Challenges and Pathways in Global Geothermal Resource Assessment standards: Toward a Sustainable Framework

Yifan Bao[1,2,*], Peng Tian[1,2], Fengnian Zhao[1,2], Xu Huang[1,2], Chunhong Ma[1,2], Jiachao Huang[1,2], Peihao Wang[1,2]
1 State Key Laboratory of Deep Geothermal Resources, Beijing 100083, China
2 Sinopec Star Petroleum Co., Ltd, Haidian District, Beijing 100083, China
baoyifan.xxsy@sinopec.com(*)

INTRODUCTION

Against the backdrop of the global low-carbon energy transition, geothermal energy has gained strategic importance as a stable and reliable renewable energy source for achieving carbon neutrality goals. However, the sustainable development of geothermal resources heavily depends on scientifically sound and accurate resource assessment standards. A core challenge currently faced in international geothermal resource evaluation is the significant lag of standardization behind rapidly advancing technologies. The International Energy Agency (IEA) has highlighted the considerable potential of emerging technologies such as enhanced geothermal systems (EGS) for power generation is second only to solar photovoltaic, while also emphasizing that their commercialization urgently requires robust standard support (IEA, 2024). Existing standard systems are often fragmented, lack dynamic evaluation mechanisms, and fall short in quantifying sustainability, resulting in orders-of-magnitude discrepancies in resource estimates even within the same region. These limitations severely hinder the high-quality development of the geothermal industry.

CURRENT STATUS OF GEOTHERMAL RESOURCE ASSESSMENT STANDARDS

The international framework for geothermal resource assessment is exemplified by systems such as the United Nations Framework Classification for Resources (UNFC-2021) (IRENA and IGA, 2021), the ASTM series from the United States, and the Indonesian SNI classification system (Table 1). The UNFC-2019 provides a global assessment structure based on environmental, technical, and confidence dimensions (E-F-G). Nevertheless, its confidence axis relies heavily on the completeness of exploration data and lacks probabilistic statistical methods, leading to subjective classification. ASTM standards in the U.S. focus primarily on exploration aspects, such as fluid sampling and terminology. However, they exhibit notable gaps in dynamic parameter monitoring—such as fracture permeability—and lack a comprehensive risk assessment framework for EGS. Moreover, their update cycle, typically ranging from five to seven years, fails to keep pace with the rapid iteration of drilling and reservoir technologies. The Indonesian SNI system employs a multi-tier resource classification system (including speculative, hypothetic, possible, probable, and proven reserves) that integrates multidisciplinary data sources. However, it still relies on empirical coefficients for dynamic parameter estimation, suffers from insufficient deep geological data (with most drillings limited to depths under 3,000 meters), and exhibits misalignment in economic feasibility indicators (Larasati et al.,2024).

China has established a national and industrial standard system centered on the Specification for Geological Exploration of Geothermal Resources (GB/T 11615), with the newly released Assessment of Dry Hot Rock Resources (DZ/T 0505-2025) in 2025 marking progress in hot dry rock evaluation. Despite this, several critical issues persist. Different standards, such as the NB/T and DZ/T series, show poor coordination and contain overlaps and gaps in key areas including reservoir parameter selection and reinjection management. Static assessment methods, such as the volumetric and analytical methods, remain dominant and conflict with the need for dynamic development planning, often leading to significant discrepancies in evaluation results. Furthermore, the absence of standardized protocols for numerical simulation impedes accurate prediction of thermal breakthrough, reflecting the partial lack of industrial application standards. Common challenges across global standards include the ambiguous definition of recoverable resources and the absence of long-term stability evaluation metrics, such as thermal decline rate and reinjection efficiency. High levels of uncertainty—arising from geological heterogeneity, complexities in fluid flow, and model assumptions—further amplify prediction errors. In addition, a noticeable disconnect exists between technological advances and standard development, particularly in frontier areas like deep drilling and microseismic monitoring for EGS, where standardized norms are critically lacking.

FUTURE DIRECTIONS AND RECOMMENDATIONS

A comprehensive and integrated standard framework should be established, encompassing the entire development chain (Fig.1). This includes implementing a staged evaluation system—P1 (potential assessment), P2 (feasibility assessment), P3 (validation assessment)—based on exploration maturity, and incorporating Thermo-Hydro-Mechanical (THM) coupling models. Dynamic parameter quantification should be enhanced through Monte Carlo simulations and machine learning techniques to optimize probability distributions, with emphasis on sustainability indicators such as reinjection efficiency and thermal breakthrough time.

Technological innovation and data integration are also essential. A multi-source database combining geological, geophysical, and geochemical data should be established. Advanced monitoring technologies, such as distributed fiber optic sensing and microseismic monitoring, must be standardized. In addition, industrial guidelines for numerical simulation should be developed to improve the accuracy of dynamic reservoir predictions.

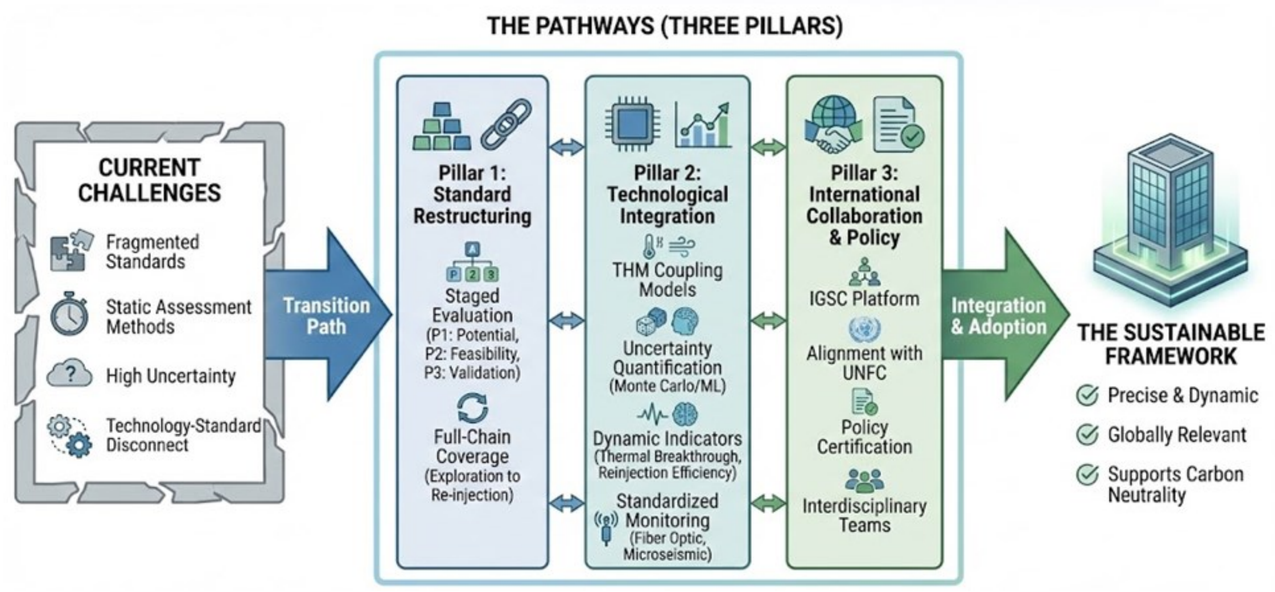


Figure 1. A conceptual framework for transitioning from current fragmented standards to a sustainable, integrated geothermal resource assessment system. The framework is built on three interconnected pillars: (1) A Full-Chain Graded Evaluation system (P1-P2-P3) aligned with project maturity: (2) Technological Integration through dynamic models (THM), uncertainty quantification (Machine Learning/Monte Carlo), and standardized monitoring; and (3) International Colboration and Policy support to ensure global relevance and adoption. The ultimate goal is an assessment framework that is Precise, Dynamic, and Sustainable.

Policy and collaborative mechanisms play a critical role in this evolution. International standard cooperation should be strengthened through platforms such as the International Geothermal Standards Committee (IGSC), promoting the global adoption of Chinese standards, including the Recommended Practice for Geothermal Heating in China. Interdisciplinary collaboration across geology, engineering, and data science is essential to address complex challenges in deep geothermal assessment. Finally, a long-term monitoring mechanism covering the entire project lifecycle should be established, accompanied by robust certification systems for equipment and personnel qualifications.

CONCLUSION

Geothermal resource assessment standards form the foundation of sustainable industry development. Although current international systems have been initially established, they remain fragmented, static, and fraught with uncertainty. Moving forward, it is essential to advance along three main pathways: standard restructuring (through full-chain graded evaluation), technological integration (via THM models and uncertainty quantification), and international collaboration (under frameworks such as IGSC). These efforts will drive the transformation of geothermal resource assessment toward greater precision, dynamism, and global relevance, ultimately supporting the achievement of worldwide carbon neutrality goals.

ACKNOWLEDGEMENTS

Funding: This work arose from National Science and Technology Major Project-Deep Earth Probe and Mineral Resources Exploration (No.2024ZD1003600).

We gratefully acknowledge the State Key Laboratory of Deep Geothermal Resources. Special thanks are extended to Expert Fengnian Zhao for his invaluable assistance and guidance throughout this work.

References

International Energy Agency (IEA): The Future of Geothermal Energy, IEA Publications, Paris, France (2024).

IRENA and IGA:United Nations Framework Classification for Geothermal Energy: Pilot applications in the Caribbean, Ethiopia and Indonesia, International Renewable Energy Agency, Abu Dhabi, International Geothermal Association, Bonn (2021).

Larasati, T., Adityatama, D., Gentana, D., Purba, D., Chandra, V.R., Shalihin, M.G.J., Al Asyari, M.R., Brillian, V.A., Erichatama, N., Mustika, A.I., Fadhillah, F.R., Permadi, G.B., and P, S.A.: Indonesia Geothermal Energy Updates and Identification to Harness Future Geothermal Development, Proceedings, The 10th Indonesia International Geothermal Convention & Exhibition (IIGCE), Jakarta, Indonesia (2024).

Chinese National Standards: Geologic exploration standard of geothermal resources, GB/T 11615-2010, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization Administration of the People's Republic of China, Beijing, China (2010).

Ministry of Natural Resources of the People's Republic of China: Evaluation of dry hot rock resources, DZ/T 0505-2025, Ministry of Natural Resources of the People's Republic of China, Beijing, China (2025).

Table 1: Summary of International Technical Standards and Guidelines for Geothermal Resource Assessment

Issuing Organization	Standard Title	Status/Replacement
ISO	Geotechnical investigation and testing — Geothermal testing — Determination of thermal conductivity of soil and rock using a borehole heat exchanger	Current
IRENA/IGA	Application of United Nations Framework Classification for Resources (UNFC) to Geothermal Energy Resources	Replaces original UNFC-2009 geothermal specifications
IGA/Sinopec	Recommended Practice for Geothermal Heating in China	Current
USGS	An Overview of Techniques Applied to the Estimation of Known Geothermal Resources	Free public report
ASTM	Standard Terminology Relating to Geothermal Energy	Current
ASTM	Standard Practice for Sampling Two-Phase Geothermal Fluid for Purposes of Chemical Analysis	Current
ASTM	Standard Specification for Sampling Single-Phase Geothermal Liquid or Steam for Chemical Analysis	Replaces E947-83(2018)
ASTM	Standard Test Method for Testing Polymeric Seal Materials for Geothermal/Hot Water Service	Replaces E1069-85(2018)
ASTM	Nuclear Energy (II), Solar, and Geothermal Energy (Standards Volume)	Handbook (contains multiple geothermal standards)
BSN	Classification of Geothermal Resources and Reserves	Current. SNI 6009:2017
BSN	Parameters for Estimation of Geothermal Energy Resources	Current. SNI 6482:2018
BSN	Specification for Identification of Geothermal Wells	Current. SNI 8300:2016
BSN	Test Methods for Fluid Flow in Geothermal Wells	Current. SNI 13-6605-2001
BSN	Procedure for Execution and Reporting of Geothermal Surveys - Detailed Investigation Stage	Current. SNI 13-7122-2005
AFNOR (France)	Water and geothermal drilling — Vertical geothermal probes — Part 3: Cross-linked polyethylene (PE-X) probe loops	Current. NF X10-960-3-2013
Australian Geothermal Energy Group	Australian Code for Reporting of Geothermal Resources (2nd Edition)	Free public guideline