits the local community*
- *Consider NZ model for including community as partners in projects (Māori as business partners for projects on tribal lands)*
- *Provide scholarships for local students.*

8 Concluding remarks

This technical roadmap report is meant to complement existing efforts on the part of the Indonesian geothermal community to accelerate geothermal deployment in Indonesia to help achieve the country's net zero carbon goals and provide clean, indigenous energy to its people. Adoption of improved technology to reduce the costs and risks associated with geothermal exploration and development activities is critical to increasing the competitiveness of geothermal energy as a contributing renewable energy source. Given the abundance of geothermal resources in Indonesia, they can play an important role in Indonesia's energy future, provided that they are cost competitive with other energy alternatives, and that they are developed in a responsible manner that results in social acceptance. International collaboration is an important mechanism for transfer of technology to Indonesia to facilitate geothermal resource development. These technology improvements can help reduce resource risk, lower drilling costs, and allow for an expanded utilization of geothermal resources beyond conventional high temperature hydrothermal systems. Continued workforce development and improved community engagement are additional key factors required for geothermal resource utilization to grow in Indonesia. The Net Zero World initiative and other collaborative intergovernmental programs can assist Indonesia in this effort.

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Appendix A. Interactions with Indonesian geothermal community during Sept. 2024 visit

The NZW team (Bruce Hamilton and Pat Dobson) participated in a one-day U.S.-Indonesia geothermal workshop organized by Baker Hughes in Jakarta on Sept. 13, 2024, where a variety of relevant presentations were given. Gigih Udi Atmo, the Director of Geothermal Energy for EBTKE (MEMR), gave an expanded discussion on Indonesia's geothermal energy outlook and its energy transition commitment by along with an introduction to MEMR's 2040 geothermal roadmap. Bruce Hamilton, the Indonesia country coordinator for NZW, talked about sustainable renewable energy and gave a brief overview of NZW activities in Indonesia that help with decarbonization. Patrick Dobson, the Indonesia NZW geothermal subject matter expert, gave a talk on developing a technical geothermal roadmap for Indonesia. Ajit Menon, the Geothermal VP for Baker Hughes, gave a presentation on fostering partnerships in geothermal, where partnerships between companies along the entire value chain can result in a connective workflow that reduce costs. Baker Hughes has developed an integrated approach to their geothermal activities that uses a baseline model that includes both subsurface and surface components of a geothermal project and then applying the workflow to implement improvements that reduce costs and project timelines. Monica Ferro, APAC Director, GaffneyCline Energy Advisory (a subsidiary of Baker Hughes), discussed how her team provides techno-economic advice over a wide range of topics to help optimize the workflow of geothermal projects. Ajit Menon, VP Geothermal, Baker Hughes, then gave a presentation on behalf of Greenfire Energy, which has developed a closed loop heat recovery system that can be deployed in idle or underperforming wells for power generation or direct use applications. Andrea Burrato, the Geothermal Sr. Product Manager for Baker Hughes, talked about the steam turbine and ORC units that range in capacity from 10 to 80 MW that his team manufactures, as well as the remote monitoring of power plant systems that allows for detection of potential failure before it happens. Sabardi, the APAC Pressure Pumping Manager for Baker Hughes, discussed the ThermaStim technique developed by Baker Hughes, which allows for feed zone stimulation of geothermal wells to remove without needing to inject acid at the surface Will Pettitt, the Baker Hughes global geothermal lead, gave an overview of other geothermal applications, such as enhanced geothermal systems (EGS), geothermal drilling operations, and lithium co-production from geothermal brines.

The last two presentations for this workshop focused on financing. **Douglas Midland**, the Managing Director in Indonesia for the U.S. International Development Finance Corporation, the U.S. government's development bank. This bank focuses on private sector-led investment related to the energy transition in emerging and developing markets. One area of interest is the decarbonization of industry in Indonesia, as these projects help advance U.S. foreign policy objectives and deepen bilateral economic relationships. The U.S. IDFC has $46 billion in global exposure in over 112 countries. It offers debt financing, equity instruments, feasibility studies, investment funds, political risk insurance, and technical assistance. Funding in Asia for climate finance (including renewable energy) was $1.37 billion in FY23, and mitigation (under which renewable energy falls) was $1.9 billion of the total (worldwide) funding portfolio for that year. **Hanna Yolanda**, the Senior Country Representative for USTDA Indonesia, gave a presentation on project preparation grant financing partnership building tools to support geothermal energy. There are 123 infrastructure projects supported in Indonesia by USTDA, and renewable energy projects are a priority. The grant proposals look at positive development impact, economic viability, and U.S. export potential. These grants typically range from $500k to $1500k. Partnership building tools include study tours for training purposes (reverse trade missions).

U.S. Embassy staff members **Amy Padilla** (Energy and Minerals officer) and **Rosabelle Purnama** (Energy and Mineral Resources specialist) also arranged a series of face-to-face meetings with important geothermal stakeholders during this visit. **Pat Dobson** met with Aulia Rizky Pratama (Ministry of Energy and Mineral Resources) and Christovik Simatupang (Baker Hughes) on Sept. 16 to talk about MEMR's planning for the growth of geothermal development in Indonesia, and to discuss other uses of geothermal resources, such as geothermal projects supporting nearby mining operations, and recovery of lithium and other critical materials from geothermal brines. On Sept. 17, **Pat Dobson** and **Rosabelle Purnama** met with **Adrian Lembong, Arthur Simatupang, Fajar Putranto,** and one other person with Mahardika, an energy consulting firm. They expressed the need to derisk geothermal projects to make them more attractive to developers and financiers. They were interested in the EGS advances made by Fervo Energy in the U.S., and asked how commercially competitive EGS was relative to conventional geothermal fields. They also expressed interest in how new technologies, such as fiber optic sensing, can help improve subsurface characterization and reservoir monitoring.

Later on Sept. 17, Rosabelle Purnama and Pat Dobson next met with Dr. **Surya Darma**, from the Indonesia Center for Renewable Energy Studies. He has published books on geothermal power generation and geothermal engineering and noted that it is challenging for geothermal to obtain power purchase agreements with PLN due to the abundance of cheap coal power generation, which conflicts with the goal of Indonesia becoming net zero by 2060. He mentioned the potential for using geothermal resources for alternative direct use applications such as greenhouses, coffee drying, and tea drying.

The following three days, Pat Dobson attended the Indonesia International Geothermal Convention and Exhibition (IIGCE), held at the Jakarta Convention Center. This conference provided an excellent opportunity to attend a wide range of presentations related to geothermal energy projects in Indonesia. **Patrick Dobson** was also invited to give a presentation entitled "The future of Indonesia's geothermal energy – Collaboration between the U.S. and Indonesia via the Net Zero World Initiative". This talk described the current status of geothermal development in Indonesia, described some of the challenges that have been encountered, and highlighted some of the technological advances, such as database development and data sharing, implementation of geothermal play fairway analysis, improved targeting of geothermal wells, improved drilling methods and technology, and utilization of geothermal resources beyond conventional hydrothermal systems (EGS, AGS, direct use, mineral extraction, etc.). Questions posed by the audience following this presentation at the Value Creation stage included: 1) Could the geothermal drilling advances demonstrated in Utah be applied to Indonesia? 2) How can DOE's Geothermal Data Repository be used to improve the MEMR Genesis system? 3) What types of regulatory and permitting challenges exist in the U.S.? 4) Are there issues of bad actors within geothermal developers in the U.S. that impact the public's perception of geothermal?

In addition to attending many relevant presentations, Pat Dobson was also able to engage in discussions with a large number of individuals while attending the IIGCE conference. He and Amy Padilla (U.S. Embassy) met with Paul Reddell from TetraTech to learn more about the new agreement between the governments of Indonesia and New Zealand related to geothermal energy. This five-year partnership will focus on three main areas: 1) sector policy, regulation, and planning support; 2) planning, executing, and recalibrating exploration drilling for the Government of Indonesia led geothermal exploration and project preparation; and 3) increasing geothermal workforce skills and capacity.

Pat Dobson also visited the MEMR booth to get an introduction to the newly launched Genesis geothermal database system (https://genesis.ebtke.esdm.go.id/gdr/). This system provides a map-based array of geothermal resources throughout Indonesia that have linked digital data resources relating to geological, geophysical, and geochemical datasets.

Pat Dobson attended many of the plenary session talks and panels of the IIGCE conference, which provided very useful information on the current state of geothermal activities in Indonesia.

On the morning of Sept. 19th, Pat Dobson visited the **U.S. Embassy** to talk with Amy Padilla and Rosabelle Purnama. They mentioned that the U.S. works with like-minded countries, and that the Just Energy Transition Partnership (JETP) is focused on the longer-term clean energy mix for Indonesia. We discussed that it would be beneficial to develop a best-practices guide for community benefits and engagement. We also talked about how to accelerate drilling technology transfer – the suggestions included bringing Indonesian drillers to the U.S., bringing U.S. drilling experts to Indonesia, and working with Indonesian university students – we also discussed how U.S. businesses might have a role in this. The U.S. Embassy could help amplify the results of this NZW project by arranging a visit to local universities to communicate the findings to students – this could also be achieved through a virtual presentation. A visit of an Indonesian contingent to the U.S. could be conducted as a reverse trade mission sponsored by the USTDA.

Later on Sept. 19, Rosabelle Purnama arranged a meeting with the **Chevron geothermal group** (Teddy Abrian, Ferita Damayanti, and Dionisus Kumboro (via Zoom)) in their office in Jakarta. Chevron is a partner with Pertamina Geothermal on the Way Ratai geothermal project in South Lampung, which is still in the early phases of exploration. Geothermal is part of the Chevron New Energies group (low carbon footprint), which also contains hydrogen/ammonia and carbon sequestration. Issues that Chevron sees with pursuing geothermal development in Indonesia include a prolonged permitting process, a business structure where power can only be sold to PLN, a lack of knowledge within different government agencies about geothermal projects, and the challenge of land acquisition. One potential option is to export power to Singapore and Malaysia, if underseas transmission lines can be installed.

Pat Dobson met with **Aulia Rizky Pratama (MEMR)** at the MEMR booth in the IIGCE expo hall on Sept. 20. He noted that the 2040 and 2060 MEMR roadmaps focus on demand projection, and not on the geothermal delivery side, so a technology roadmap that would support geothermal development would be complementary to the MEMR effort. Key topics for a roadmapping discussion with members of Indonesia's geothermal community could be grouped under geoscience, drilling, and power plants and technology. The focus should be on brainstorming and discussion rather than being a series of presentations. This meeting should occur after the COP meeting in November.

Pat Dobson's final meeting was with **Christovik Simatupang of Baker Hughes**, also on Sept. 20. We talked about the geothermal roadmapping effort, and he mentioned that Baker Hughes would be very interested in participating in any follow-up discussions.

Appendix B. Meeting agenda, presentation slides, and photos from the Jan. 8, 2025, focus group meeting

Working Agenda

Venue: Auditorium Direktorat Jenderal EBTKE, Gd. Slamet Bratanata.

Jl. Pegangsaan Timur No. 1, Menteng, Jakarta.

Time	Agenda	Speaker / Presenter
Wednesday, 8 January 2025		
08.30 – 09.00	Registration	All participants
09.00 – 09.30	Opening and keynote remarks	Dr. Gigih Udi Atmo, Director of Geothermal Energy, EBTKE
09.30 – 09.50	Introduction to the Net Zero World Initiative program • NZWI Program • Geothermal Roadmap	Patrick Dobson, Lawrence Berkeley National Laboratory
09.50 – 10.00	Coffee Break	
10.00 – 11.15	Reviewing the draft of technical geothermal roadmap, highlighting: ▪ Reducing resource risk ▪ Improving well targeting and drilling techniques ▪ Expanding geothermal utilization beyond conventional systems ▪ Evaluating technical transfer and development opportunities	Patrick Dobson, Lawrence Berkeley National Laboratory
11.15 – 12.00	Question and Answers Session	All participants
12.00 – 13.00	*Lunch Break*	
13.00 – 14.30	Breakout Groups Discussion to review each of the draft topic areas discussed earlier and to address the following questions: ▪ How significant are these challenges? ▪ What is currently being done to address them? ▪ What new technologies or workflows could be used?	All participants
14.30 – 15.30	Short presentation by each breakout team on results of their discussions	All participants

15.30 – 15.45	*Coffee Break*	
15.45 – 16.15	Strengthening business collaboration between the U.S. and Indonesia on geothermal	Melissa Marszalek, Commercial Attaché, U.S. Commercial Service, U.S. Embassy Jakarta
16.15 – 16.45	Brainstorming on different ideas to facilitate collaboration between the U.S. and Indonesia.	All participants
16.45 – 17.00	Conclusion and way forward	Aulia Pratama, Subcoordinator of Geothermal Partnership, EBTKE, and Patrick Dobson, Lawrence Berkeley National Laboratory

NZW Indonesia Geothermal Roadmap
Introduction Presentation

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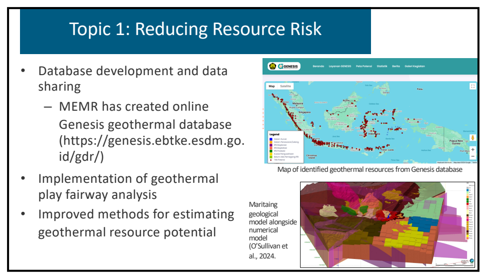

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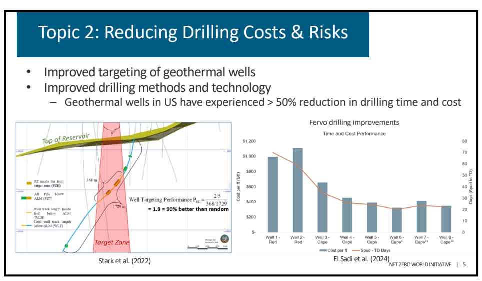

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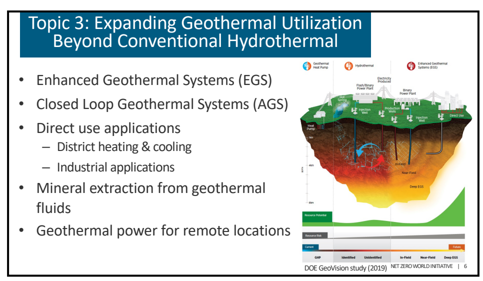

6

NZW Indonesia Geothermal Roadmap
Introduction Presentation

Topic 4: Workforce Development & Community Engagement

- Growth of geothermal deployment in Indonesia requires:
  - Trained workforce
  - Public acceptance
- Outreach efforts can provide public with knowledge about geothermal resource utilization, benefits, and impacts
- International exchanges can help capacitate geothermal workforce (e.g., Indonesia-Aotearoa New Zealand Geothermal Energy Programme - https://www.gns.cri.nz/news/from-jakarta-to-japan-taking-new-zealand-geothermal-innovation-global/)

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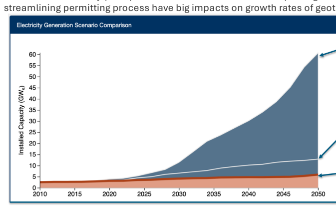
Why technology matters

https://apps.openei.org/geovision/electricity-generation

DOE GeoVision study (2019) examined various scenarios – improving technology and streamlining permitting process have big impacts on growth rates of geothermal deployment



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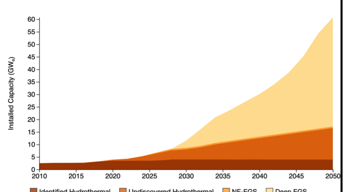
How technology impacts different resource types

https://apps.openei.org/geovision/electricity-generation

- EGS doesn't develop unless technology improvements occur
- 70% of capacity in 2050 would be EGS



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Geothermal Roadmapping Timeline

- Began role as geothermal SME for NZW, beginning with review of prior reports and studies on status of geothermal in Indonesia – Sept. 2023
- Initial Zoom discussions with INAGA members – Dec. 2023
- First draft roadmap report shared with NZW & MEMR – July 2024
- Presentation of initial geothermal roadmap results at Baker Hughes US-Indonesia geothermal workshop and IIGCE meeting – Sept. 2024
- Preliminary copy of updated Indonesia geothermal roadmapping report sent to DOE & MEMR – 12/23/24
- **In-person focus group discussion of technical roadmapping study in Jakarta - week of Jan. 6, 2025**
- Incorporation of focus group feedback into geothermal roadmap report and submission of report to DOE for comments – 1/17/25
- Continued collaboration and technology transfer between US and Indonesia

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10

NZW Indonesia Geothermal Roadmap
Overview Presentation

1

Developing a Geothermal Roadmap for Indonesia: Key Steps

- Examination of past studies of Indonesia's geothermal sector
- Review of recent geothermal roadmapping activities around the world
- **Input from Indonesian geothermal stakeholders**
- Identification of potential methodologies and technologies that could reduce risk, shorten timelines, and reduce costs for geothermal exploration and development activities in Indonesia

Field work in Lumut Balai

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2

Geothermal Roadmap Report Sections

- Introduction
- Previous evaluations of the status, challenges, and path forward for geothermal development in Indonesia
- Technical priorities identified by geothermal roadmaps in other countries
- Current status of geothermal exploration and development in Indonesia
- Initial stakeholder feedback on technical challenges and research needs
- MEMR 2060 geothermal roadmap effort
- Potential technologies that could be applied to Indonesia
- Next steps – potential ways to spur technology advances in Indonesia

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3

Prior detailed studies included in review of geothermal in Indonesia

- West Japan Engineering Consultants, Inc. (2007) Master plan study for geothermal power development in the Republic of Indonesia.
- GeothermEx, Inc. (2010) An assessment of geothermal resource risks in Indonesia
- PT Castlerock Consulting (2010) Ministry of Energy and Mineral Resources. Phase 1 report: Review & analysis of prevailing geothermal policies, regulations and costs
- WWF (2012) Igniting the ring of fire – A vision for developing Indonesia's geothermal power
- Meier, P., Vagliasindi, M., and Imran, M. (2014) Case Study: Indonesia. Chapter 5 in The design and sustainability of renewable energy incentives: An economic analysis.
- Meier, P., Randle, J.B., and Lawless, J.V. (2015) Unlocking Indonesia's geothermal potential
- Purwanto, E.H. (2019) Assessment of exploration strategies, results and costs of geothermal fields in Indonesia

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4

Common themes from prior reviews geothermal sector in Indonesia

Derisking of exploration

- Government investment in early-stage geoscience exploration and drilling to better characterize geothermal prospects
- Development of an accurate catalog of geothermal prospects that provides realistic resource assessment using accepted methodology, along with uncertainty

Reduction in costs and timelines

- Improve drilling technologies to reduce cost and time needed to drill wells
- Improve well targeting using 3D visualization and integration of new data to continuously improve conceptual model of system
- Reduce number of roads and well pads needed to lower costs and minimize environmental impacts

Derisking of development and exploitation

- Develop strategies to deal with acidic fluids, high NCGs, and scaling
- Consider using binary power plants as bottoming cycle to increase field productivity
- Develop mitigation approaches to address volcanic and seismic hazards
- Conduct outreach with all stakeholders, including local communities, throughout all phases of the project, to ensure that good communication exists and that the project obtains public acceptance

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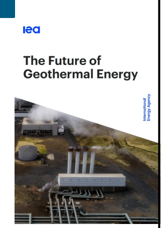
5

Other geothermal roadmap studies reviewed for technical priorities

- IEA Technology Roadmap – Geothermal heat and power (2011)
- European Technology and Innovation Platform on Deep Geothermal (ETIP-DG) (2018). Strategic research and innovation agenda
- FORGE roadmap (2019)
- DOE Geothermal Technologies Office Fiscal Years 2022-2026 Multi-year program plan (2022)
- DOE Pathways to commercial liftoff: Next-generation geothermal power (2024)
- IEA The future of geothermal energy (2024)



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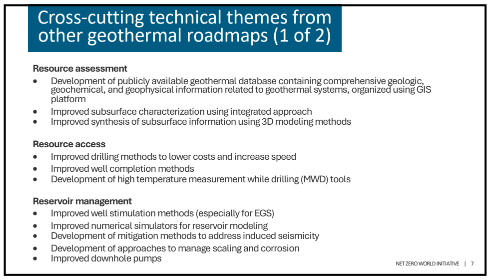
NZW Indonesia Geothermal Roadmap
Overview Presentation



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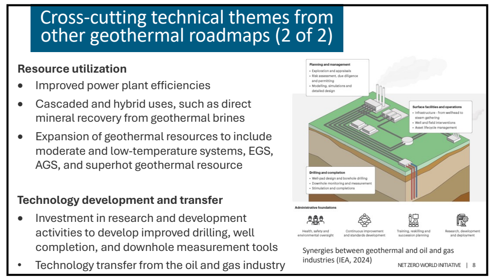

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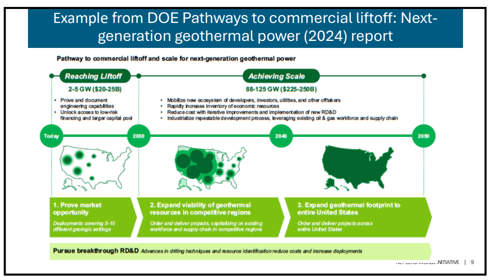

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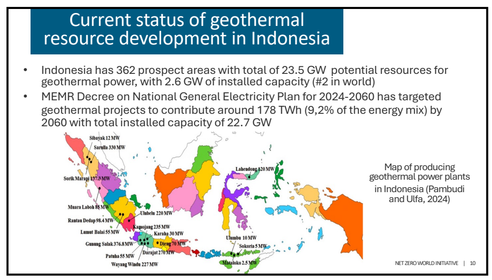

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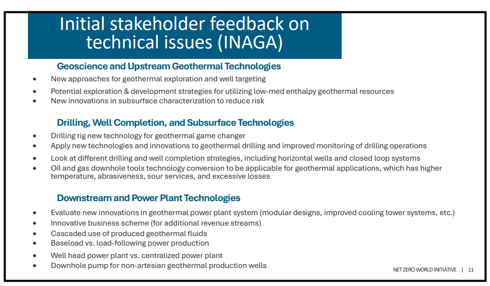

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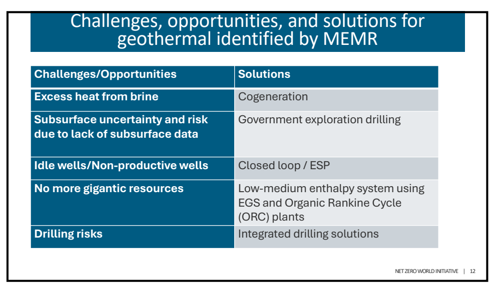

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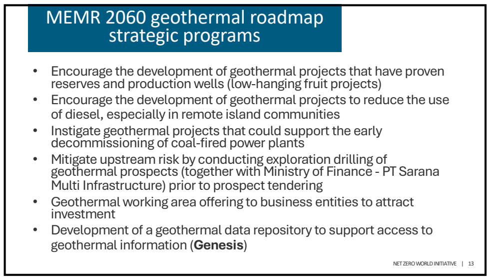

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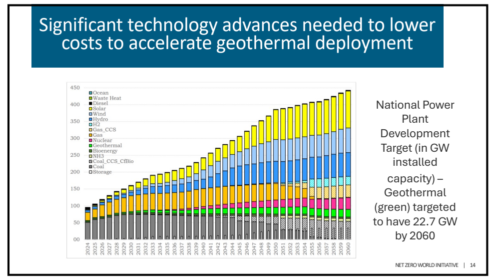

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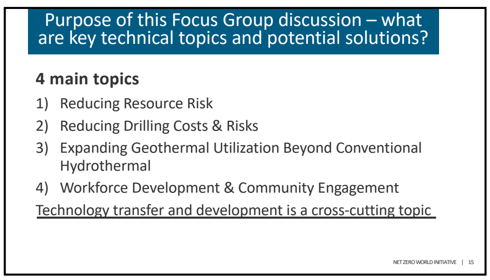

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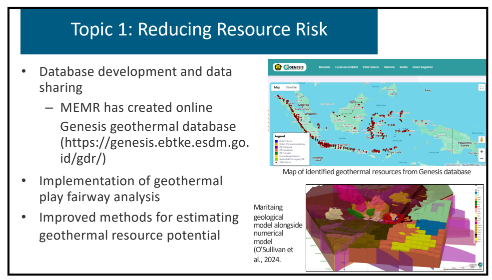

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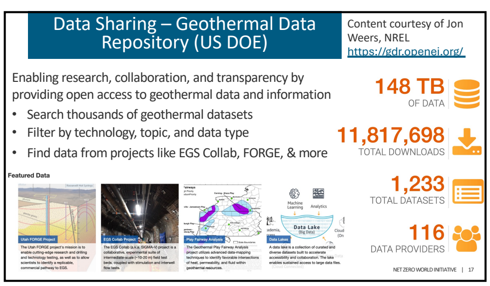

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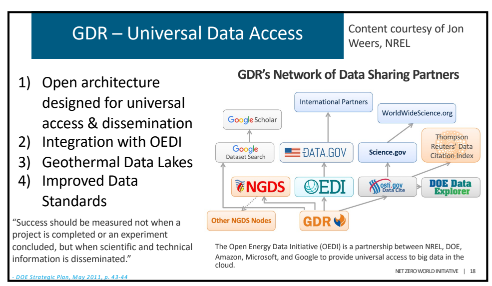

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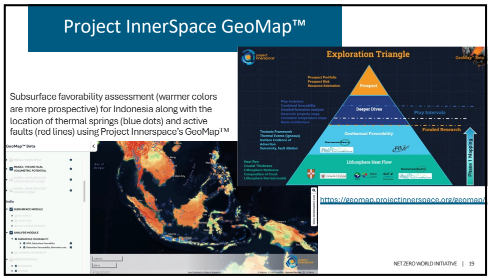

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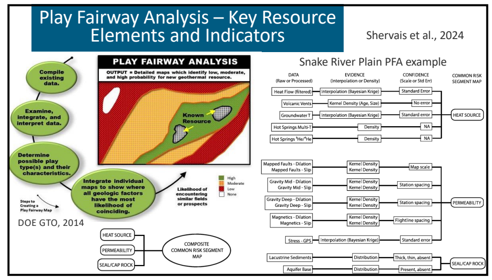

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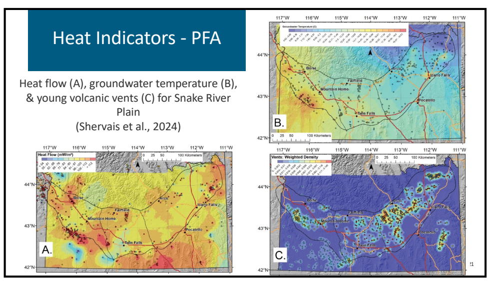

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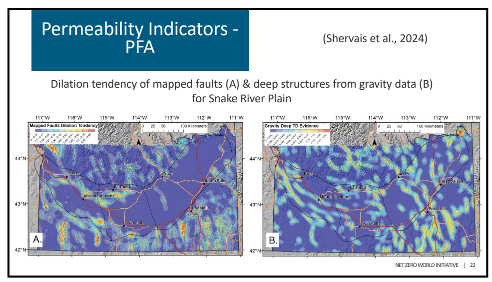

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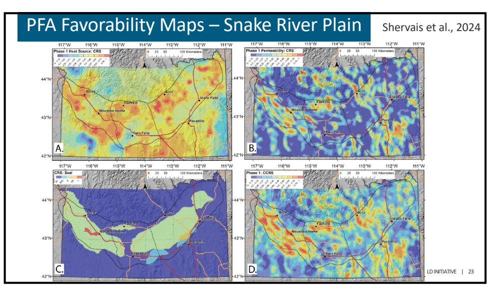

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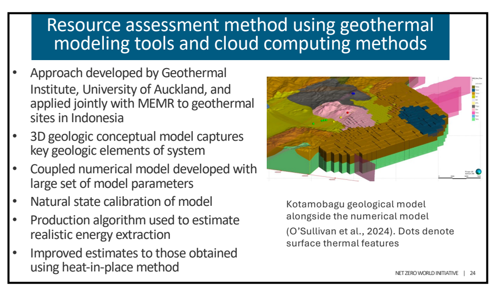

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Next steps: Reducing resource risk

- Link newly developed MEMR Genesis database to other relevant data sources
- Digitize and upload relevant published maps and reports
- Reach out to oil and gas and mining data sources
- Develop training data sets and analytical tools for AI and ML methods
- Collaborate with current international geothermal data mapping efforts (e.g., Project InnerSpace's GeoMap™) that include Indonesia
- Identify and fill key data gaps with regional data collection efforts
- Expand application of new resource assessment tool to improve resource estimates
- Include other geothermal resource types in future resource assessments of Indonesia

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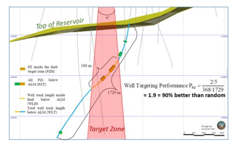
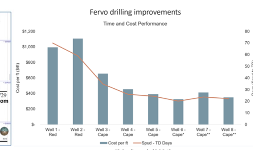
Topic 2: Reducing Drilling Costs & Risks

- Improved targeting of geothermal wells
- Improved drilling methods and technology
  - Geothermal wells in US have experienced > 50% reduction in drilling time and cost



Stark et al. (2022)



El Sadi et al. (2024)

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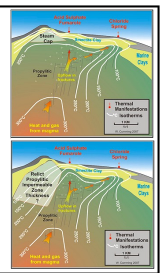
Improving Well Targeting Methods

- Conventional geothermal wells are sited to encounter heat and permeability in the subsurface
- Conceptual geologic models are usually created to capture key geologic features and indicate upflow and outflow regions of geothermal systems
- However, many exploration wells fail to encounter both temperature and permeability due to uncertainty in subsurface conditions



Cumming, 2016

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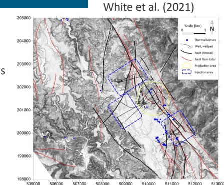
Finding Permeability

- Mapping of faults and fractures
  - Location of thermal features
  - Surface mapping of faults
  - Remote sensing detection of fractures (LiDAR)
  - Subsurface fracture detection (loss zones, cores, borehole image logs)
  - Rock type and alteration
- Representation of discrete fracture network within 3D geologic modeling system (e.g., Leapfrog Geo, JewelSuite™)
- Incorporation of stress conditions to identify orientation of dilated fractures

White et al. (2021)



LiDAR image of Silangkitang area, with faults from Unocal mapping and LiDAR interpretation

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Next steps: Reducing drilling costs and risks (well targeting)

- Better integration of all available geologic, geophysical, hydrologic, and geochemical data into a 3D model
- Utilization of LiDAR and borehole image logs to better constrain structural features
- Joint inversion of geophysical datasets to improve model resolution
- Continuous review of "target" success from drilling operations, with regular conceptual model updates as new data become available

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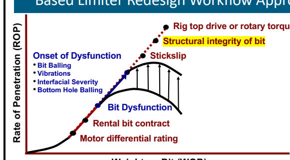
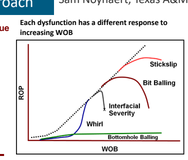
Drilling Improvements at Utah FORGE - Physics-Based Limiter Redesign Workflow Approach

Content courtesy of Prof. Sam Noynaert, Texas A&M





- Changing the way you drill a well requires:
  - No more empiricism, organizational move to physics-based practices
  - Understand the physics
  - Teach the physics to the people who do the work, and support them

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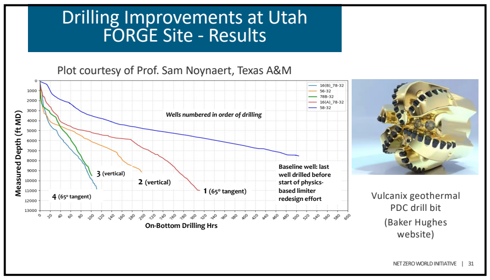

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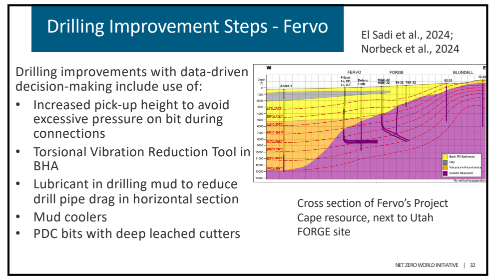

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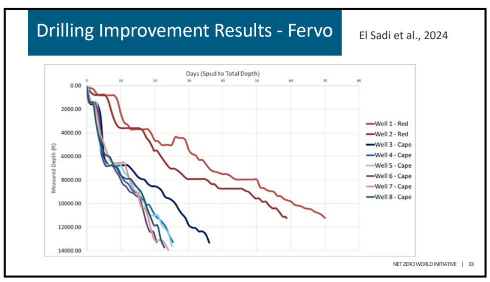

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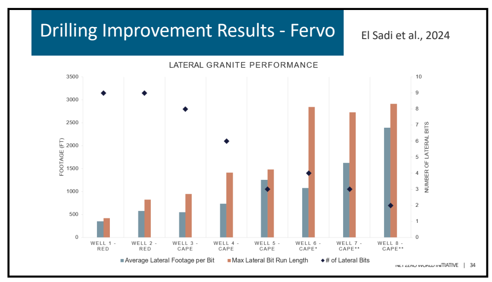

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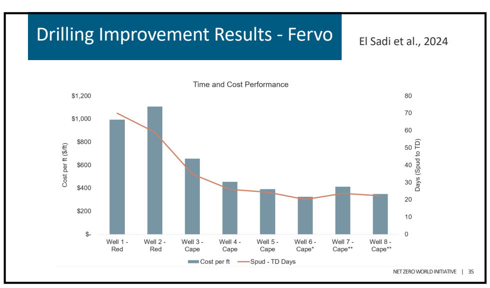

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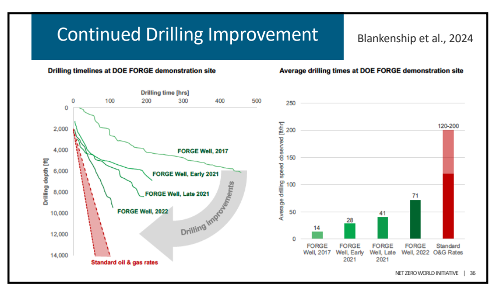

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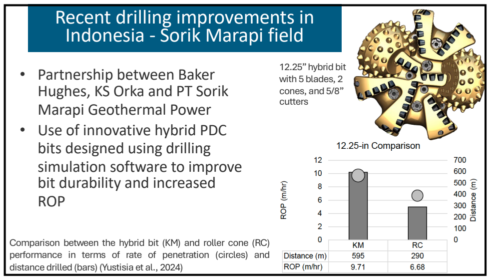

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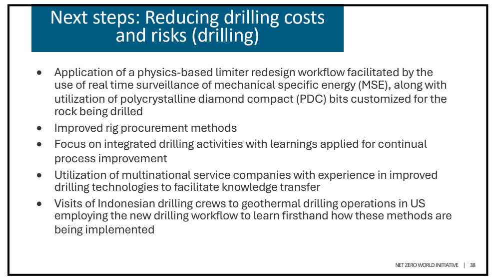

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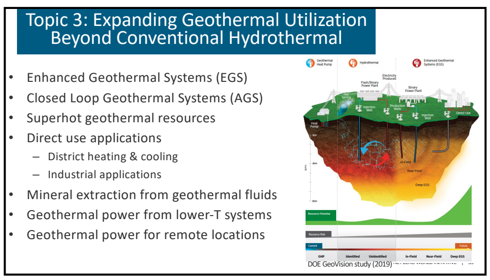

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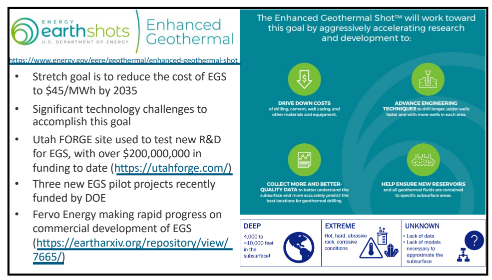

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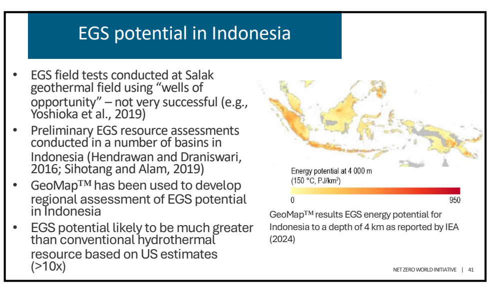

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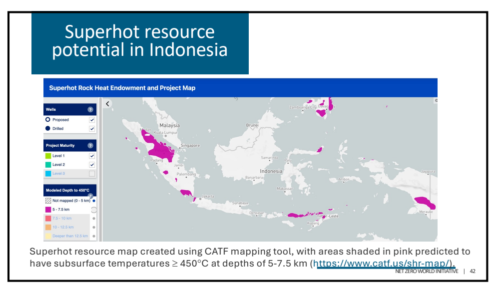

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Other Uses

- Heating and cooling
- Bathing and health
- Cooking
- Greenhouses
- Fish farms
- Timber drying
- Milk drying
- Health products
- Biological resources
- Mineral resources
- Desalination
- Hydrogen production
- Thermal energy storage

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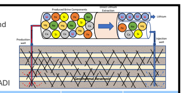
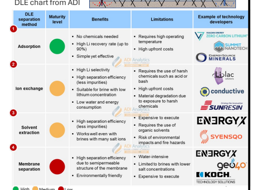
Mineral recovery from geothermal brines

- Critical materials such as Li, Zn, Mn can be found in commercial quantities in some geothermal brines (and some oilfield waters)
- Direct recovery methods can be used to extract minerals from brine
- Salton Sea geothermal field brines estimated to have up to 3.4 million tons Li (18 million tons LCE)
- Commercial-scale LCE operations yet to be established

Graphic from Stringfellow and Dobson, 2021



DLE chart from ADI



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Next steps: Expanding uses of geothermal resources

- Evaluate resource potential in Indonesia for unconventional geothermal resources (EGS, AGS, superhot, moderate and low-temperature resources, mineral recovery, and direct use applications)
- Look at proximity of companies who might be able to use heat for industrial processes (such as crop and timber drying) to both developed and undeveloped geothermal resources
- Encourage companies who are commercially developing unconventional geothermal resources in other countries to visit and consider doing business in Indonesia

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Topic 4: Workforce Development & Community Engagement

- Growth of geothermal deployment in Indonesia requires:
  - Trained workforce
  - Public acceptance
- Outreach efforts can provide public with knowledge about geothermal resource utilization, benefits, and impacts
- International exchanges can help capacitate geothermal workforce (e.g., Indonesia-Aotearoa New Zealand Geothermal Energy Programme - https://www.gns.cri.nz/news/from-jakarta-to-japan-taking-new-zealand-geothermal-innovation-global/)

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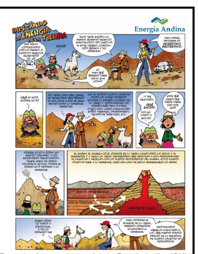
Community outreach and social acceptance

- Engagement needs to be continual and two-way
- Projects need to provide clear benefits for local community
- Project benefits and impacts need to be clearly communicated to public, and local concerns need to be heard



Example of outreach materials by Energia Andina (Chile)

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Next steps – Workforce development, community outreach and social acceptance

- Develop geothermal drilling capabilities involving MEMR training center and Jakarta Drilling Society
- Create educational materials geared to a public audience on geothermal energy
- Promote outreach activities to local communities and schools
- Provide job training and employment to the local community
- Improve infrastructure (roads, water, sewage systems, power, internet, etc.) for the local community
- Develop and implement corporate best practices relating to environmental and community issues
- Promote transparent and constant communication between geothermal companies and local communities
- Make sure that communities benefit rather than are harmed by geothermal development projects

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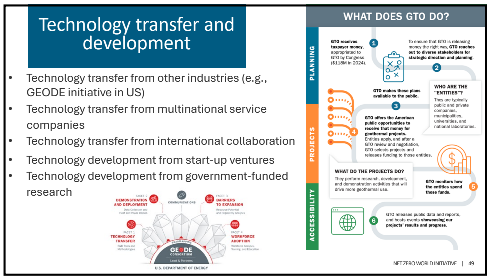

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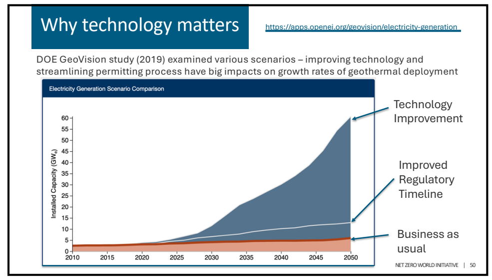

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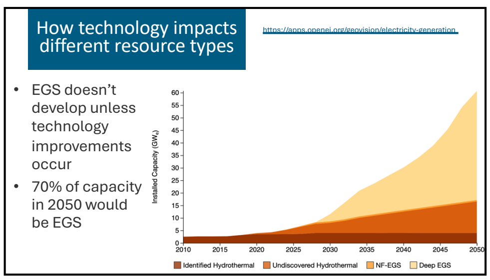

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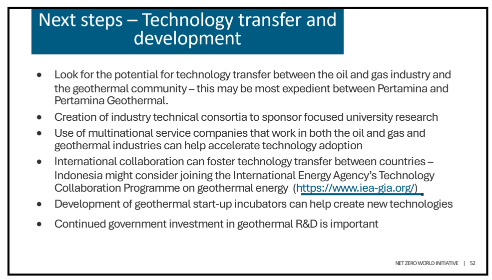

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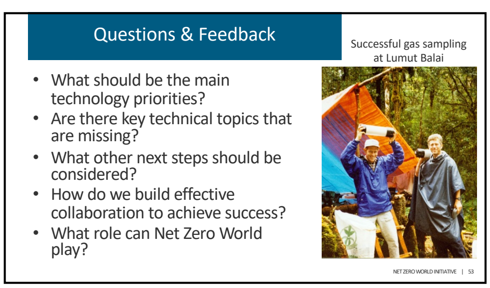

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Photos from the Jan. 8th workshop

Figure B-1. Dr. Gigih Udi Atmo giving his opening remarks (Photos courtesy of MEMR)

Figure B-2. Dr. Patrick Dobson (LBNL) presenting the NZW Indonesia geothermal roadmap (photo courtesy of MEMR)

Figure B-3. Audience attentively listening to presentations (photo courtesy of MEMR)


NET ZERO WORLD INITIATIVE
Accelerating Global Energy System Decarbonization
USAID
EXIM
EXPORT-IMPORT BANK OF THE UNITED STATES

Figure B-4. Photos of the four breakout groups discussing their topic (photos courtesy of P. Dobson, LBNL)

NREL Transforming ENERGY
BERKELEY LAB Bringing Science Solutions to the World
Pacific Northwest NATIONAL LABORATORY
Argonne NATIONAL LABORATORY
Brookhaven National Laboratory
INL Idaho National Laboratory
Lawrence Livermore National Laboratory
NETL NATIONAL ENERGY TECHNOLOGY LABORATORY
OAK RIDGE National Laboratory
Sandia National Laboratories

USAID FROM THE AMERICAN PEOPLE
U.S. DEPARTMENT OF ENERGY
USTDA U.S. TRADE AND DEVELOPMENT AGENCY
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