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Geothermal energy – from potential plays to successful growth

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ABSTRACT

In the last decade and a half the Netherlands has seen a significant increase in the application of geothermal energy production. The most prolific geothermal reservoirs are Lower Cretaceous-Upper Jurassic fluvial sandstones of the Delft Sandstone Member in the West Netherlands Basin and the Permian predominantly eolian and fluvial Slochteren Formation in the northern half of the country. Runners-up are reservoirs of the Triassic terrestrial Main Buntsandstein Subgroup and the Lower Cretaceous marine Vlieland Sandstone Formation. The Carboniferous Limestone Group was the target reservoir for two geothermal systems in the Roer Valley Graben. The heat produced is primarily used in the horticultural sector, which has played a pivotal role in the initiation and first development of geothermal energy in the Netherlands. Developing geothermal energy is a complex multi-issue exercise that involves numerous surface and subsurface uncertainties. The matching of heat supply to demand is just one of the surface uncertainties. Main uncertainties from the subsurface geological point of view are reservoir quality and potential for seismicity, while main points of attention from an operational point of view are well integrity, productivity and injectivity maintenance and scaling. Geothermal development has been aided by various financial and other supportive governmental measures. The sector is maturing by integrating experience, (well) design standards, seismicity protocols, innovations and lessons learnt in multistakeholder networks. These include operators, service industry, national and local governments, academia and research/knowledge-institutes and -centres. The initial focus on the horticultural sector has widened to include district heating and light industry applications. Additionally, the single system operator model has evolved into a portfolio operator model. The aim of all this is to achieve the ambitious target of supplying a large part of the Dutch heat demand with geothermal heat by 2050.

<< Drill rig at the location of the Monster geothermal doublet (west Netherlands).
Photo courtesy of HVC.

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Introduction

Since 2007 the Netherlands has seen a significant development from the identification of a small inventory of prospective areas without active geothermal systems (Lokhorst & Wong, 2007) to 27 realized geothermal systems at 1-1-2022. Nineteen of the 27 systems were in operation in 2021 (Ministry of Economic Affairs and Climate Policy - MEACP, 2022; Fig. 19.1) adding up to 6.3 PJ of heat produced, equal to 176 x 10^6 m^3 of (Groningen quality) natural gas and a contribution to CO_2 emission reduction of approximately 0.35 Megaton.

Geothermal exploration studies in the Netherlands started in the late 1970s (Visser & Heederik, 1987). In this era of geothermal exploration and development five relatively shallow (<1 km) spa or balneology development wells and one deep (ca. 2 km) research/exploratory borehole, the well Asten-GT-02, were drilled. The latter for the purpose of assessing the suitability of lower Cenozoic sediments for direct heat application and high temperature storage. Asten-GT-02 failed because the transmissivity encountered was insufficient for economically feasible heat production or high temperature storage (Dufour & Heederik, 2019). The well was used in the next decades as a groundwater monitoring well. The disappointing results of the Asten well, combined with low hydrocarbon prices, halted the development of geothermal exploitation for two decades.

Current geothermal developments are contributing to the transition from fossil fuels to sustainable energy sources and the ambition to reach the Paris Agreement goals (UN, 2015). The Dutch government aims to have a CO_2 neutral energy system in 2050. Geothermal energy production is proven to have a relatively low CO_2 footprint, taking into account the whole project chain (Gonzales, 2017) and is well suited to the future energy mix. In 2050 the ambition of the Dutch Government is to produce 80 PJ/yr from systems at production temperatures <120°C and some 60 PJ/yr from systems with production temperatures >120°C, in total comprising some 14% of the domestic heat demand (MEACP, 2018). Moreover, the ambition of the geothermal sector is to ramp up the geothermal production to 200 PJ in the year 2050 (Stichting Platform Geothermie et al., 2018; Fig. 19.2). Besides the climate policy ambition there are other drivers, as for example in the horticultural sector, where the urge to be independent of volatile and high gas prices and to replace them with a stable and sustainable heat price was felt. Additionally, the transition to renewable energy sources is becoming more and more a condition for the placement of horticultural products in the market.

All of the geothermal systems presently producing are for direct use of heat, mostly for the heating of greenhouses (Fig. 19.3), which suits the local high heat demand of the Dutch horticulture sector with its numerous greenhouses. The first companies that utilized geothermal energy systems were predominantly horticulturalists; only one district heating company was among the pioneers. The Van den Bosch tomato nursery was the first to realize a doublet. Its example was quickly followed by its colleague innovators in the vicinity and in other parts of the country. They proved that geothermal energy is a successful al-

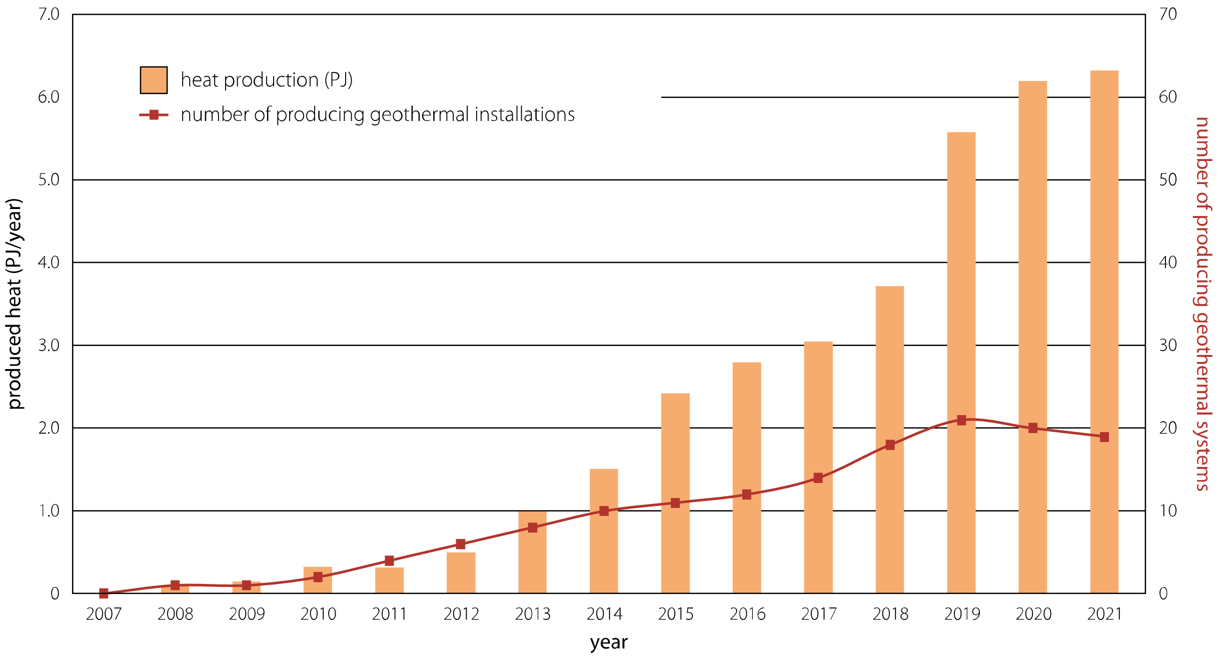


Figure 19.1. *The development of geothermal heat production and number of geothermal systems (status date 1-1-2022).*

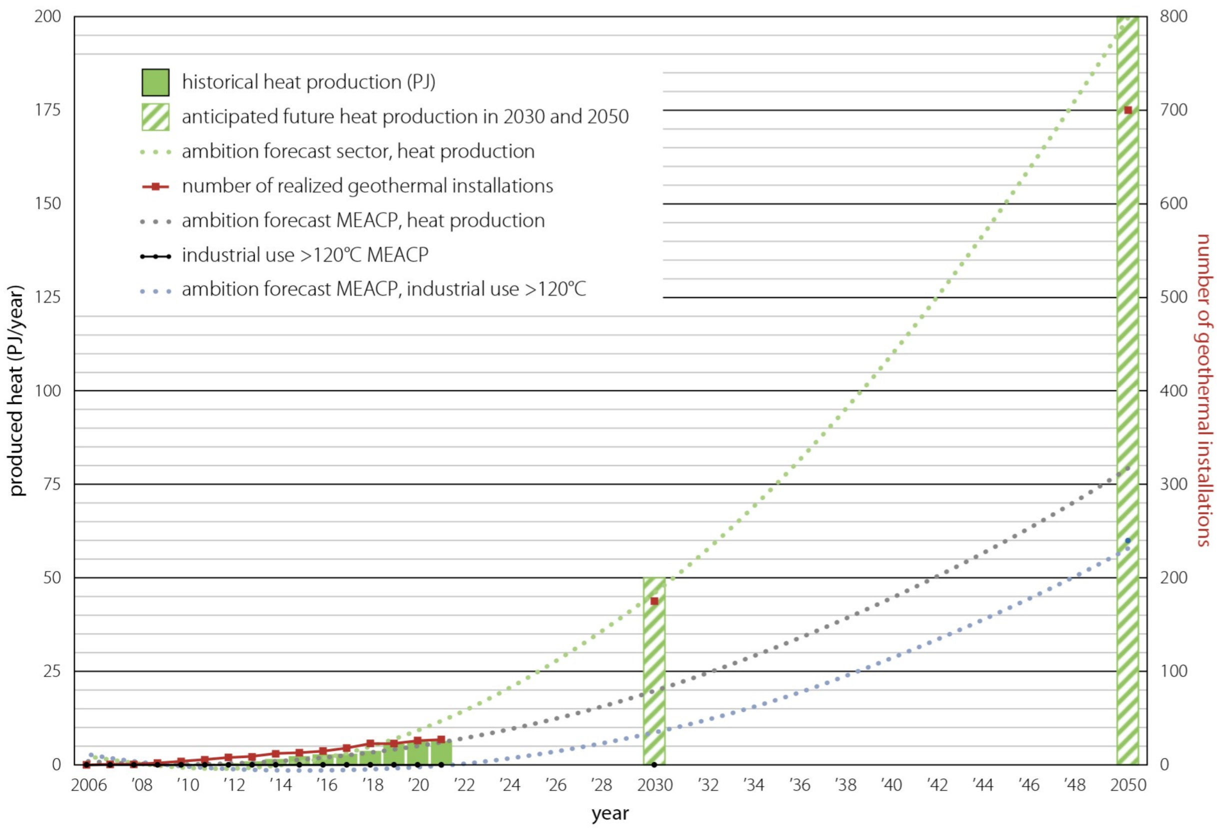


Figure 19.2. *Graph of the ambitions set by the geothermal sector in the Masterplan 2018 and the Ministry of Economic Affairs and Climate Policy (MEACP, 2018) including the historical production figures up to status date 1-1-2022.*

ternative for the gas fired heat production. Subsequently, other horticultural entrepreneurs entered the sector as 'early adaptors'. Presently, geothermal operators have become diverse with the arrival of portfolio operators, the entrance of traditional oil & gas companies, the participation of the state owned EBN company (www.ebn.nl) and a shift from direct use in the greenhouse sector towards the urban environment. This change of operators, whose main aim and core business is to produce and sell heat, will change the geothermal landscape in the coming decade.

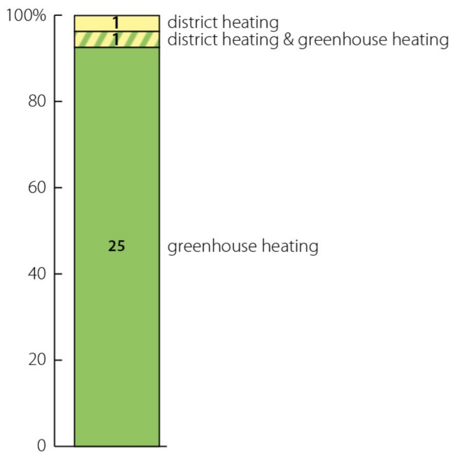


Figure 19.3. *Utilization of heat from the Dutch geothermal systems (MEACP, 2022, status date 1-1-2022; numbers refer to amount of realized doublets).*

The Heerlen mine-water project realized in 2006 is regarded (legally) as a geothermal project although it is better characterized as a thermal energy storage project (TES) according Verhoeven et al. (2014). The thermal energy is stored within shafts and galleries of an abandoned mine in upper Carboniferous strata and is deemed a different type of 'geothermal reservoir' which will not be discussed in this chapter.

The technology adaptation graph (Fig. 19.4) illustrates that the sector is still in the early stage of its development, but it is eager to grow (Stichting Platform Geothermie et al., 2018). However, as emphasized in a number of publications by the Dutch State Supervision of Mines (SodM, 2017, 2021) the journey towards a mature sector will encounter hurdles. To ensure a safe, socially and environmentally responsible sector, the sharing, preservation and growth of practical, scientific, and operational knowledge and experience are key. Various initiatives have been taken by the government and the geothermal sector to ensure this growth. Studies have been executed, legislation is being improved, and standards and methodologies are being developed. For example (sectoral) guidelines for geothermal well design and for community engagement have been issued.

At present, geothermal development in the Netherlands is in a transition phase towards a more mature position in sustainable heat supply. In this chapter an overview is presented of geothermal developments in the Netherlands, emphasizing the uncertainties and hurdles encountered, as well as the lessons learned. It will also shed some light on perceived future perspectives. It is written from a geo-scientific point of view, but will address both subsurface and surface development challenges as well as the related technical, economic and environmental challenges.

Uncertainties in both supply and demand have significant negative impacts on the business case of a project. Despite these uncertainties, the development of geothermal projects in the last one and a half decades has been generally successful. The following technical, economic, legislative, and policy factors spurred this development:

- High and volatile gas price;
- Environmental awareness and peer pressure;
- Targeted and fit-for-purpose financial support and subsidy schemes like Market introduction, Energy Innovation in the horticultural sector (MEI) and Stimulating Sustainable Energy production (SDE), together with the guarantee scheme for exploration risk (RNES);
- Supportive governmental licensing policy towards geothermal exploration and production;
- Supportive governmental policy towards geothermal research and data acquisition;
- Probably the most important factor: the window of opportunity in especially the horticultural sector in combination with active and dedicated greenhouse entrepreneurs.

The policy incentives listed above were installed with the aim of directly or indirectly reducing the *uncertainty* of an element in the project maturation trajectory, aiming to increase the bankability of the project. For example:

- The Exploration Guarantee Fund (RNES), the Market Introduction of Energy Innovations in the horticultural sector (MEI) and a Feed-In Premium scheme for produced sustainable energy products (SDE) give more comfort to parties who finance the project
- Installation of a 'temporarily policy' that allows production under an exploration license prior to award of a production license. This reduces the 'legal risk' to the operator
- More and better data to reduce the geotechnical uncertainty. Government funded projects include:
  - o 'KennisAgenda' projects have increased the knowledge base of the geothermal sector and have provided the first steps towards detailed research project descriptions and initiatives
  - o Research on Ultra Deep Geothermal targets based on existing data (UDG)
  - o Reprocessing of existing vintage 2D-seismic data and acquisition of new 2D-seismic data (SCAN project)
- Resource assessment and integration of geothermal resources in urban heating:
  - o High temperature heat storage
  - o Embedding in heat networks and
  - o Portfolio development

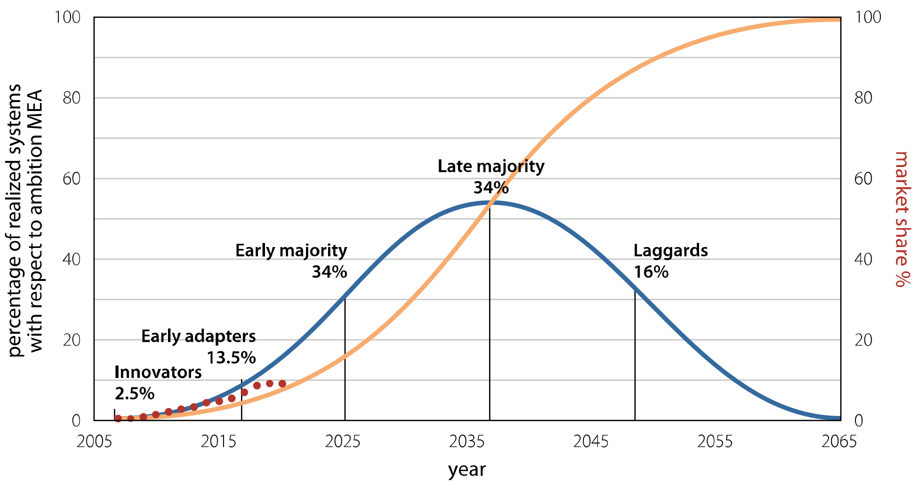


Figure 19.4. *Categories of adopters in the Dutch geothermal arena (background graph after Rogers, 1962) projected 100% of market share in accordance to the MEACP ambition of ca. 260 projected conventional geothermal systems in 2050. The Dutch geothermal sector started with the innovators in 2007 and entered the early adaptors class in 2017 (red dotted line).*

Reading guide

This chapter is organized as follows. In the first section, we introduce the Dutch geothermal setting and highlight the key role the availability of comprehensive subsurface data sets and information in the public domain will play in geothermal growth. This section also describes the different geothermal plays that are currently being developed, the geothermal production systems and the geothermal licensing system. In the second section the uncertainties and potential hazards related to geothermal sources are described. Geothermal prospects are marked by significant subsurface uncertainty and associated project development risks, both during the exploration and exploitation phases. In the third section we address the challenges currently faced by operators in relation to uncertainties on the supply and the demand side of geothermal heat. In the fourth section, challenges related to organizational and public engagement aspects, financing, policy and legal frameworks are described. The last section highlights some future developments and sheds some light on the Dutch geothermal resource potential.

In geothermal nomenclature the words 'aquifer' and 'reservoir' are used for the subsurface rock interval in which the hot geothermal water/brine resides, is produced from and is subsequently injected into. Although they are largely synonymous, here we use the term reservoir, as the term aquifer is commonly used in the very shallow subsurface domain in relation to fresh water resources.

Dutch geothermal setting

A wealth of subsurface data is available thanks to over 60 years of hydrocarbon exploration and production. It includes excellent seismic coverage and imaging of the subsurface to some 4 km depth (available from www.nlog.nl). About 40% of the Dutch onshore area is covered with 3D-seismic surveys. As the exploration risk is lowest in the data-rich areas, geothermal exploration started in the 3D-seismic covered West Netherlands Basin, where also many boreholes have been drilled. Outside the 3D-seismic covered area numerous 2D-seismic lines cross-cut the country, but despite this there are still areas of poor data coverage that carry a higher exploration risk. The governmental seismic data acquisition and reprocessing program (*Seismische Campagne Aardwarmte Nederland*: SCAN) aims to improve the coverage of these areas with a dedicated programme of 2D-seismic lines complemented with boreholes for reservoir data-acquisition to even further reduce the exploration risk.

All available subsurface data are used for regional maps prepared by TNO – Geological Survey of the Netherlands (Digital Geological Model-deep or DGM-deep v5.0, 2019). Next to the depth, thickness and distribution maps of the main stratigraphic intervals, special products have been made based on the regional mapping. One of the products, ThermoGIS is geared towards mapping the geothermal potential (Kramers et al., 2012; Pluymaekers et al., 2012; Van Wees et al., 2012; ThermoGIS, 2019; Vrijlandt et al., 2019). It is web-based and draws on the regional mapping results to calculate, amongst other things, Heat In-Place (HIP), geothermal power potential and, given certain technical and economic cut-offs, resource potential. As such ThermoGIS-v2.1 provides overall insight into the resource potential of geothermal plays in the Dutch subsurface (Mijnlieff et al., 2019, 2020; Van Wees et al., 2020).

Geothermal plays

In the maturation of a geothermal project the geological evaluation starts from a broad basin wide assessment (Limberger et al., 2014) within which geothermal plays characterize reservoirs that have a set of similar denominators (Moeck, 2014; Breede et al., 2015; Mijnlieff et al., 2020; Van Wees et al., 2020).

The Dutch geothermal reservoirs belong to a sequence of intracontinental sedimentary basin formation stages, marked by limited tectonics and absence of magmatic activity (Bonté et al., 2012; Békési et al., 2020; De Jager et al., 2025, this volume). Heat flow is largely conductive and significant hot spots are not found, so depth, facies and burial history, affecting reservoir temperatures and flow properties, largely determine the geothermal potential. In our approach, a geothermal play is defined by the presence of water and sedimentary formations with suitable flow properties that have comparable geological characteristics. As such the Dutch geothermal play is a hydrothermal one, specifically defined as a Hot Sedimentary Aquifer play (HSA; Breede et al., 2015), in which either the matrix or the fractures/faults form the dominant permeability system. This differentiation is essential because the seismicity hazard of geothermal systems in fracture/fault plays is higher than in matrix permeability plays (Buijze et al., 2019). Dutch geothermal plays are then divided into subplays according to the lithostratigraphic label of the reservoir sequence (Mijnlieff et al., 2020). The various geothermal reservoir-seal pairs are depicted in Figure 19.5, which shows top and base seals in relation to the stratigraphic column. The permeable sandstones of the Permian, Triassic, Upper Jurassic, Lower Cretaceous and Paleogene, plus the fractured carbonates of the lower Carboniferous form the proven sub-plays. Most units occur under large parts of the Netherlands, but their depth (and thus temperature), thickness and permeability vary greatly. The distribution of these geothermal reservoirs with their expected potential is depicted in Figure 19.6. Porous and to some extent permeable rocks of upper Carboniferous, Zechstein and Upper Cretaceous age may mature into proven sub-plays in the future. From a geological point of view the geothermal plays and reservoir distribution are described in the stratigraphic chapters of this book (Ten Veen et al., 2025) and definitions of the stratigraphic units can be found online in the Dutch Stratigraphic Nomenclature at www.dinoloket.nl/en/stratigraphic-nomenclature. The geothermal plays are described in Mijnlieff (2020). Their geothermal potential was mapped and assessed regionally in ThermoGIS (www.thermogis.nl; Vrijlandt et al., 2019; Van Wees et al., 2020 ; Stafleu et al, 2025, this volume).

The production temperature and reservoir transmissivity are of prime importance to the geothermal potential estimate of prospects and their application domain (Gudmundsson et al., 1985). The reservoir temperature

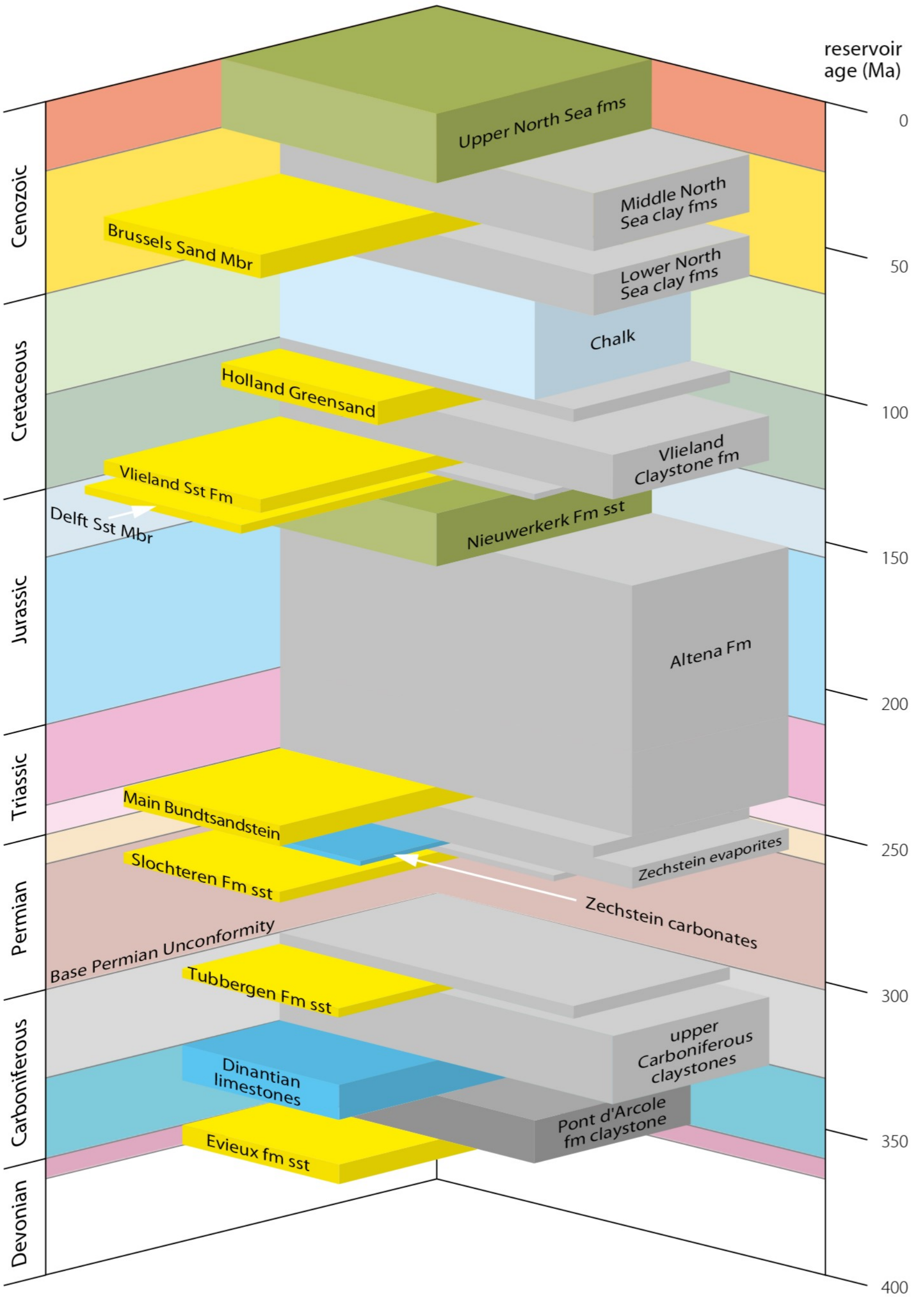


Figure 19.5. Generalized stratigraphic column of the Netherlands showing the geothermal reservoirs and sealing/aquitard packages: sandstone reservoirs in yellow, carbonate reservoirs in blue. The extent to the left of these reservoir 'boxes' gives an indication of the reservoir quality. The grey boxes denote the sealing clay-rich formations and their extent to the right gives an indication of the seal quality. The green and light blue boxes include poor quality reservoir and sealing lithologies. Note that the vertical scale is in millions of years, not stratigraphic thickness in metres.

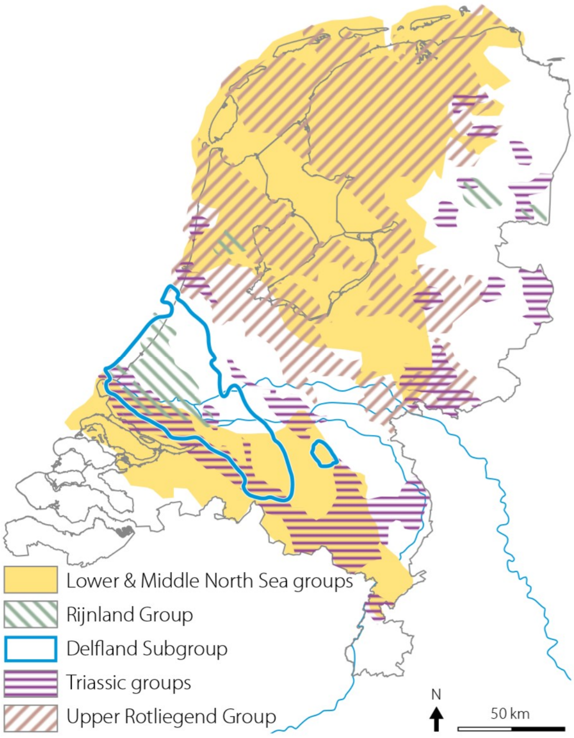


Figure 19.6. *Distribution of the main perceived productive geothermal reservoirs in the Netherlands (after P50 Power maps of the various geothermal plays from ThermoGIS, 2019, consulted in February 2022).*

is relatively easy to predict because all geothermal plays, fields or reservoirs, lie within a certain depth domain, while the average geothermal gradient is 31°C/km (Bonté et al., 2012), although more recent insights suggest a higher average geothermal gradient for the Netherlands. More detailed temperature estimates which take into account lateral and vertical variations in the thermal gradient are presented in Bonté et al. (2012) and Békési et al. (2020). Deviation, from the overall straight gradient line within certain intervals is caused, amongst others, by variations in thermal conductivity between the rock types and paleo-surface temperature changes related to the latest glacial period (Gies et al., 2021). Transmissivity, the product of thickness and permeability, is a key performance indicator for successful geothermal exploration, since it is linearly proportional to the achievable flow rate in the reservoir (e.g. Van Wees et al., 2012).

A geothermal project aims to harvest geothermal heat from the subsurface through one or more production systems. Initiation is linked to a (company) decision and is followed by a series of staged investment decisions towards maturation of the project to production. Within the Netherlands geothermal systems and projects are classified as shallow, deep, or ultradeep which correspond to specific depth domains which in turn grossly define temperature domains. The latter are largely related to specific direct use purposes. Electricity generation from geothermal energy is presently not implemented in the Netherlands as production temperatures are barely sufficient for efficient conversion. Suitable temperatures occur at depths in excess of 4 km where reservoir properties generally are poor. In the future electricity generation using Organic Rankine Cycle (ORC)-systems might be an option as they become progressively more efficient (albeit that even for a temperature of 180°C efficiency will never exceed 20%).

Figure 19.7 shows the depth and stratigraphic distribution of Dutch geothermal systems. It shows that individual geothermal reservoir at the various locations occur at different depths, as is evident from the top reservoir depth maps (DGM-deep v5). It also shows that the main targets are situated at depths ranging from 1600 to 2800 m, at which production temperatures vary from 60 to 100°C. Finally, it shows that most geothermal systems are developed in the prolific Delft Sandstone reservoir of the Nieuwerkerk Formation of Late Jurassic to Early Cretaceous. Runners-up are geothermal systems in the Slochteren Formation (Upper Rotliegend Group) of Permian age. As yet under-represented are the Vlieland Sandstone Formation, North Sea Supergroup and Triassic Main Buntsandstein reservoirs. In addition, two geothermal systems have been developed within a lower Carboniferous carbonate reservoir. They belong to the fracture/fault play, in contrast to all other systems which are assigned to the clastic Hot Sedimentary Aquifer matrix permeability play.

Table 19.1. *Depth classification of geothermal systems in the Netherlands.*

Depth denominator	Depth domain (m)	Temperature domain (°C)	Direct use domain
Shallow	500-1500	25-55	Greenhouses and well-insulated housing districts. Often combined with heat pump technology
Deep	1500-4000	55-125	Greenhouses and district heating. Optionally combined with heat pump technology to realize deeper cooling to increase the geothermal heat production and simultaneously resulting in lower injection temperatures
Ultradeep	>4000	>125	Light industry like food and paper

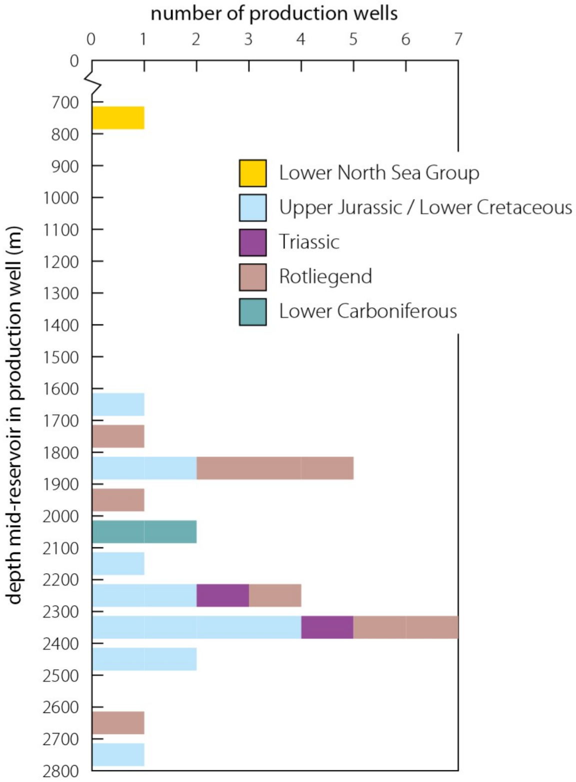


Figure 19.7. *The depth and reservoir lithostratigraphy of Dutch geothermal systems (status date 1-1-2022).*

Geothermal production systems

Most geothermal systems in the Netherlands are doublets. A doublet consists of a production and injection well, both completed in the same reservoir interval (the geothermal source) at a subsurface distance at reservoir level of up to approximately 1.5 km (Fig. 19.8). Dutch triplets presently have one production well and two injection wells. The production is executed as follows:

1. Hot geothermal brine is brought to the surface by using a pump, an Electrical Submersible Pump (ESP) placed in the production well at depths between 300 and 700 m;
2. Heat is extracted from the geothermal brine in a surface heat exchanger;
3. Finally, the cooled brine is re-injected into the reservoir via the injection well, often facilitated by a pump at surface.

Since the heat extraction from the well proceeds faster than the heat replenishment from the earth, a cold waterfront will form around the injection well in the reservoir and will eventually reach the production well (Fig. 19.9a). The moment it does so is referred to as thermal breakthrough. During production a pressure difference is imposed between the well and the reservoir. By definition, the pressure difference is negative in the production well and positive in the injection well (Fig. 19.9b). The area in which the original reservoir temperature and pressure are influenced, can be called the *subsurface area of influence* of the geothermal system.

Geothermal licensing

In the onshore Netherlands (Fig. 19.10) there are presently 96 exploration and 33 production licenses (status date 1-1-2022), including the ones in application status (MEACP, 2022). Geothermal projects targeting reservoirs deeper than 500 m are subject to Dutch Mining Act (*Mijn-*

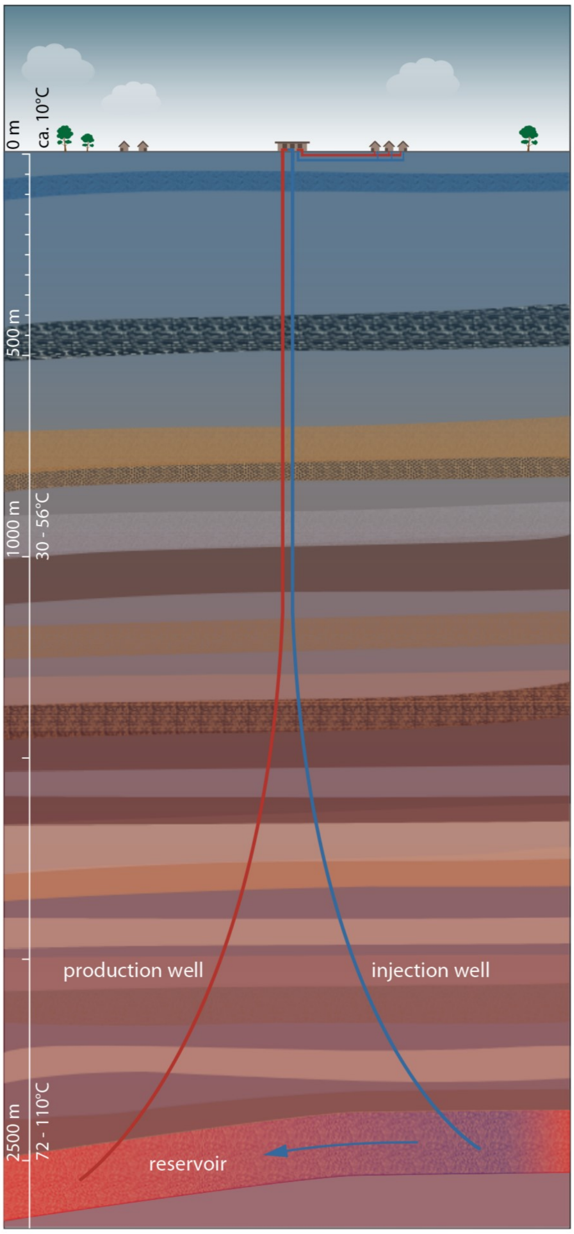


Figure 19.8. *Sketch of a typical doublet configuration with a production well (red) and an injection well (blue) targeting the same deeply buried reservoir. In this case a reservoir at about 2.5 km depth with an approximate temperature of 70°C.*

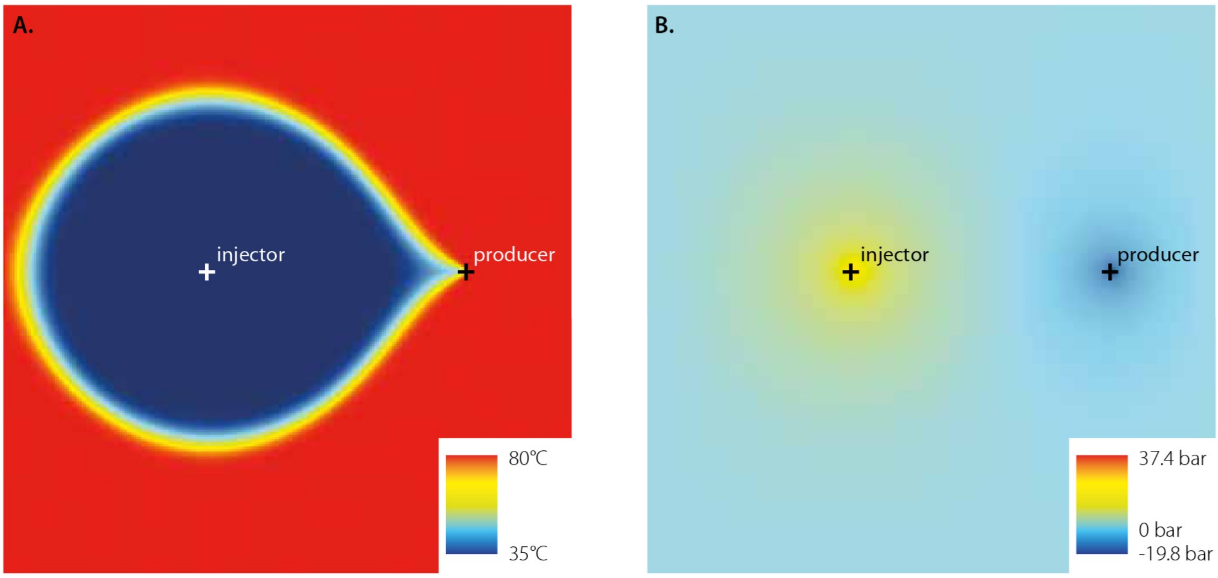


Figure 19.9. *Approximation of the subsurface area of influence of a geothermal doublet in an homogeneous reservoir. a) The extent of the cold waterfront in the reservoir at thermal breakthrough. b) The extent of the pressure perturbation (ΔP in bar) in the reservoir. Modelled with DoubletCalc2D (DoubletCalc, 2014).*

bouwwet), which means that separate licenses are required for geothermal exploration and production. Licenses are concentrated in areas with prominent presence of the horticultural sector like South Holland or the north of North Holland (Fig. 19.11). Actually, as shown in Figure 19.3, the majority of past geothermal development has been for greenhouse heating. However, the number of exploration licenses overlapping urban areas is growing rapidly (Fig. 19.11) and is in line with the ambition to supply geothermal heat to residential areas. In general, an exploration licence is granted for a depth domain from 500 m to infinite depth, although in some cases it is truncated at 4000 m to separate geothermal exploration at conventional depths from that for ultra-deep targets. Production licenses are usually restricted to specified intervals, in order to prevent the possibility of interference between vertically stacked geothermal systems. In such cases the upper and/or lower, license boundary is generally defined as the top or base

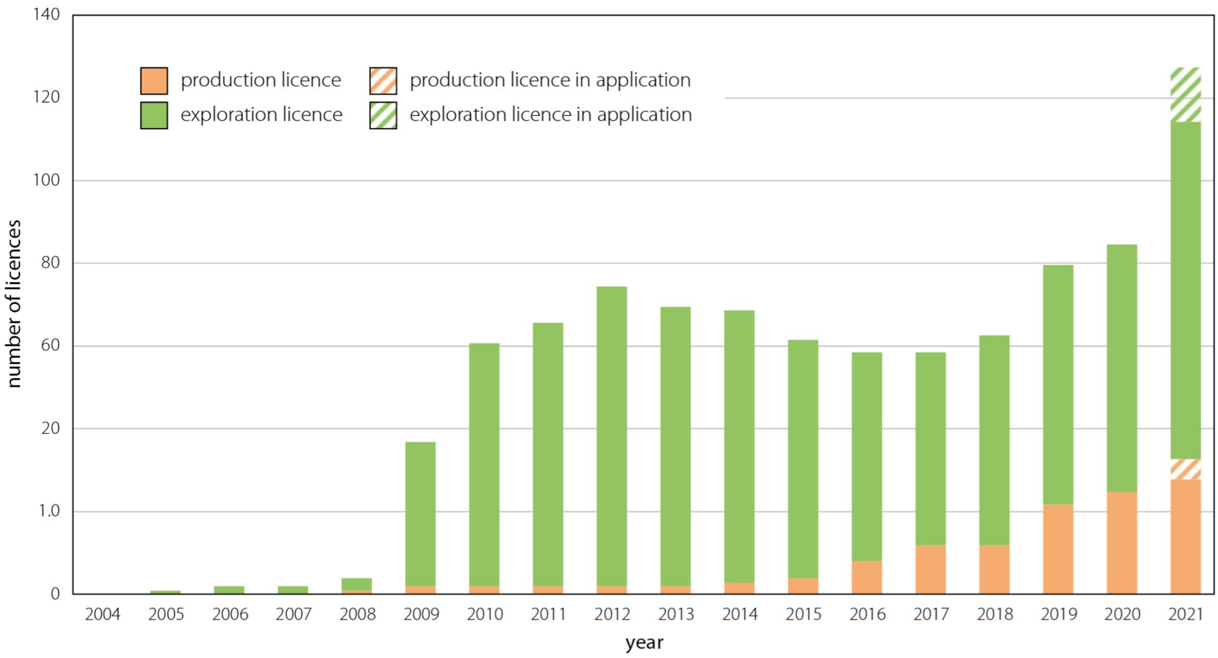


Figure 19.10. *Geothermal license development between 2004 and 2021 (MEACP, 2022).*

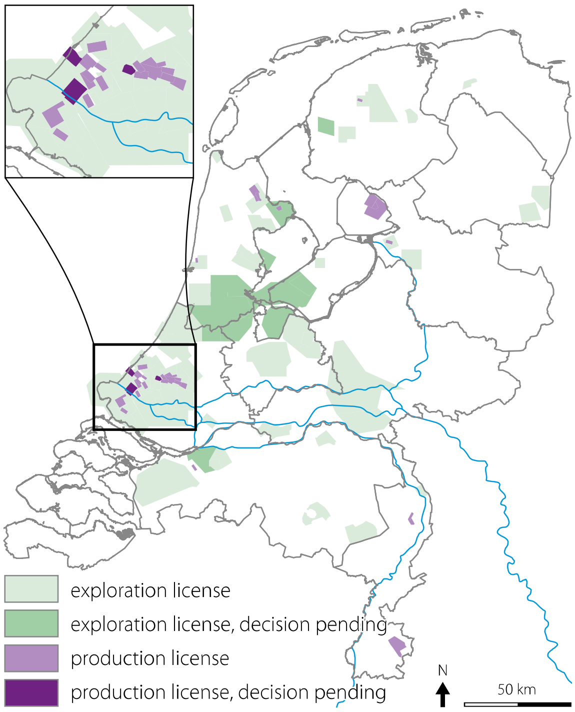


Figure 19.11. Geothermal license position at status date 01-01-2022.

of an impermeable lithostratigraphic interval that acts as a laterally continuous aquitard (Fig. 19.12; TNO, 2014a). Occasionally an absolute depth domain is licensed when it is evident that no vertical interference is possible within the licenced area.

Complementary to the licencing process, regulations demand reports detailing the process from incipient project idea to production, for example the drilling plan must be submitted to the mining authority (SodM) and the anticipated production plan (*Winningsplan*) to the Ministry of Economic Affairs and Climate Policy (MEACP) before the actual wells are drilled. The Mining Act and regulations have been revised in 2023 to better accommodate geothermal energy. The procedures in this revised Mining Act, and its subordinate regulations, are depicted in Figure 19.13 including the responsible authorities and advisory bodies.

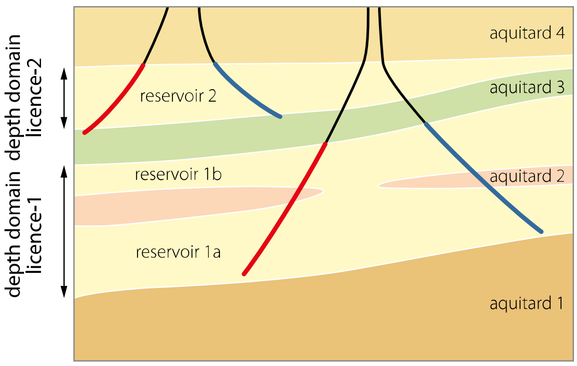


Figure 19.12. Vertical license delineation strategy on basis of laterally continuous lithostratigraphic units which act as aquitards (from TNO, 2014a).

Besides the Mining Act, the Environment and Planning Act (Omgevingsvergunning) applies to the impact of a geothermal system at the surface. Permit application can start as soon as a project location has been found and must be completed before any on-site activities start.

Managing the geothermal source; uncertainties and hazards

In the development of a project, uncertainties are supposed to reduce with maturation through time (Fig. 19.14; Van Wees et al., 2020). At project conception the uncertainties are large, but decrease gradually as geological, geophysical, and geochemical studies are executed prior to the drilling of a well. The well results record the actual reservoir parameters and productivity potential and consequently what the most likely production capacity of the system will be.

Low risk during the 'operation and maintenance' phase depends on thorough pre-operational studies, modelling, monitoring, and control during operation of the behaviour of the reservoir and reservoir fluids in relation to the imposed pressure (ΔP) and temperature (ΔT) differences and their impact on scaling, well integrity, and seismicity. In the Netherlands and neighbouring countries early production has seen unanticipated problems like casing and screen failure, ESP failure, scaling and in a few special cases induced seismicity. This emphasizes that a 'perception of low risk' in the operational stage as depicted in Figure 19.14 is only valid when the behaviour of the reservoir, the wells and the facilities under the imposed operational conditions are thoroughly known.

Uncertainty in reservoir flow properties and performance

Despite the wealth of subsurface data and knowledge of the Dutch subsurface (available from www.nlog.nl) pre-drill estimates of the geothermal power at any particular location still carry uncertainty related to the geology and the amount of relevant data. The primary geologic parameters for calculating geothermal power and energy are reservoir thickness, the net-to-gross ratio, porosity, permeability, reservoir depth, geothermal gradient or reservoir temperature and geothermal brine salinity as well as derived parameters like viscosity, density and fluid heat capacity. Also important are permeability anisotropy and rock thermal properties such as heat capacity, thermal

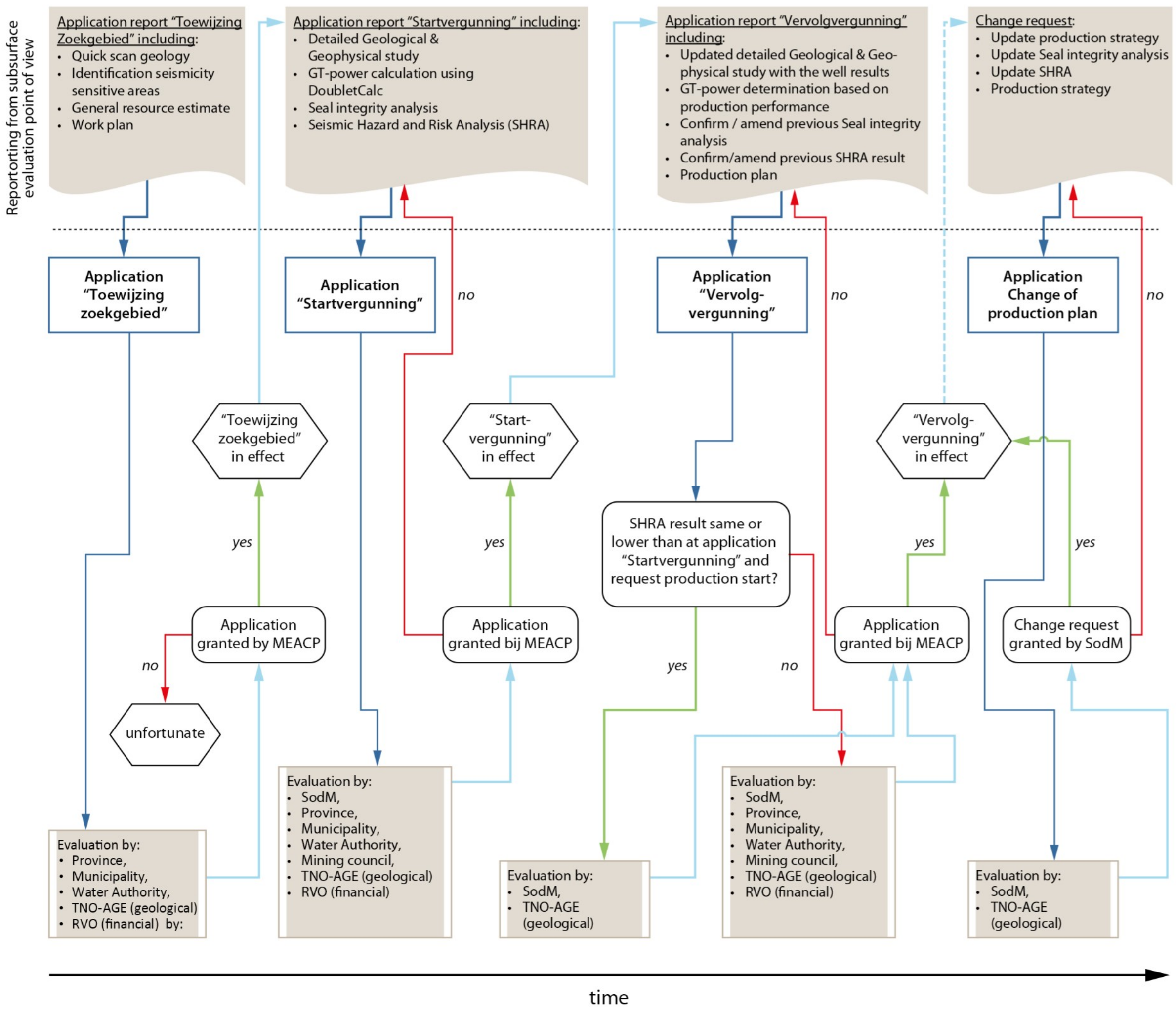


Figure 19.13. *Steps to take in mining licensing for geothermal energy under the revised Mining Act (since 2023). The top row lists reports to be filed; the row in bold shows the subsequent application steps. The lowest row shows the evaluation and advisory bodies (MEACP or SodM, shown as rectangles with rounded corners). A requested element (diamond shape) is subsequently granted or denied. Toewijzing zoekgebied can be seen as exploration license phase 1, Startvergunning as exploration license phase 2 and Vervolgvergunning is similar to production license. TNO-AGE = Advisory Group for Economic Affairs (part of TNO - Geological Survey of the Netherlands); RVO = Netherlands Enterprise Agency.*

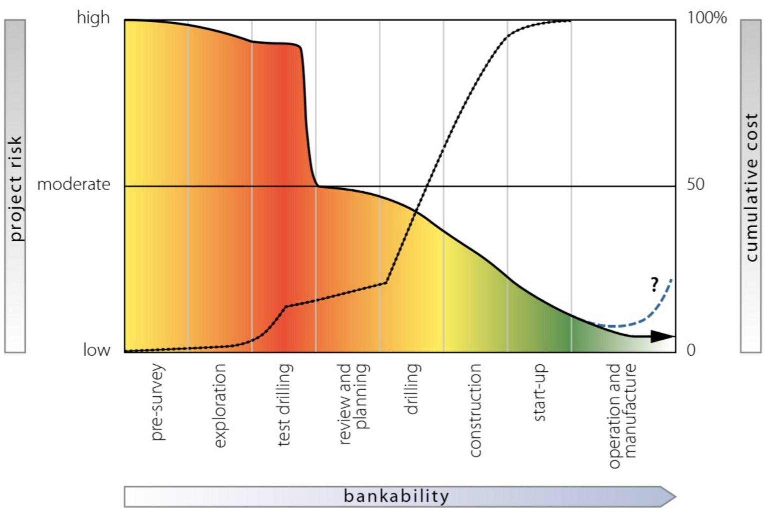


Figure 19.14. *Project risk/uncertainty during the progressive project phases from incipient thoughts to producing system (after ESMAP 2012).*

conductivity and diffusivity, both of the reservoir and of the surrounding rocks. An early estimate of the geothermal power range for a location can be calculated from the geological parameters and their uncertainty range coupled with the intended production engineering parameters and operational settings, for instance using the free DoubletCalc1D software tool (Van Wees et al., 2012; DoubletCalc, 2014; Fig. 19.15). The resulting flow rate and geothermal power are represented by an expectation curve. Threshold expectation values can be compiled on maps representing most likely (P50), the low (P90) and high (P10) estimates of the nominal thermal power as presented in ThermoGIS (Fig. 19.16). Subsequently, these most likely, low, and high values can be multiplied by the expected yearly amount of full load hours. This results in low, medium and high case yearly energy production estimates.

Over the lifetime of the project the yearly energy production estimates can be displayed as a production profile. Figure 19.17 gives an example of such a production profile for a geothermal system anticipated to produce 0.1 PJ of geothermal heat per year (in the most likely case). Uncertainty in geological parameters is reflected in a bandwidth around the most likely production profile. In addition, due to uncertainty in timing of the thermal breakthrough, the total energy produced during the systems' lifetime can be variable. The cumulative heat production in this profile defines the project resource with its uncertainty range.

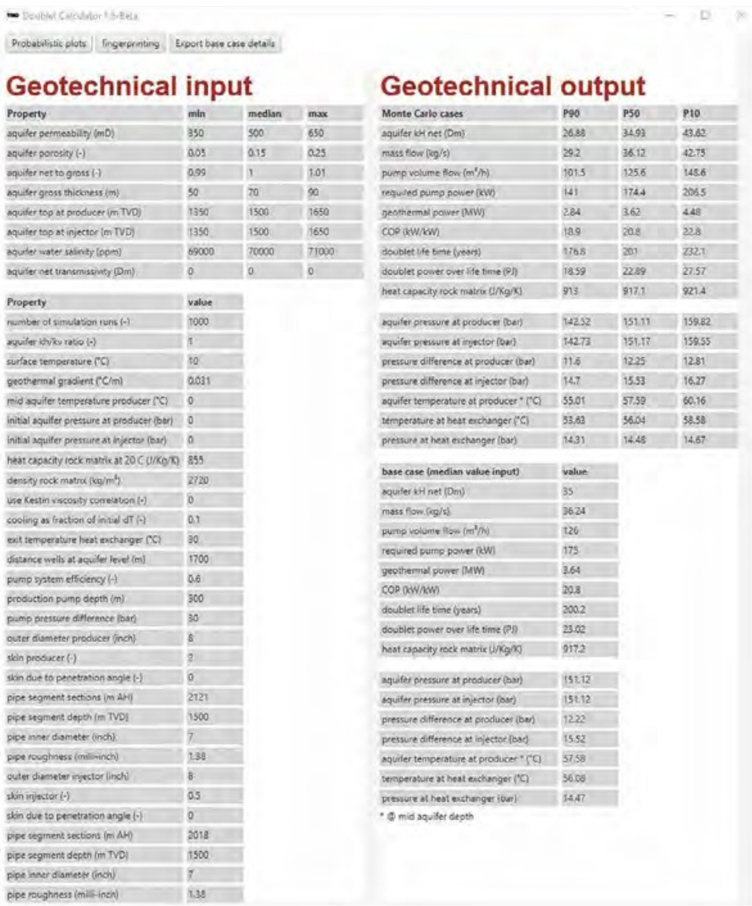
Better and more comprehensive geological mapping based on progressively more data, information and experience will result in a better understanding of the reservoirs and the geothermal plays. It will reduce the geologic uncertainty but also the exploration/play uncertainty, ultimately to a level inherent to the subsurface reservoir typed (Van Wees et al., 2020).

Operational regimes and environmental hazards and risks

Nothing in the world comes free of risk and the same applies for geothermal energy production. Those related to geothermal energy production include corrosion and scaling, system integrity, groundwater pollution, subsidence and induced seismicity.

Subsidence

In systems that rely on circulation of the formation water there is in general no pressure depletion in the reservoir because the produced geothermal water is re-injected in the same reservoir. The cooling of the rock volume around the injection well due to injection of cooled water causes a shrinkage of the reservoir of less than 0.1%, but it chang-



Probabilistic plots | Fingerprinting | Export base case details

Geotechnical input

Property	min	median	max
aquifer permeability (mD)	350	500	650
aquifer porosity (-)	0.05	0.15	0.25
aquifer net to gross (-)	0.99	1	1.01
aquifer gross thickness (m)	50	70	90
aquifer top at producer (m TVD)	1350	1500	1650
aquifer top at injector (m TVD)	1350	1500	1650
aquifer water salinity (ppm)	69000	70000	71000
aquifer net transmissivity (Dm)	0	0	0

Property	value
number of simulation runs (-)	1000
aquifer kh/kv ratio (-)	1
surface temperature (°C)	10
geothermal gradient (°C/m)	0.031
mid aquifer temperature producer (°C)	0
initial aquifer pressure at producer (bar)	0
initial aquifer pressure at injector (bar)	0
heat capacity rock matrix at 20 C (J/Kg/K)	855
density rock matrix (kg/m³)	2720
use Kestin viscosity correlation (-)	0
cooling as fraction of initial dT (-)	0.1
exit temperature heat exchanger (°C)	30
distance wells at aquifer level (m)	1700
pump system efficiency (-)	0.6
production pump depth (m)	300
pump pressure difference (bar)	30
outer diameter producer (inch)	8
skin producer (-)	2
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2121
pipe segment depth (m TVD)	1500
pipe inner diameter (inch)	7
pipe roughness (milli-inch)	1.38
outer diameter injector (inch)	8
skin injector (-)	0.5
skin due to penetration angle (-)	0
pipe segment sections (m AH)	2018
pipe segment depth (m TVD)	1500
pipe inner diameter (inch)	7
pipe roughness (milli-inch)	1.38

Geotechnical output

Monte Carlo cases	P90	P50	P10
aquifer kH net (Dm)	26.88	34.93	43.62
mass flow (kg/s)	29.2	36.12	42.75
pump volume flow (m³/h)	101.5	125.6	148.6
required pump power (kW)	141	174.4	206.5
geothermal power (MW)	2.84	3.62	4.48
COP (kW/kW)	18.9	20.8	22.8
doublet life time (years)	176.8	201	232.1
doublet power over life time (PJ)	18.59	22.89	27.57
heat capacity rock matrix (J/Kg/K)	913	917.1	921.4
aquifer pressure at producer (bar)	142.52	151.11	159.82
aquifer pressure at injector (bar)	142.73	151.17	159.55
pressure difference at producer (bar)	11.6	12.25	12.81
pressure difference at injector (bar)	14.7	15.53	16.27
aquifer temperature at producer * (°C)	55.01	57.59	60.16
temperature at heat exchanger (°C)	53.63	56.04	58.58
pressure at heat exchanger (bar)	14.31	14.48	14.67

base case (median value input)	value
aquifer kH net (Dm)	35
mass flow (kg/s)	36.24
pump volume flow (m³/h)	126
required pump power (kW)	175
geothermal power (MW)	3.64
COP (kW/kW)	20.8
doublet life time (years)	200.2
doublet power over life time (PJ)	23.02
heat capacity rock matrix (J/Kg/K)	917.2
aquifer pressure at producer (bar)	151.12
aquifer pressure at injector (bar)	151.12
pressure difference at producer (bar)	12.22
pressure difference at injector (bar)	15.52
aquifer temperature at producer * (°C)	57.58
temperature at heat exchanger (°C)	56.08
pressure at heat exchanger (bar)	14.47

* @ mid aquifer depth

Figure 19.15. *Output screen of DoubletCalc version 1.5 (Beta) showing the geologic input value ranges and typical system architecture and operational setting in the left column. The stochastic and deterministic (base case scenario) calculation results are in the right column (see www.nlog.nl/tools).*

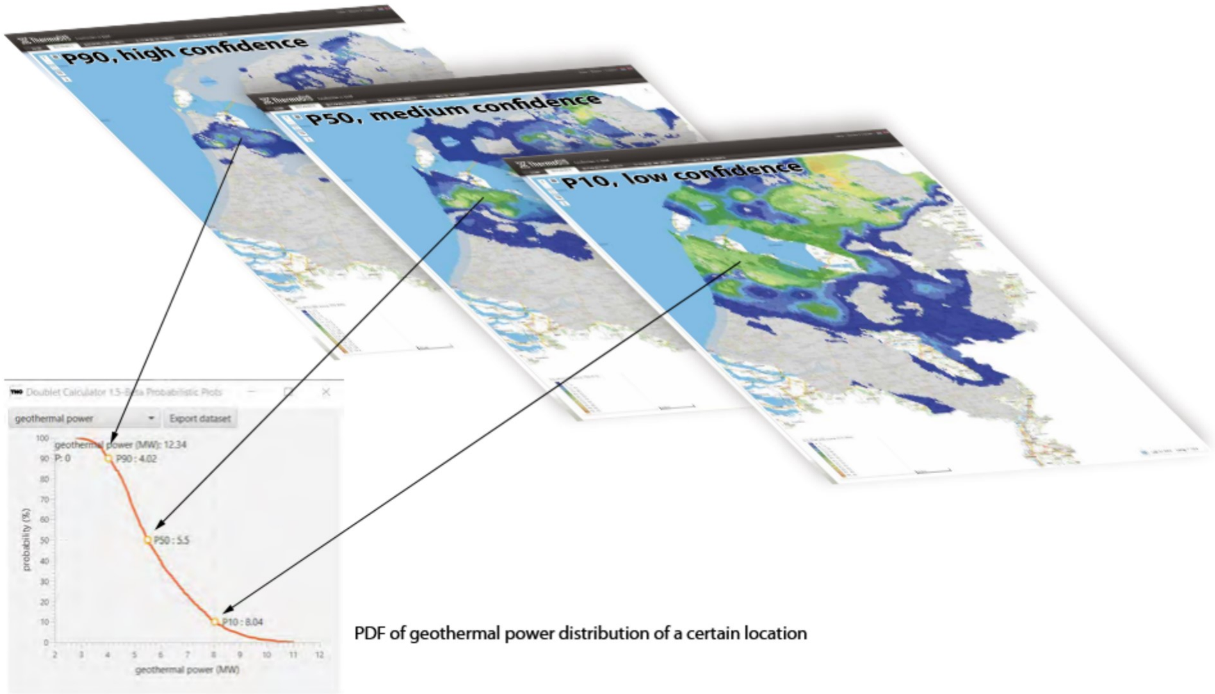


Figure 19.16. *Three maps (P90, P50 and P10) of the probabilistic geothermal power potential in the Netherlands. This is the result of the stochastic calculation using ranges of the geologic parameters of the 2D reservoir maps: permeability, thickness, net-to-gross ratio, depth and salinity. PDF = Probability Density Function.*

es the local stress field in the *subsurface area of influence*. The shrinkage may lead to subsidence from a few millimeters to a maximum of 2 cm in the centre of the subsidence bowl (Fokker et al., 2015). All subsidence modelling results of operating Dutch geothermal systems included in the 'production plan' evaluations at 1-1-2022, indicate that the effect of cooling of the reservoir at surface is in the order of a few to tens of millimetres over the licensed period of some 35 years.

Induced seismicity and seal failure

The imposed temperature and injection pressure changes on the reservoir lead to stress changes in the subsurface that potentially might reactivate existing faults in the subsurface area of influence of the geothermal system. If such fault reactivation occurs it may induce a-seismic or seismic activity. If the seismic events can be felt at the surface it may cause anxiety to the public or damage to infrastructure and housing.

A balanced mass-flow with the same production and injection volume is obligatory. Pressure communication between the injection and production well is ensured by for example interference testing. Therefore, on average there is no pressure depletion in the reservoir and no stress changes due to pressure depletion are anticipated. In the close vicinity of the injection and production wells, pressure changes do occur, but they typically decay logarithmically with distance from the well in the matrix of the porous reservoir and cause only local stress changes (e.g. Buijze et al., 2022; Kivi et al., 2022). This is in contrast to gas production where pressure in the entire reservoir is decreased by up to several hundred bar over a field's lifetime, (Roholl et al., 2021; Buijze et al., 2023).

Substantial cooling is expected to occur in the reservoir as the reinjection temperature is often several tens of degrees lower than the in-situ reservoir temperature. The lateral extent of the cooled reservoir can attain several hundreds of metres, or even more than one kilometre, depending on the subsurface injection-production well distance, the flow rate, porosity and reservoir thickness (Buijze et al., 2022, 2023). Part of the top and base seals that are in contact with the reservoir also cool due to heat diffusion. The resultant shrinkage will induce stress changes in the reservoir and surrounding rocks. These cooling-induced stress changes may cause slip along pre-existing faults when the fault strength is exceeded, primarily within the cooled zone where stress changes are largest (e.g. Van Wees et al., 2019). Cooling-induced stress changes dominate the imposed effect of the pressure changes in the matrix permeability dominated Dutch systems (Buijze et al., 2019, 2022; Kivi et al., 2022).

In fracture dominated systems however, elevated pressures at an injection well diffuse rapidly and directionally through the pre-existing fracture and fault network and can cause induced seismic events. This holds especially for hydraulic stimulations where large volumes are inject-

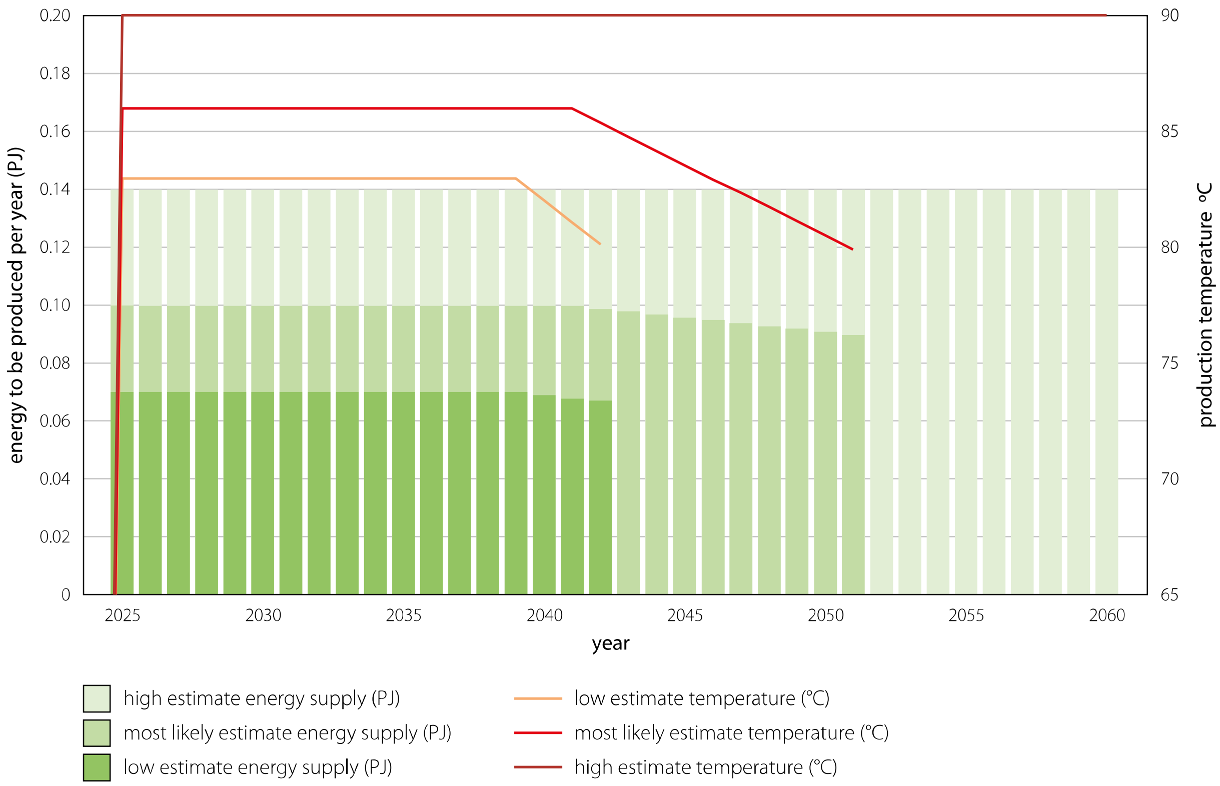


Figure 19.17. Example of a future production profile of a geothermal system. The low value of the expected geothermal power estimate times the amount of full load hours per year results in the 'low estimate' of energy production. The same calculation is for the most likely and high estimates. Additionally, the expected production temperature profiles are given in low, most likely, and high estimates. Production in this case ceases when the production temperature drops below the minimum threshold of some 80 °C.

ed under relatively high pressures (Wassing et al., 2014; Gaucher et al., 2015). Such stimulations have not yet been put into practice in the Netherlands. The injection pressure stress perturbation normally fades away quickly when pumps are stopped, however in fracture permeable systems larger seismic events sometimes follow such a shut-down as pressure diffusion is still ongoing. The inferred pressure changes at hypocentre locations can often be small, reflecting a close to critical state of stress in these systems.

A worldwide inventory of geothermal production systems (Buijze et al., 2019) demonstrated that geothermal systems that rely on matrix permeable systems induced no seismic events with magnitudes of more than 2.0 on the Richter scale. In contrast, seismicity occasionally occurs when production and injection of water is in fault/fracture related permeability systems and even more often when it is in Enhanced Geothermal Systems (EGS). All but two Dutch geothermal systems produce from reservoirs with predominantly matrix permeability (Mijnlieff, 2020) and no seismicity has been recorded which could be unambiguously linked to such systems (Muntendam-Bos et al., 2022). In the local seismic monitoring network that was installed in the surroundings of the two systems producing from faulted and fractured (and maybe partly karstified) carbonate reservoirs sub-feelable seismic events were recorded, although the largest (<M_L= 1.7, (Baisch & Vörös, 2018) could potentially have been felt at the surface.

Seismic hazard and risk analysis is performed before activities commence. Screening takes into account a set of key elements that may cause seismicity (Baisch et al., 2016). Depending on the outcome of the screening, additional studies and measures which may include a detailed location-specific seismicity evaluation and the installation of a monitoring and control system to ensure safe and responsible operations.

In addition to balanced production it is mandatory that the geothermal water does not escape and leak into other reservoirs through seal failure. An injection protocol (SodM, 2013, 2019; MEACP, 2021) has been established in order to define a safe operational space with respect to imposed pressure and temperature changes on the subsurface reservoir. SodM considers that unsolicited and hazardous events like seal failure or induced seismicity can be mitigated by applying safety limits in the operational space combined with monitoring to validate operational conformance. Operational constraints define the project's 'installed capacity', which may then be lower than what would be technically achievable if limits were not imposed (Fig. 19.18). Additionally, limiting the ΔP and ΔT may not only contribute to mitigation of environmental hazards, but also to sustainable performance of the system during its lifetime. For example, limitations in ΔT may prevent certain scaling. If these uncertainties are addressed in a comprehensive manner with proper methodologies to monitor, control, learn, and adapt, geothermal projects can flourish.

Corrosion and scaling

In the production phase operational issues rooted in geological causes may arise. The geothermal brines circulating in the system are highly saline and corrosive. Elements in the brine can react with the steel and corrode the piping, impacting the well integrity (TNO, 2016). The change of pressure and temperature of the circulating brine when its heat is harvested disturbs its geochemical equilibrium and chemical reactions will take place. An example includes precipitation of solids like calcium carbonate onto the steel piping of the well (TNO, 2013).

Currently operational systems (except the shallow North Sea Supergroup system (Fig. 19.7)) have salinities between 100,000 and 300,000 ppm NaCl eq. Figure 19.19 illustrates the amount of salt that precipitates from 100 ml of approx. 180,000 ppm salinity geothermal brine. Sodium and chloride dominate the brine, however other ions are also present in lower concentrations. Additionally, various gases, including methane, carbon dioxide and nitrogen are dissolved at reservoir depth (solution gas). The water-gas ratio is in the order of 0.3 to 1.0 m^3/m^3 in the hydrocarbon producing provinces (Dijkstra et al., 2020) but the exact value varies per location, depth and reservoir. In the production well, the temperature and the pressure decrease in the brine's path to the surface and when the pressure drops below the bubble point, solution gas escapes from the brine. When the gas escapes the geochemical equilibrium in the brine is distorted and the acidity is changed, favouring chemical reactions.

The brine-piping contact, the degassing, temperature and pressure changes and subsequent brine chemistry change may cause corrosion of the piping and pumps and/or precipitation of minerals. A few years after the start of the first projects this became clear and repairs to several existing wells and alterations to the well designs were made. Lead is seen to react (redox) with the casing, corroding the steel and forming a lead residue in the injection well (TNO, 2014b). Carbonate scaling on the ESP rotors was observed. In some cases the mineral deposits include naturally occurring radioactive material (NORM). These are caught in the filters or accumulate in the system and have to be removed periodically. Nowadays, most systems use inhibitors to effectively mitigate and minimize the corrosion and scaling issues, use glass fiber reinforced epoxy (GRE) piping for their surface installations or use GRE and coated materials for their sub-surface casing/piping.

System integrity (leakage)

To ensure balanced flow it is essential to keep the geothermal brine confined and contained within the reservoir interval and in the primary loop that comprises the (two) wells and the surface installation, including the heat exchanger. This is also of prime importance to minimize the pollution risk of fresh groundwater aquifers (Hartog,

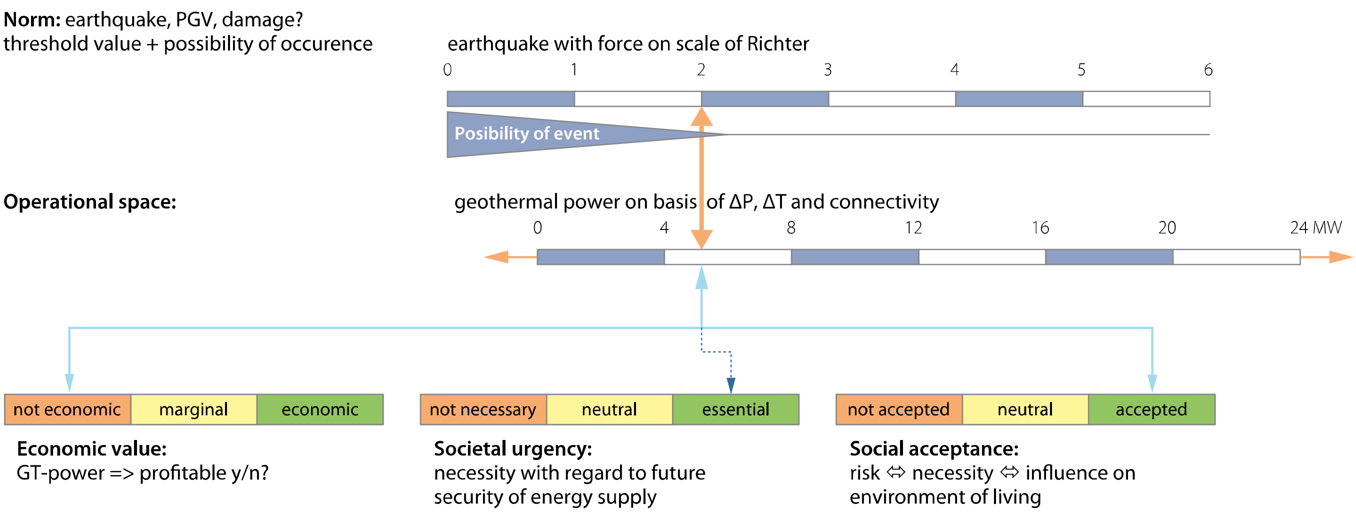


Figure 19.18. Operational space defined by (i) the threshold value of an earthquake both in magnitude and chance of occurrence, (ii) the installed power of that geothermal system given the maximum injection pressure (ΔP), (iii) the minimum injection temperature (ΔT) matching the seismicity norm, and subsequently (iv) the relation to economic value, societal urgency and social acceptance. PGV = Peak Ground Velocity.

2016). Various processes may cause the well barriers, conductor, casing or liners to fail. As the geothermal brine is highly saline and corrosive, the metal piping may corrode and ultimately lead to a leakage pathway. Similarly, flow of water with suspended particles (sand) may result in erosion of the piping, while turbulent flow with local degassing may cause pitting, which may eventually result in holes in the piping. In addition, stresses exerted on the piping by ductile lithologies like rock salt may deform it to the point that it partially breaks and creates a leakage pathway.

The choice of material and well design is essential to reduce the corrosion, pitting, and deformation processes. The improved well design, which was adopted in 2020 as an industry standard, also proposes improved monitoring options (Geothermie Nederland, 2021). The annulus between the first and the second barrier is to be monitored continuously. A compromised production or injection tubing can then be adequately identified. Secondly, adequate periodical monitoring and inspection of the installation can indicate if, for instance, the wall thickness or the shape of the piping is reduced and when they become critical. All these measures and more are detailed by the operator in a well integrity management system (WIMS).

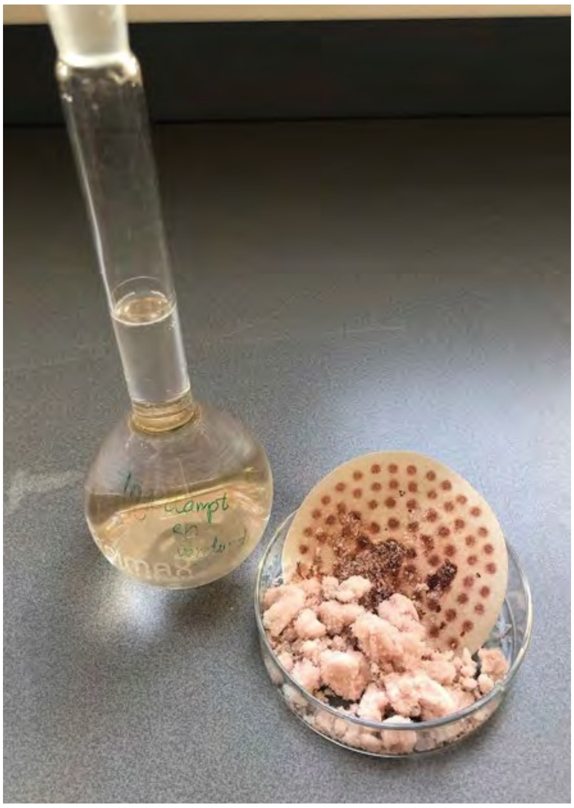


Figure 19.19. *Example of the amount of salt precipitated from 100 ml of geothermal brine from the Koekoekspolder geothermal system after evaporating the water. The reddish colour of the salt precipitate indicates that the geothermal brine is rich in iron, which forms iron oxide when in contact with the atmosphere (photo courtesy of Viola Lucza).*

Matching supply and demand: organizational and public engagement aspects

In the horticultural sector geothermal heat replaces local gas fired heat and power plants or boilers. Although this heat source was reliable, flexible, and efficient it has major drawbacks, like the volatile pricing, geopolitical issues and CO_2 footprint. Nevertheless, in horticulture the CO_2 contributes to the growth of the plants and thus needs to be available. The use of the co-produced solution gas in the heat and power plants and boilers partly satisfies the horticultural CO_2 demand. As the required geothermal temperature for greenhouses is relatively low, in the order of 70 to 50°C, geothermal heat from the Dutch subsurface is very well suited to match the demand. Moreover, it can provide a stable year-round base load, independent of weather conditions and as such it provides the user with a future-proof alternative energy source. Additionally, the transition to renewable energy sources can be a bonus to the placement of horticultural products in the market.

A project initiative in the horticultural sector is mostly taken by an individual or a cluster of greenhouse companies that purchase the heat and become project-owners at the same time. This way the offtake risk is small, in contrast to the uncertainty of producers who sell heat to third parties and have to rely on 'heat purchase agreements'.

The first geothermal system exclusively designed to provide heat for the urban environment is the 'The Hague' geothermal doublet, drilled in 2010. The wells were successfully tested and proved able to match the pre-drill anticipated heat demand. However, due to a crisis in the housing market the demand was not developed in time and the company faced bankruptcy (Haagse aardwarmte, 2021). However, at the end of the 2020s, the local heat demand was back to pre-drill expectation and the geothermal system production started to deliver heat to residential, office and hospital buildings early 2022.

About forty percent of the Dutch energy consumption is used for direct heat (CBS & TNO, 2020). This includes heating residential, recreational and business buildings, as well as greenhouses and industrial processes. The first three building types and to a lesser extent the greenhouses have a seasonal heat demand profile. The demand is low in summer and high in winter months, resulting in a typical curved demand profile (Fig. 19.20). Where the geothermal system matches the full heat demand, it operates at full capacity during the winter months and at low capacity during the summer months. From both the project economics

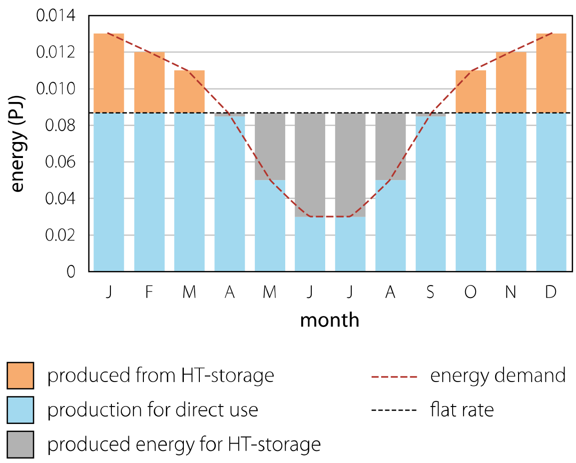


Figure 19.20. An ideal supply and demand graph for a combined deep geothermal system and a HT-ATES facility. The red dotted line depicts a typical profile of energy demand through the year. It displays the 'bath tub' profile as a consequence of the monthly varying heat demand; low in summer and high in winter. The black dashed line is the ideal flat rate supply profile from a deep geothermal system. Overproduction in the summer months with respect to the demand is buffered in the HT-ATES facility (grey bars) to be produced in winter (orange bars).

and the production and reservoir technical point of view this is sub-optimal. Geothermal systems perform better technically and are more economical when they produce at a stable rate year-round. The combination of a deep geothermal system with a seasonal high temperature heat buffer system is a solution to mismatches in monthly heat demand and supply. When the system operates year-round at full capacity, the excess heat production can be stored in shallow geologic formations in summer and later produced during the winter period to match the higher heat demand (Fig. 19.20). In 2021 in the north of North Holland a High Temperature Aquifer Thermal Energy storage (HT-ATES) pilot system that is linked to a deep geothermal system (www.heatstore.eu/) was realized.

In addition to the seasonal demand-supply match challenges, there can also be a mismatch in energy capacity (PJ), temperature of the geothermal supply and requirements on the demand side. In all cases a heat pump which can raise the production temperature of the heat produced by the system may cover the gap. Alternatively, it can produce more energy from the primary loop by lowering the injection temperature while delivering heat at the desired temperature level. Heat pumps are frequently applied in Dutch geothermal systems because they are a cost-efficient way to raise the energy output of deep geothermal systems. Moreover, a heat pump is an essential component in shallow geothermal systems (~500-1500 m depth) as they provide the required temperature levels for direct use applications. In the future use of geothermal in high temperature district heating networks or industrial applications, the use of industrial heat pumps is foreseen (Dijkstra et al., 2020).

Another challenge, as seen in the 'The Hague' project, is the alignment of geothermal heat supply and district heat network demand. Ideally the demand should be in line with the maximum capacity that the geothermal source can deliver at the start of production. For projects in the horticultural sector this appears to be fairly well matched due to clustering of demand and optimization of available buffer capacity. However, connecting customers to a heating network can lead to a timing mismatch, for instance when demand lags behind the supply offered by the geothermal resource (Fig. 19.21). In addition, the temperature provided by the geothermal system may be insufficient for the traditional heat grids, as the latter are generally designed for 90°C or more. Finally, project developers are confronted with the chicken or egg problem: "who is developing first?". Building a heat district network with sufficient offtake and developing a geothermal project both carry large pre-execution uncertainties in relation to the energy demand or supply profile, and the large stakeholder group involved.

Resource potential

The Dutch subsurface holds ample geothermal resources to match the ambition of the geothermal sector or the MEACP as depicted in Figure 19.2. The first quantitative geothermal resource assessment for the Netherlands was published by Kramers et al. (2012). Building on that approach an update was presented in 2020 (Mijnlieff et al., 2020). First, the Heat In-Place is calculated based on geological maps (Muffler & Cataldi, 1978). Subsequently the technical potential is determined by extracting the relevant input data from the ThermoGIS map set to compute the geothermal capacity in MW at every grid location. The economic potential is evaluated using the geothermal capacity together with an economic model and subsequently, the resource is be matched to the local heat demand. Geothermal heat is only of value when heat demand exists at more or less the same location, so the matching is preferably done on a local level where a heat transition strategy is to be developed.

Once the resource potential is mapped and estimated, the resources can be classified with respect to their maturity in (potential) development. The various hurdles in the project maturation have to be addressed. There might be obstructions in the maturation that lead to a

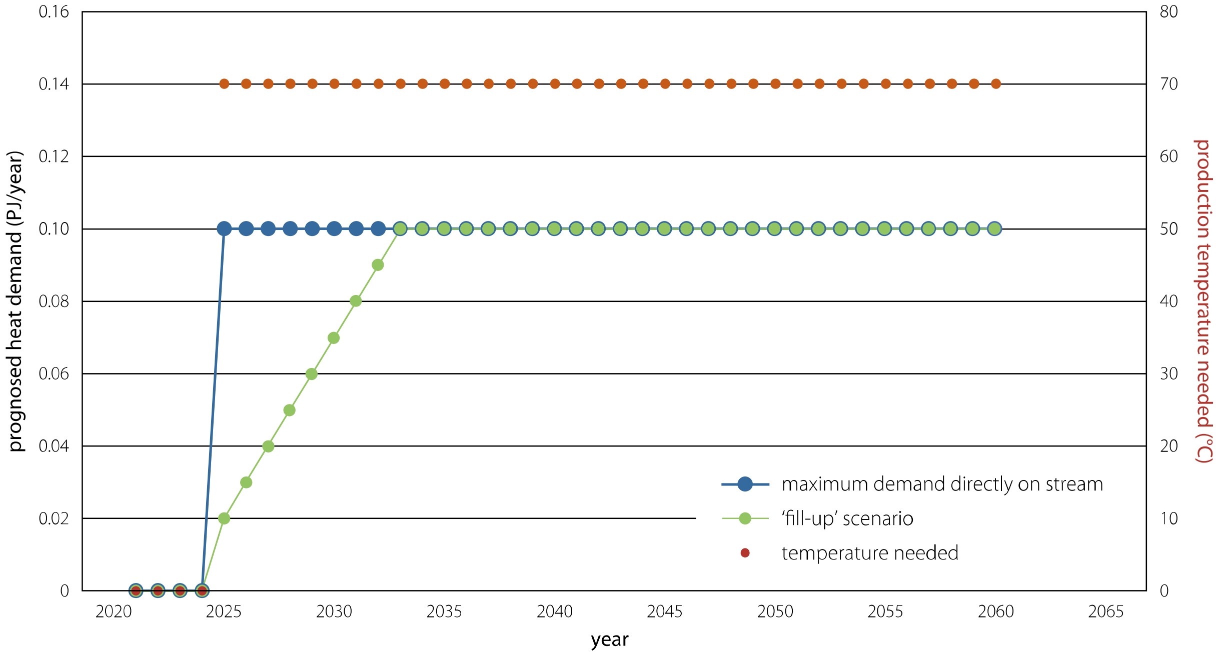


Figure 19.21. Example of expected heat demand profiles in 'energy volume' and temperature. The blue line represents a system for which the heating demand matches the geothermal capacity profile from the start. The green line illustrates a case where the heat demand starts at zero and increases ('fills up') over a period of 10 years to its maximum. This may reflect the development of the heat network only after it is proven that the geothermal source works as expected.

prolonged development time or even prohibit the source to be developed at that location. Examples of resource development hurdles involve overlapping drinking water protection areas, nature reserves and seismicity sensitive areas, but may also include economic hurdles (e.g. areas that are too far away from the demand location). The installed capacity together with development hurdles and perceived risks define the project categorization in terms of economic, social, environmental, and societal viability (UNFC, 2019).

Next to hurdles at the surface the subsurface uncertainty has an impact on the project maturation speed. Van Wees et al. (2020) illustrated that this hurdle can effectively be lowered by an orchestrated exploration approach where learnings, data and information are shared to lower the geological exploration risk. Using this play-based exploration approach the geothermal sector ambition to produce 50 PJ in 2030 could be efficiently matched.

Subsurface spatial planning

As the heat demand is quite localized (cities, light industries and greenhouse clusters), it is expected that geothermal systems will interfere with each other more than is presently the case. 3D or even 4D (taking time in consideration) subsurface spatial planning will be necessary. Orchestrated development of neighbouring systems, to optimize heat recovery and efficiency and simultaneously ensure safe operations, is expected to become common practice in geothermal subsurface domains. A prerequisite for a long-term joint production strategy between neighbouring geothermal projects is the presence of a linked heat distribution system at the surface, which can ensure that the security of supply is not compromised for individual operators in a jointly developed geothermal field.

Support measures and policy

The previous sections illustrated that developing the geothermal resource is a trajectory riddled with uncertainties. Governmental support measures soften the sharp edges of some of these uncertainties.

Financial support measures

The development of a geothermal system is a capital-intensive project. The drilling of deep boreholes, the construction of the surface installation and the distribution network may cost well over 30 million euros (EBN&GNL, 2021). The combination of high development costs and project uncertainties in, for example, the exploration and production phases, the cost price, the licensing and the offtake, represent major challenges in developing geothermal projects. The current legal, regulatory, financial and market frameworks are not optimised for initiating new heat value chains where offtake and infrastructure still need to be acquired and built.

On average the cost price of geothermal heat per PJ is/was higher than the equivalent gas price, which in the Netherlands (still) is the reference and in addition, the uncertainties and risks discussed in the previous sections negatively influence the business case. To support the development of geothermal energy several policy measures have been taken and some of these will be discussed.

Often, it takes a long time to reach financial closure, typically three years or more after the application for an exploration license. Convincing the different financiers that there is enough certainty for the project to be executed according to plan and the result will match pre-drill expectations despite all the uncertainties, proves to be complex. Three governmental financial support measures have been installed in the Netherlands in order to reduce the financial risk to the owner and investors. Firstly, the investment subsidy, secondly the exploration risk scheme and thirdly the feed-in premium scheme SDE (*Stimulering Duurzame Energie & Klimaattransitie*).

Dumas et al. (2019) visualized financial and risk mitigation support schemes with respect to the maturity of the geothermal development. In the Netherlands the development of support measures largely coincides with the maturity sequence. In the start-up phase (2006-2013), in addition to the project financing from banks, the investment costs of the first ten systems were supported by the Market Introduction Energy Innovation (MEI) subsidy grant, special loans from the Ministry of agriculture and the agricultural organization LTO. The exploration risk mitigation scheme, a public risk insurance, was installed by the Ministry of Economic Affairs in 2010 and updated in 2013. It offers an insurance against disappointing well productivity and/or injectivity and therefore lower than expected realized geothermal power, caused by less favourable geologic conditions than used in the pre-drill P90 power estimate (Mijnlieff et al., 2013).

In 2013 the geothermal energy production was incorporated in the feed-in premium scheme '*Stimulering Duurzame Energie*' (SDE) (Mijnlieff et al., 2013; RVO, 2021). Upon admittance of a project to the SDE scheme, a budget is reserved, based on the pre-drill expected capacity of the geothermal project times a fixed amount of full load hours during a 15 years period. The government pays-out the unprofitable top (GJ cost price of geothermal heat minus GJ cost price of natural gas) of the energy cost price per kWh when produced over the lifetime of the project with a maximum of 15 years.

A recent governmental financial initiative is the state participation in geothermal projects by EBN, which may take a 20 to 40% share in geothermal projects as has been done for decades in the gas exploration and production sector.

Regulations

The Dutch Mining Act was designed for the exploration and production of oil, gas, and salt. In 2003 the law was amended to include geothermal projects in the legal framework. The law stipulates that all data retrieved from the subsurface must be delivered to the MEACP. After a 5 years confidentiality period the data become public. This ensures the possibility that geothermal projects can use almost all available subsurface data in order to minimize the exploration risk.

Geothermal energy operates in the same subsurface environment as oil and gas production, and the (oil and gas based) legal and governance frameworks (Mining Act, Environment and Planning Act, Heat Act) used to misfit the development of geothermal energy in a number of important aspects. For example, for economic reasons and subsidy rules, production of heat needs to start shortly after wells are drilled and the surface facility is ready. However, the exploration licence did contain a permit for the production of the resource at that moment. This, in combination with long lead times related to review and approval of the production license and development plan, showed that application and granting procedures were unpractical and uneconomical for geothermal development. The revised Mining Act of 2023 takes care of this (Fig. 19.13) and, in addition, geothermal applicants will need to prove that there is a demand for heat in the application area through indicative heat offtake arrangements.

Future outlook

The so-called Masterplan Geothermal Energy (Stichting Platform Geothermie et al., 2018) outlines a number of bottlenecks in the development of the sector. It also lists innovations for the benefit of risk reduction, safety, optimization of the geothermal value chain, increasing the effectiveness of geothermal projects and cost reduction. Future research activities are likely to address topics in these areas. One focus area is the standardization of, amongst others, the design of wells, surface systems materials, and reporting. Second focus area is technical innovation, execution of which demands that funds are made available, The Netherlands Enterprise Agency (RVO) subsidizes innovation projects in the applied technical domain through subsidies. Next to these national funds there are numerous European Union calls for innovative research and demonstration projects with an international (EU) component. The list of innovation possibilities is almost endless; a number of spearhead innovation domains are described below.

The Koekoekspolder geothermal system

The Koekoekspolder geothermal system is one of the first systems developed in the Netherlands. The wells of the doublet were drilled in 2011 and production started in 2012. The doublet comprises a production and injection well and the surface installation comprising the heat exchanger. The geothermal heat is carried by water from the reservoir at 1950 m depth to the surface via the production well. After extracting the heat in the heat exchanger, the cooled-down formation water is re-injected via the injection well into the same reservoir, but at a distance of approximately 1500 m from the producer. In the first ten years the system produced more than 1,600,000 GJ of geothermal heat, the equivalent of 50 million cubic metres of natural gas. The produced heat directly feeds into a cluster of greenhouses where tomatoes, cucumbers, peppers, strawberries and more flourish on the geothermal heat.

The oblique aerial photo shows the facilities and greenhouse complex in a green rural area in the close vicinity of the towns of IJsselmuiden and Kampen. The present-day temperate coastal climate contrasts sharply with the paleo-environment in which the reservoir sediments were deposited. At the time of deposition of these sediments, some 258 million years ago during the Permian period, the area was part of an extensive desert, somewhat like the present-day Sahara. Sand was blown in from the northeast, forming extensive sand sheets which in time were stacked on top of each other ultimately forming the about 100 m-thick Upper Slochteren Member reservoir.

The reservoir productivity and injectivity is moderate, yet in the past production years the injectivity increased, resulting in better performance. The doublet yields a yearly heat production of up to 0.18 PJ. The success of this project and an increased local heat demand warranted the extension of the doublet to a triplet configuration. The photo shows the rig drilling of the third well in 2022, to boost future production and add heat to the future energy mix of this horticultural region.

Photo courtesy of R. Vorage.

Reduction of pre-drill mining risk

To ramp up the deployment of geothermal resources, it has long been considered that the Netherlands stood to benefit effectively from the wealth of existing oil and gas data (worth over 50 billion euros in terms of original acquisition costs), combined with common practice methodologies from extensive R&D and industrial experience (Van Wees et al., 2012, 2017). However, in recent years it has become apparent that such an approach is significantly less than optimal. This conclusion relates largely to the following pre-drill stage challenges:

Data-poor areas: Geothermal operations in the Netherlands have been developed primarily in two areas from reservoirs that have been well-characterized from previous conventional geo-resource (mostly oil and gas) exploitation. To meet the targets of the Dutch Climate Agreement (Klimaatakkoord, 2019), however, the existing resource base needs to be extended to areas where the data density is relatively low, and/or where existing information indicates that reservoirs are not suitable for sustainable oil and gas production, but which may be suitable for geothermal production. In order to decrease the uncertainty and exploration risk, data resolution needs to be enhanced by reprocessing existing data and the acquisition of new data (SCAN data acquisition programme). In addition, unconventional geothermal resources in lithologies and at depth levels not so far studied in detail need to be considered, including Ultra Deep Geothermal (UDG) resources at a depth range of 4-8 km.

Unknown/less-known specific properties and processes: Geothermal energy exploitation involves knowledge of rock properties and reservoir processes that may be different from those relevant for conventional oil and gas exploitation. Such properties and processes relate, for instance, to diagenetic transformation of reservoir properties during geological history, to in-situ stress conditions and thermo-mechanical properties essential to the establishment of stress changes related to cooling that may have an impact on safety. Predictions of the lateral variability of properties (i.e. porosity, permeability, geochemical, mechanical, thermal etc) can benefit considerably from high resolution understanding of structural and sedimentation processes and the link with external forcing factors (e.g. tectonics, climate) at the time of deposition.

The play-based portfolio approach for unlocking Dutch geothermal energy (Van Wees et al., 2020) has facilitated the development of various nationally funded Public-Private Partnerships for the investigation of data-poor areas. One example is the MEACP funded SCAN project (SCAN, 2024) that focuses on reprocessing of vintage seismic data, acquisition of 2D reflection seismic lines and, drilling of ~10 scientific wells in an exploration campaign. Other examples include the LEAN project (discontinued) that aimed at developing the data-poor Utrecht area, the Ultra Deep Geothermal Project (UDG, 2018) and the EU funded DGE-rollout project which targets the lower Carboniferous Dinantian reservoir (DGE-Rollout, 2024). These efforts will greatly improve regional subsurface resolution and information in data-poor areas, create extensive new datasets, know-how and provide the basis for an active and lively research and development collaboration.

Induced seismicity

One of the hazards associated with altering the subsurface pressure or temperatures during subsurface mining activities (see section on induced seismicity and seal failure) is induced seismicity. Induced seismicity related to gas production is a prominent issue in the societal and policy domain. With the type of geothermal systems and plays in the Netherlands (predominantly matrix permeable reservoirs) the hazard and risks are, for now regarded as very low outside naturally or induced pre-stressed areas. However, to reduce the risks further a Seismic Hazard and Risk Analysis (SHRA) is prescribed prior to drilling and operation, together with a fit for purpose seismic monitoring and response (M&R) system. Periodic review and update of the SHRA and M&R systems is required, based on the data and experiences in the field, coupled with scientific progress in the field of understanding and modelling seismicity.

Enhancing technical and environmental performance

Heat demand is sometimes located in places where due to poor flow performance known reservoirs cannot be developed by conventional techniques, (so-called marginal reservoirs). In addition, there is growing concern related to environmental safety and sustainability of geothermal developments, for instance where induced seismicity may result in early suspension or failure of system performance. For such situations alternative development approaches to deliver affordable energy need to be explored. At the same time there is a need to augment the environmental robustness of the development strategy in the face of pre-drill uncertainty of in-situ stress and fluid chemistry. The WarmingUP programme (19 million euros), part of the Multiple-year Mission-driven Innovation Program (MMIP) and the EU cofunded Geothermica project RESULT (NL budget 12 million euros) are focused on these subjects.

Alternative well designs

The productivity/injectivity of a well is directly related to the in- or out-flow surface area of the well-reservoir interface. In conventional wells this is the surface area of the borehole cylinder through the reservoir; the larger the better. To increase the inflow area, wells can be deviated to horizontal well trajectories through the reservoir. Another option is to drill multi-laterals or horizontal wells, a technique used extensively in the oil and gas industry and which potentially can be implemented in geothermal drilling (Ungemach et al., 2019). Similarly, the well-reservoir interface can be increased by stimulating the reservoir (see next section) or alternatively by radial jetting (Den Boogert, 2018; Reinsch et al., 2021). Implementation of these techniques varies from being already in execution to the design phase of a demonstration project, such as planned in the European Geothermica project RESULT.

Stimulation

The pressure required to drive flow in the reservoir is largely dependent on the permeability in the near vicinity of the wellbore, which can be improved by hydraulic or chemical stimulation (Gaucher et al., 2015; Maurer et al., 2020). Hydraulic and chemical stimulation has been proven successful in enhancing the technical performance of geothermal production systems in fractured reservoirs (Wassing et al., 2014, 2021; Gaucher et al., 2015; Maurer et al., 2020), but it also increases the risk of induced seismicity, which may result in a suspension or abortion of the development (e.g. Häring et al., 2008). In the Netherlands, neither hydraulic nor extensive chemical stimulation has been pursued yet.

Table 19.2. Definitions pertaining to geothermal resources used in this paper.

Term	Definition / Description
Geothermal power	The 'installed' or 'nameplate' capacity of a geothermal system. Power has the dimension of Watt (W) or Joule per second (J/s) and is generally reported in terms of MegaWatt (MW).
Geothermal play	A geothermal play can be defined as the area where a certain type of geothermal reservoir is present which can be described and evaluated in a uniform and reproducible manner and where data and knowledge is acquired that can be used to evaluate geothermal prospects in the same play resulting in reduction of the 'exploration' uncertainty of that prospect. Within the Netherlands two play types can be defined using the dominant permeability system as diagnostic criterium: - The dominant play is the matrix permeability dominated 'Hot Sedimentary Aquifer', 'Hydrothermal' or 'Intra-cratonic Conductive play' (Mijnlieff 2020). - The fault/fracture permeability dominated 'Hot Sedimentary Aquifer', 'Hydrothermal' or 'Intra-cratonic Conductive play'.
Geothermal project	A project is a defined development or geothermal operation which provides the basis for economic evaluation and decision-making. In the early stages of evaluation, including exploration, the project might be defined only in conceptual terms, whereas more mature projects will be defined in significant detail. A geothermal project comprises one or more geothermal systems. It is a term with an economic connotation; generally an incentive to harvest geothermal heat from the subsurface through one or more geothermal systems linked to a company policy decision and related investment decision.
Geothermal field	"A geothermal field in the 'Hot Sedimentary Aquifer play' is defined as a distinct (mappable) subsurface area where a porous and permeable reservoir is present bounded at top and base by an impermeable interval (seal/aquitard) and is laterally bounded by impermeable zones like reservoir pinch-outs or faults with adequate off-set. Essentially, it would be a subsurface domain in which there is sufficient pressure communication and if exploited with multiple geothermal systems these systems would interfere with each other in a positive or negative manner" (from Mijnlieff, 2020).
Geothermal system	"The geothermal system is the link between the geothermal source, the amount of heat in the ground, and the geothermal resource, the amount of heat which can be delivered to the user. In the Dutch context, most geothermal systems to date are doublets but at status date 1-1-2022 also some triplets are operational. A doublet consists of a production and injection well, both completed in the same reservoir (the geothermal source) at a subsurface distance of up to 1.5 km (Figure 19.8). At surface the two wells are linked via a heat-exchanger, which captures the heat, the geothermal product, from the primary, salt water loop and transfers it to the secondary, fresh water loop." (adapted from Mijnlieff, 2020). The triplets have one production well and two injection wells.
Geothermal Energy Resources (UNFC 2016)	Geothermal Energy Resources are the cumulative quantities of Geothermal Energy Products that will be extracted from the Geothermal Energy Source, from the Effective Date of the evaluation forward, measured or evaluated at the Reference Point. Quantity of energy in the form of heat which are typically reported in Joule (J) or kiloWatt hours (kWh).
Geothermal Energy Source (UNFC 2016)	In the geothermal context, the Renewable Energy Source is the thermal energy contained in a body of rock, sediment and/or soil, including any contained fluids, that is available for extraction and conversion into energy products. This source is termed the Geothermal Energy Source and is equivalent to the terms 'deposit' or 'accumulation' used for solid minerals and fossil fuels. The Geothermal Energy Source results from any influx to, outflux from or internal generation of energy within the system over a specified period of time.

Closed loop systems

The present geothermal systems in the Netherlands are typically open systems, in which the working fluid, the geothermal water, is extracted from one well and injected in another well in the same deep reservoir flowing in the subsurface through a permeable rock. Closed systems are gaining interest as they do not interact directly with the subsurface. In general, closed loop systems are a development option for non-permeable, tight rock at any depth and/or at shallower depth where interference with groundwater is to be avoided. In a closed loop system the working fluid (energy carrier) remains in the well, and heat transfer is by conduction only, as is the method of choice for shallow Borehole Thermal Energy Systems (BTES). Deep closed loop systems have also been developed as workovers for deep (hydrocarbon) boreholes, marked by a coaxial design (Kohl et al., 2002). Although the performance for such a coaxial system is significantly lower than for a doublet in some cases it may be an attractive alternative to the abandonment of wells (Lokhorst & Van Wees, 2005). Alternatively, the subsurface heat exchanger design in a closed loop system can be significantly enhanced by one or multiple connecting laterals (Holmes et al., 2021). In 2019 a pilot project in Canada by EAVOR technically proved the concept (TNO, 2021), and economic economic feasibility is under investigation.

High temperature heat storage

High temperature heat storage in a relatively shallow reservoir (in the interval between 200 and approximately 1000 m depth) is a new technique for the Netherlands. This technique is well suited for balancing the swing in winter-summer heat demand. As such it can increase the applicability and thus potential of geothermal in especially the built environment.

Metal harvesting from geothermal fluid

The geothermal production water contains metal ions that are often of high value. For example, lithium is present in most geothermal brines in the Netherlands in low concentrations of some tens of milligrams per litre. Worldwide tests have been performed to extract lithium from geothermal brines but none has yet evolved to a sustainable commercial development. With the high demand for lithium for batteries, renewed interest in lithium extraction from geothermal brine has stimulated various research projects, amongst which the European funded EuGeLi project (EuGeLi, 2019). In this project battery-grade, lithium carbonates were produced from geothermal brines from the Soultz-sous-Forêts geothermal plant in France (Jungmann et al., 2025).

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28164332.

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