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Advancing Geothermal Development: Lessons, Breakthroughs, and Drivers from Hot Sedimentary Aquifers

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INTRODUCTION

Modern geothermal development has progressed unevenly since the early 20th century. The first power generator was tested in 1904 at Larderello, Italy, followed by experimental generators in the 1920s at Beppu, Japan, and The Geysers, California. In the latter half of the century, projects expanded to New Zealand (Wairakei), Mexico (Cerro Prieto), Iceland (Nesjavellir), Kenya (Olkaria), France (Paris Basin), alongside continued growth and development at Larderello and The Geysers. The Netherlands' first geothermal doublet was commissioned in 2007 in Bleiswijk, South Holland, where a collective of opportunistic greenhouse owners drilled into sandstone at ~2 km depth in the prolific (O&G) West Netherlands Basin. Though lacking volcanic high-temperature resources, the country now targets 60–120°C sandstone reservoirs for direct heating in its greenhouse-horticulture regions. Since then, projects have grown steadily, reaching 38 active geothermal heat sites by January 2026. Geothermal development in the Netherlands mirrors trends in France's Paris Basin and Germany's Molasse Basin, where *Hot Sedimentary Aquifers* have been tapped since the 1960s–2000s, respectively. Hard-learned lessons lead to necessary innovations and advancements. These learnings, however, now play a role in guiding future geothermal development elsewhere around the world.

1 ENABLERS OF THE DUTCH GEOTHERMAL SECTOR

1.1 Typical Dutch Geothermal Operations

Typical geothermal operations in the Netherlands consist of a doublet system (*e.g.,* a well-pair consisting of a producer and an injector) that targets matrix-permeable sandstones at a depth from 1600 – 3000 mTVD. Wells are typically J-shaped, with inclinations up to ~45°, drilled from the same surface location with a spacing of 1–2 km at mid-reservoir depth (Figure 1).

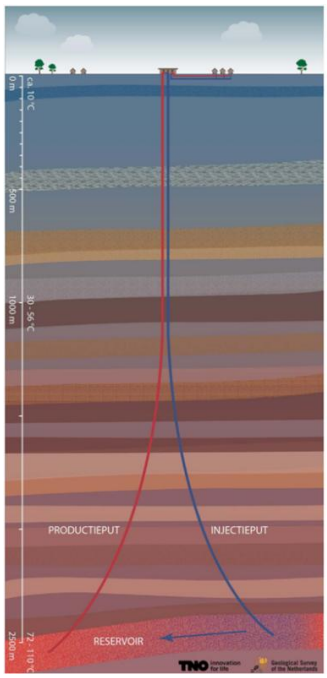


Figure 1. Schematic of a typical Dutch geothermal doublet (from Van der Molen & Tolsma, 2024).

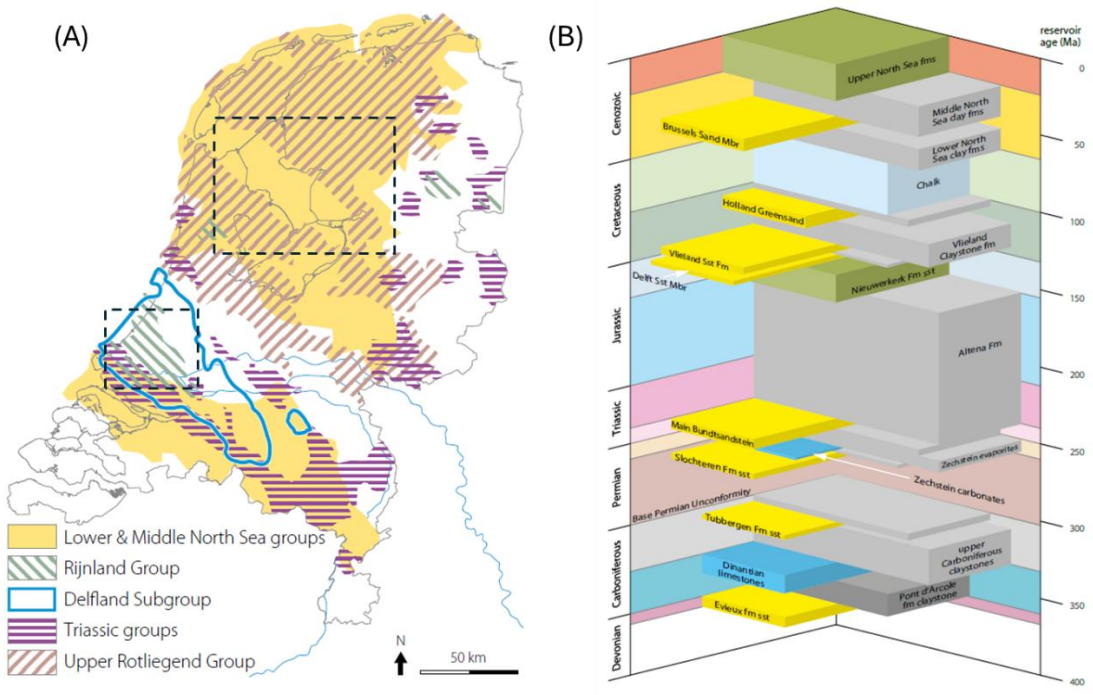


Figure 2. (a) Distribution of the main geothermal reservoirs in the Netherlands. The Carboniferous Dinantian play is not included in the figure, but is considered a potential geothermal play, especially in the southern Netherlands. The black dashed squares represent the areas where most of the installed doublet systems are concentrated. (b) Stratigraphic column highlighting the main potential reservoir zones (from Ten Veen *et al.*, 2025).

Dutch geothermal systems are largely concentrated in the southwestern and northern part of the Netherlands, and they target geological layers at different depths: the Cenozoic Lower and Middle North Sea Group play (700 – 800 m); the Upper Jurassic (Delfland Subgroup)/Lower Cretaceous (Rijnland Group) play (1600–2800 m); the Lower Triassic Main Buntsandstein play (2200–2400 m); the Permian Rotliegend play (1800–2700 m); and the Carboniferous Dinantian play (2200–2300) (Figure 2).

1.2 Early Observations and Oversights

Early results from the Bleiswijk geothermal project proved direct-use heat for greenhouses was feasible, scalable, and supported by prior subsurface data of the O&G industry. Public access to this subsurface data reduced exploration risks, though further optimization and best practices were still needed. Despite early successes, geothermal doublets soon faced major issues: injectivity decline due to clogging or scaling, brine-induced well integrity problems (high salinity and dissolved gases), and failures of standard O&G steel completions at high flow rates (150–450 m^3/hr) (Figure 3). As more doublets were built, site-specific challenges showed that no standardized design could suffice without continued learning.



Figure 3. Examples of geothermal system failure: inhibitor residue stuck to the caliper tool (left) and candle filter housing covered with mud fill (right).

2 CRITICAL IMPROVEMENTS

2.1 Data-driven Decisions and a Pro-active Mindset

Data-driven decisions and a proactive mindset helped address early geothermal oversights in the Netherlands, focusing on development, construction, and production through a stage-gate process with Capex/Opex breakdowns. In geothermal development, multilayer exploration assesses multiple aquifers, while material selection addresses failures from corrosion, erosion, and clogging. Initially protected with inhibitors, carbon steel was later replaced by more durable Corrosion Resistant Alloys (CRA's) or Glass fiber Reinforced Epoxy (GRE) tubulars, with GRE-lining and Duplex alloys preferred since 2021. Construction improvements include retrievable inner strings and injector perforations, and production now relies on Well Integrity Management Systems and continuous data monitoring.

2.2 Governance, Regulation, and Market Incentives

Beyond technical advances, Dutch geothermal development is supported by government measures: RNES insurance to offset drilling risks, SDE+/SDE++ subsidies to bridge the cost gap with natural gas, and R&D programs (HER, DEI, TSE) via the Netherlands Enterprise Agency (RVO). Alongside the public subsurface data portal (NLOG), the state-owned energy company (EBN)'s SCAN program is mapping Dutch subsurface potential by reprocessing seismic data, acquiring new 2D profiles, and drilling ten geothermal exploration wells. Moreover, the mining regulations were amended significantly (effective since July 2023), to incorporate specific regulations for geothermal, including: an independent permitting scheme for geothermal, independent regulatory methods for geothermal, and a mandatory participation option for EBN.

2.3 Current status of the Durch Geothermal Sector

Over the past two decades, geothermal development in the Netherlands has expanded rapidly, with 38 active operations by January 2026 supplying direct-use heat mainly to greenhouse horticulture and many more exploration licenses underway. In 2023, theoretical capacity reached ~13 PJ/yr (412 MW_{th}), but actual output was ~7 PJ/yr (222 MW_{th}), reflecting seasonal demand and oversized assets (Van der Molen and Tolsma, 2024). While both government and industry aim to boost geothermal's share, their ambitions remain notably misaligned (Van der Molen and Tolsma, 2024).

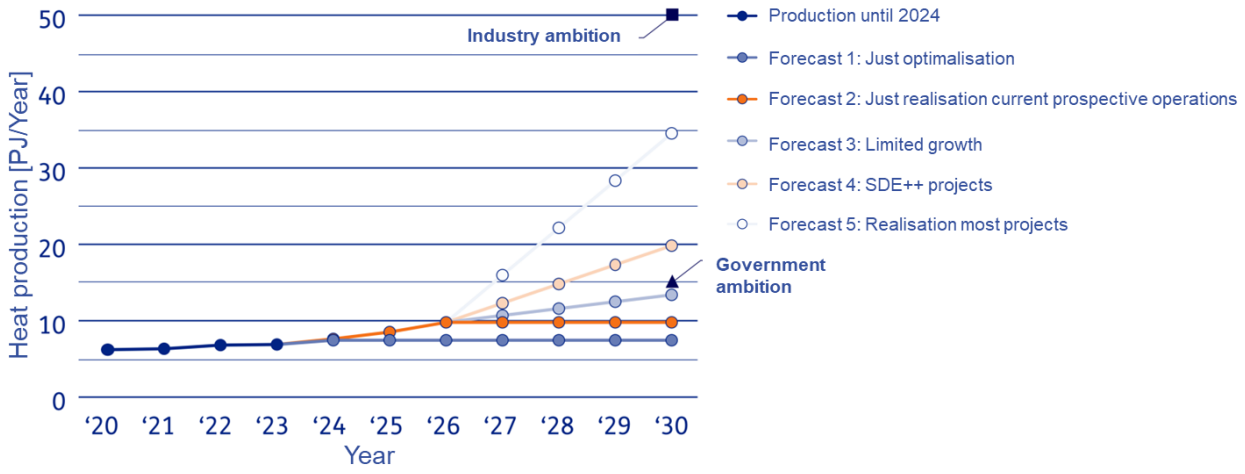


Figure 4. Industry and government ambition for the development of geothermal heat production in the Netherlands (modified from Van der Molen and Tolsma, 2024).

3 LESSONS LEARNED

3.1 Continuous Improvements by a Design-Construction-Monitoring-Maintenance Loop

Over the past decades, lessons learned have driven geothermal well optimizations, establishing industry-standard designs, improving drilling practices, and reducing sidetracks. Data-driven production has enhanced understanding of site-specific challenges, ensuring productivity and injectivity. These insights now guide new projects from feasibility and FEED to realization, with stage-gate processes helping expand opportunities and mitigate risk. Continuous improvement follows a "plan-do-check-act" cycle across design, construction,

monitoring, and maintenance (Figure 5). Exploration and engineering guide design; testing and commissioning ensure efficient construction; and production analysis, integrity checks, and geohazard management drive optimization during maintenance.

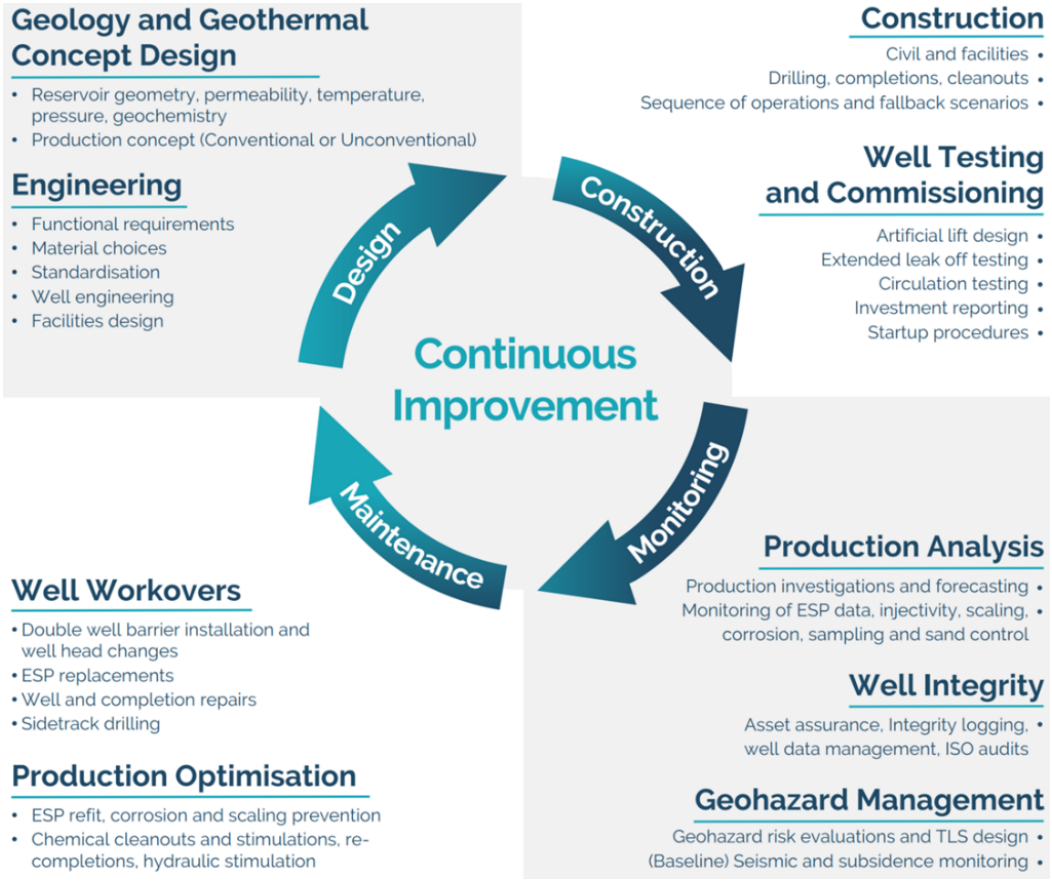


Figure 5. Continuous improvements of geothermal development based on an all informing "design-construction-monitoring-maintenance" loop.

3.2 Transferable skills and Benchmarking

Hot Sedimentary Aquifers are not unique to the Netherlands. Beyond mature plays in the Paris and Molasse Basins, they offer a promising frontier for low- to medium-temperature geothermal energy, especially in regions lacking high-enthalpy resources. They are widespread in regions such as the Texas Gulf Coast, Denver-Julesberg Basin, and Northern Germany, where decades of hydrocarbon exploration provide strong subsurface knowledge. Combined with concentrated surface demand, these shallow reservoirs are attractive for broad deployment. Because many aquifers share similar traits, transferring expertise from mature geothermal sectors is key to cost-effective development. Furthermore, in early regional projects, benchmarked energy models help identify site-specific potential and guide system design, estimating net power or heat production by accounting for aquifer properties, flow rates, ORC efficiency, and pressure losses.

4 CONCLUSIONS

Geothermal developments targeting Hot Sedimentary Aquifers in mature low- to medium- temperature geothermal regions such as the Netherlands, Paris Basin, and Molasse Basin highlight the value of past lessons learned. These lessons learned contribute not only to optimizing local assets and enhancing their future development, but they also play a key role in accelerating geothermal efforts in other greenfield regions. One of the key insights is that every geothermal phase is equally important. A stage-gate process is advised to lower the risk profile of a project, with Capex and Opex breakdowns conducted for each phase, especially for responsible contingency planning. Moreover, during the production phase, a data-driven approach should be used to optimize design and engineering decisions.

Data-driven decision-making and a proactive mindset are essential for successful deployment of geothermal energy systems. While benchmarked energy output modeling provides valuable insights in the early stages,

ongoing knowledge sharing is essential for continuous improvement. However, for the latter, caution is required, as not all local solutions are universally applicable.

In regional-scale geothermal development of Hot Sedimentary Aquifers, projected heat or power output is driven primarily by existing demand, rather than subsurface alone. As a result, expansion opportunities are closely tied to future demand growth. In this demand-driven context, it becomes essential to apply lessons learned and to streamline processes, not only for managing risk, but also for ensuring that projects remain adaptable and successful over the long term.

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