WP5

Outlook for the Netherlands

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TKI URBAN ENERGY
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Executive summary

The most important subsurface criteria for Eavor-Loop placement, as defined by Eavor in the current project, include a minimum temperature of 110 °C, a maximum depth of 4500 meter, and a minimum thermal conductivity of 2.5 W/mK. These criteria were applied to the Dutch aquifer model available through www.thermogis.nl which is based on the DGM Deep v5 geological model of TNO, a 3D subsurface temperature model, and the Dutch national fault database. The ThermoGIS spatial model contains information about the depth, thickness, porosity, permeability and temperature of aquifers between Carboniferous and Paleocene age.

Sandstone is the most favourable rock type due to its thermal conductivity and strength, while shale, marl and rock salt are unfavourable. Data about thermal rock properties is scarce. Therefore, mostly handbook values are used. High quality 3D seismic data required for accurately determining the rock layer depth and thickness is mostly available in the northern and southwestern parts of the Netherlands. In other areas the quality and density of the available 2D seismic coverage varies.

The most promising rock units are the Permian Rotliegend, and the Lower and Upper Germanic Trias. These units meet the requirements primarily in the West Netherlands Basin and the Roer Valley Graben, the Lauwerszee Trough and the Lower Saxony Basin. Older units like Carboniferous Limestone and Devonian rocks may also be suitable, but information about them is limited.

A lower temperature constraint increases the area suitable for the Eavor-Loop, but it does not open up entirely new areas or formations.

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1. Introduction

A short study was conducted in which the most relevant subsurface conditions were checked against the Eavor-Loop placement criteria provided by Eavor with the aim of determining the subsurface potential, i.e. prospective layers and areas, in the Netherlands. The studied subsurface parameters, list in the Eavor-Loop placement criteria (see Appendix A), were:

- Temperature gradient minimum 30 °C/km
- Formation minimum temperature minimum 110 °C
- Depth maximum 4500 meter
- Thickness minimum 30 meter

Most of the rock characteristics are a function of the formation and do not vary very much across the country. That makes it possible to focus on formations that are suitable based on the following characteristics:

- Rock thermal conductivity minimum 2.5 W.mK
- Hole stability
- Drillability (abrasiveness/UCS)

From an initial screening, the most prolific rocks were Triassic and Permian sandstones and possibly Carboniferous siltstones and Dinantian carbonates.

Characteristics that are considered to vary locally and can therefore not be studied using national scale databases, and characteristics for which no data were available include:

- Layer dip angle
- Stress data
- Faulting (parallel and crossing, defining layer continuity and maximum possible lateral length).

The provided conditions for the placement of an Eavor-Loop resulted from the feasibility study for the placement of an Eavor-Loop in the Tilburg area. Current technology and cost were used to assess the economic feasibility. Relative costs are expected to come down and, with that, it may become economic to consider shallower horizons for which a lower minimum temperature of 90 °C was used.

2. Data

For the analysis various datasets available at TNO were used. They include:

- Deep Digitial Geological Model (DGM Deep) v5
- 3D Temperature model
- ThermoGIS
- Rock property data
- Fault database

2.1. DGM Deep v5

The Digital Geological Model (DGM[1]) Deep v5 is a geological layer model of the Dutch subsurface. It is based on seismic interpretation of 3D and 2D data (Figure 1). The layer depths have been calibrated using well data. Figure 1 shows that onshore in the northeast (Groningen, Friesland, Drente), and west (North Holland, South Holland, western North Brabant) 3D seismic is available. In other parts of the onshore Netherlands 2D data is available but the quality and spacing varies. Within the SCAN Aardwarmte project[2] several hundreds of kilometers of high quality 2D seismic data was acquired between 2019 and 2022 in areas where the data density is low and/or the geological uncertainty large. The SCAN seismic will be used to update DGM Deep in the coming years.

The current DGM Deep v5 model contains maps of the top and thickness of 13 main lithostratigraphic units ('Groups[3]'). Lithostratigraphy is a way of subdividing the rocks in the subsurface using common properties like age and rock type ('lithology'). The highest level is the Group level, lower hierarchical levels are Formations and Members. The lower the level, the more homogeneous the units become. The lithological (rock) content of the highest-level Groups is heterogenous. All may contain different rock types like sandstone, shale and salt layers etc. Some rock types are more attractive for heat production than others. Figure 2 shows a cross section through the model between Terneuzen in the southwest and Delfzijl in the northeast. It is clear that different layers are present at different depths along the cross section. This implies that the depth at which prospective rocks are found varies throughout the country. The rocks belonging to the Carboniferous Limestone Group, the Rotliegend Group and the Lower Germanic Trias Group were previously identified as targets for the Eavor-Loop.

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[1] http://www.nlog.nl/en/dgm-deep-v5-and-offshore

[2] http://www.scanaardwarmte.nl

[3] http://www.dinoloket.nl/en/stratigraphic-nomenclature/via-diagram/group-by-age

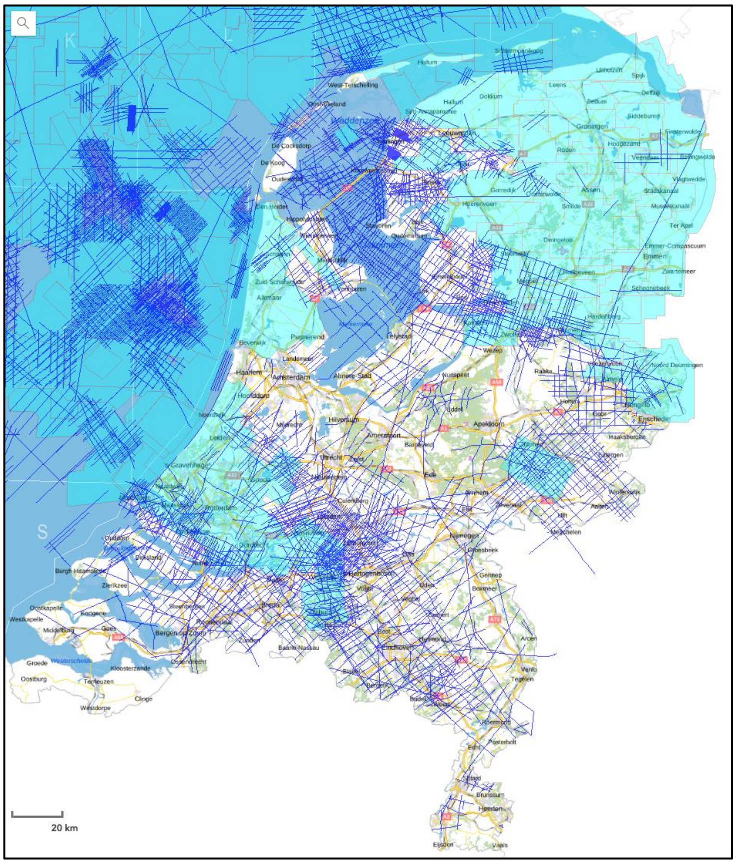

Figure 1 3D and 2D (digital) seismic coverage of the Netherlands. Source: www.nlog.nl

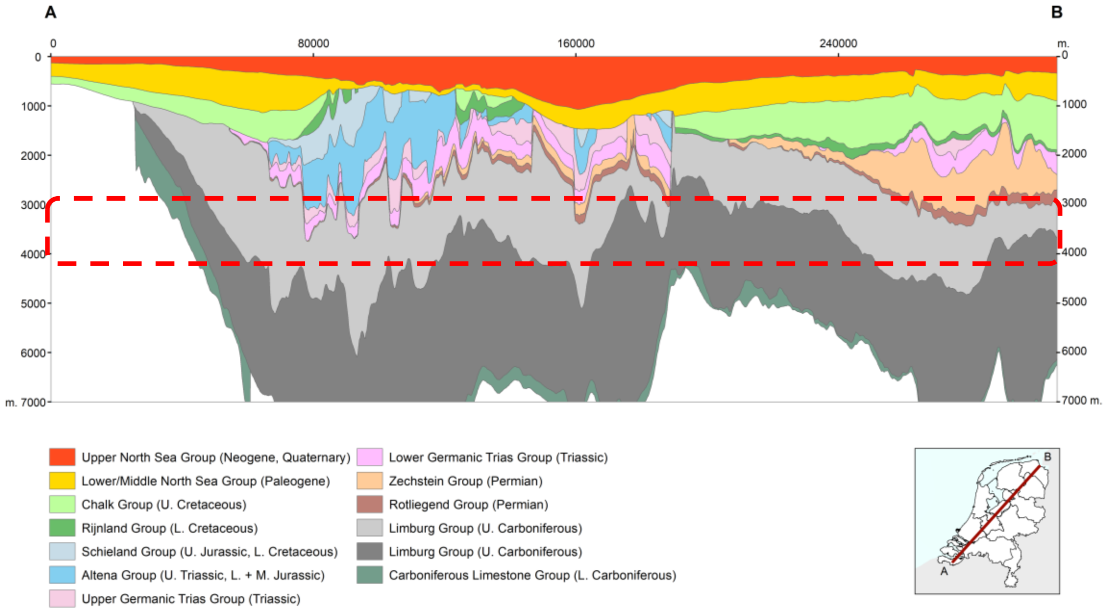

Figure 2 Cross section through the Netherlands based on DGM Deep v5 showing 13 lithostratigraphic units. The dashed box is the approximate target area based on minimum temperature and maximum allowed drilling depth.

2.2. 3D Temperature model

A 3D temperature model of the subsurface is developed by TNO (Békési et al. (2020); Bonté et al. (2012); Gies et al. (2021); Veldkamp & Hegen (2020)). The model consists of a 3D grid with cells measuring 1000x1000x200 meter. Each cell contains a temperature estimate as well as the main lithostratigraphic unit and bulk thermal conductivity. The model is based on a forward heatflow model in which a temperature is calculated for each cell by solving the heat equation using estimates of the lithological composition and thermal rock properties of each cell (based on DGM Deep), lower and upper temperature boundary conditions and data on heatflow and authigenic heat production. The prior temperature estimate is then calibrated to a database of subsurface temperature measurements using an Ensemble Smoother with Multiple Data Assimilation (ES-MDA). In this stage, the prior thermal rock properties thermal conductivity and authigenic heat production are iteratively adapted within set boundaries in order to obtain a better fit between the calculated and measured temperatures.

Given an average geothermal gradient of slightly more than 30 °C/km and an average surface temperature of approximately 10 °C (Békési et al. (2020); Bonté et al. (2012)), the target depth for the Eavor-Loop is deeper than 3 kilometers. At this depth, in large parts of the Netherlands, rocks belonging to the Upper Carboniferous Limburg Group are found (light grey colour in Figure 2, Westphalian, and dark grey, Namurian). This unit consists primarily of shale and coal seams, but also sandstone layers are present.

2.3. ThermoGIS v2.2

ThermoGIS[4] is a geothermal potential tool for the Netherlands, developed by TNO. It is based on DGM Deep v5 and the 3D temperature model described above. In addition, it also contains the depth and thickness of the sandstone aquifers that are present within the DGM Deep v5 groups. It is therefore more detailed than DGM Deep v5. Apart from depth and thickness, ThermoGIS also contains porosity and permeability maps for all aquifers. The maps are interpolated from porosity and permeability measurements on rock samples, on petrophysical evaluations on deep drillings, and on well test results.

2.4. Rock property data

The loop placement criteria of Appendix A state that the porosity and permeability should be low, and the thermal conductivity at least 2.5 W/mK.

Porosity and permeability data are available through ThermoGIS (see above). At depths required to reach a temperature of ~110 °C the expected porosity and permeability are usually low.

Little information is available about the thermal properties of the rocks encountered in the Dutch subsurface. Figure 3 shows for the main occurring rock types the range (min-average-max) of the vertical thermal conductivities presented by Hantschel & Kauerauf (2009). The range is determined by various types within the main rock types, such as (for sandstone) clay-rich, clay-poor, and various types of quartzites, arkoses, wackes etc. Figure 3 suggests that shale, and to a lesser extent limestone and chalk are less suitable than sandstone and dolomite. Shale is also unfavourable because of its rock strength. Salt has a very high thermal conductivity but is not suitable because of its mechanical and chemical properties. The observations from Hantschel & Kauerauf (2009) are confirmed by data from Fuchs et al. (2015) shown in Figure 4 from a deep well in Hannover. The lithologies encountered in this borehole may be considered comparable to those found in the Netherlands. The very low thermal conductivities (TC) down to 1335m are Cretaceous chalk. Between 1335 and 2375 rocks of Jurassic

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[4] http://www.thermogis.nl

age are found, also mostly limestone. Between varying lithologies are found (gypsum, sandstone, marl, evaporites). The high thermal conductivity values deeper than 2800m are Muschelkalk and Buntsandstein.

Dalby (2018) measured thermal conductivities on core samples of various Dutch rock types. Table 1 shows the results of the measurements. All thermal conductivities are above the threshold of 2.5 W/mK with the exception of those measured on rock belonging to the Lower North Sea Group (NL).

It should be noted that the thermal conductivity depends on temperature (Figure 5). Usually, reported rock thermal conductivities are valid for ambient temperatures. For higher temperatures the thermal conductivity is lower. Between ambient temperatures and 100 °C the decrease is around 20-25% for limestones and dolomite.

The bulk thermal conductivity is a combination of the thermal conductivity of the rock itself and the brine inside the pores. Water has a low thermal conductivity; therefore high porosity rocks have lower bulk thermal conductivities (Figure 6). Deeply buried rocks – required to reach the minimum temperature ~110 °C – generally have a low porosity (for the Rotliegend, for instance, the average porosity decreases from ~16% @2000m to ~10% @4000m (source: www.ThermoGIS.nl). Hence, deeply buried quartz sandstones like those belonging to the Triassic Bunter and the Rotliegend are likely to have a bulk thermal conductivity above the threshold of 2.5 W.mK.

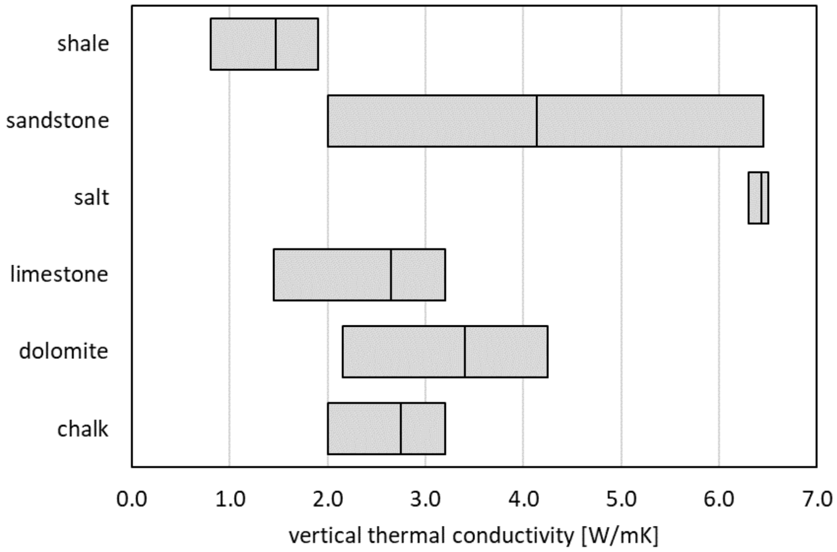

Figure 3 Vertical thermal conductivity value ranges for common rock types (min-average-max). Source: Hantschel & Kauerauf (2009)

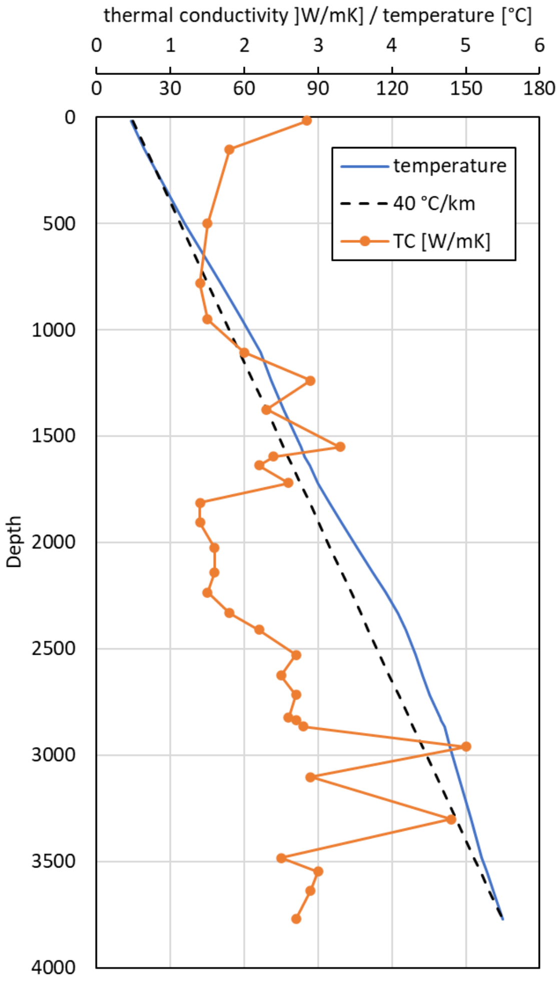

Figure 4 Mean bulk thermal conductivity values from the Gross Buchholz GT1 borehole having rock types comparable to those in the Netherlands. Data: table 4 from Fuchs et al. (2015)

Table 1 Thermal conductivities averaged by lithostratigraphic group. Source: Dalby (2018)

Stratigraphic group	**Average horizontal thermal conductivity [W/mK**	**Average vertical thermal conductivity [W/mK**	**N**	**Main lithology**
NL Lower North Sea	2.20	1.96	1	
CK Chalk	2.99	2.79	2	Chalk
KN Rijnland	3.98	3.54	2	Sandstone
RN Upper Germanic Trias	3.77	3.35	12	Sandstone
RB Lower Germanic Trias	4.07	3.47	15	Sandstone
ZE Zechstein	4.01	3.65	14	Anhydrite, carbonate
RO Rotliegend	3.33	2.97	2	Sandstone
DC Carboniferous	3.61	2.49	7	Shale
CL Carboniferous Limestone	2.90	2.45	2	Limestone

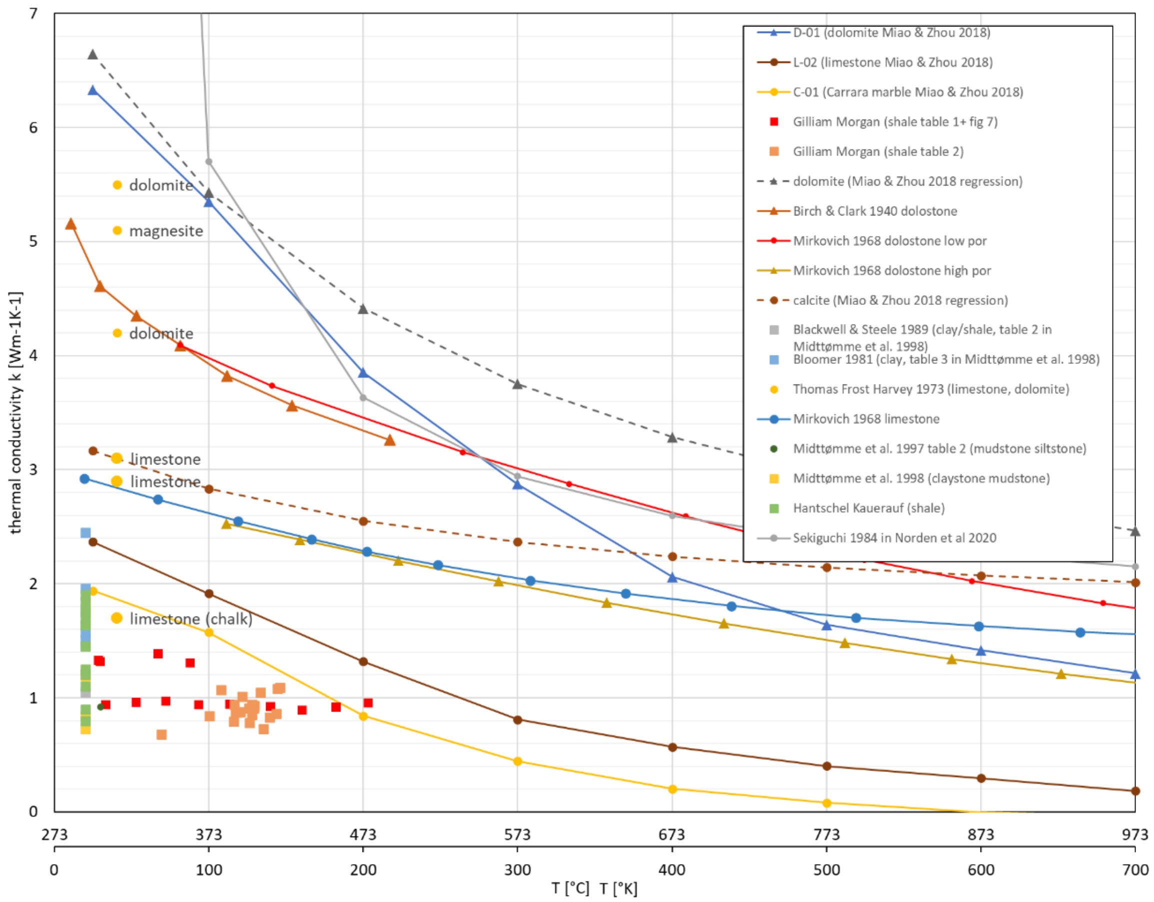

Figure 5 Thermal conductivity dependence on temperature for limestone, dolomite and shale.

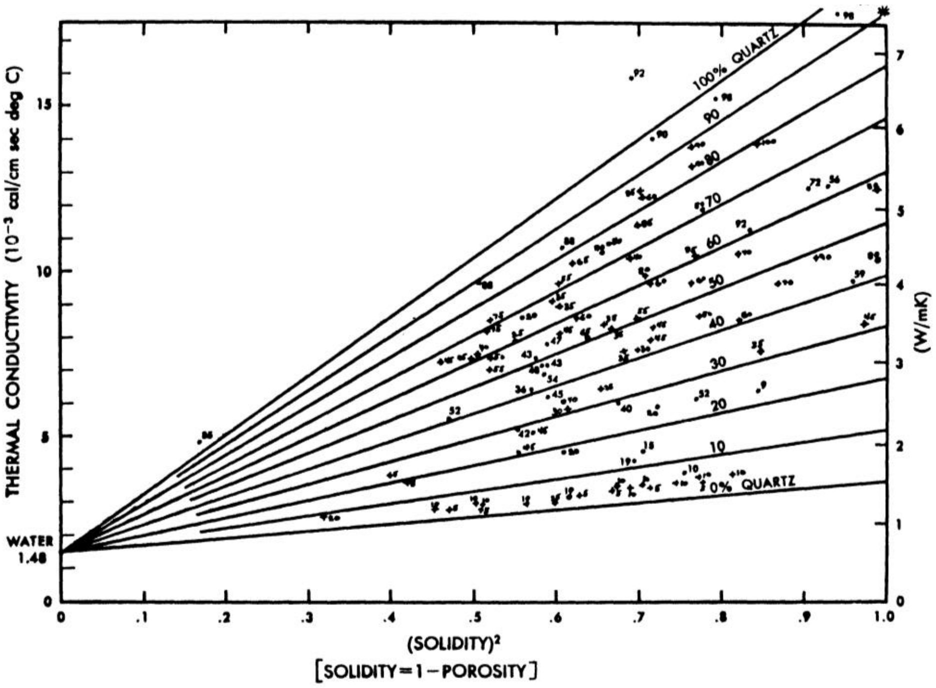

Figure 6 Thermal conductivity of sandstone with water in the pores showing dependency of porosity. Source: Robertson (1998).

2.5. Faults

In the GeoERA HIKE project[5] a fault database was generated. For the Netherlands, this database contains faults that were mapped on seismic during the construction of the DGM Deep model. For the Dutch part, each fault in this database contains information about the youngest and oldest layers ut by the fault, the fault type (normal, reverse etc.), timing of activity, length, dip angle, dip and strike, and the reference surface. For a single faults, intersection lines of the fault with all of the intersected layers at the top and bottom of the units are stored.

Because the faults were mapped on seismic, the level of detail is highest in those parts of the country where 3D seismic is available (Figure 1). Because the mapping is for regional modeling purposes, not all faults were mapped. Figure 15 shows the mapped faults for the four most promising rock units.

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[5] https://geoera.eu/projects/hike10/

3. Results

3.1. Screening using 3D temperature model

A first screening was performed on the 3D Temperature model. On the model, the temperature constraints of 110 (strict) and 90 °C (stretched) were applied as well as the maximum depth constraint. Figure 7 shows the grids, viewed from above and coloured by lithostratigraphic unit. All cells with a temperature lower than the constraint were removed. The figures therefore show the lithostratigraphy at the 110 and 90 °C isotherms. The image confirms the general impression of the cross section of Figure 2: at the depths where the temperature constraints are met, the most common stratigraphic unit is the Upper Carboniferous (depicted in grey). The 110 °C subcrop shows significantly more Carboniferous subcrop than the 90 °C one. Further observations include:

- Mainly in the South, Devonian and older rocks (depicted in brown) are present. These rocks are relatively unknown because very few wells reached this unit. In the wells of the Californië geothermal doublet near Venlo, this unit consists of tight quartz sandstone but otherwise its rock properties are unknown.
- The sea green unit is the Carboniferous Limestone from which the Californië doublets produced. These rocks have very low porosity (<1%) and also very low permeability. The geothermal production in Californië relies on fracture permeability.
- The Triassic is depicted in dark purple. In the southwest the Triassic mainly contains significant sandstone, but in the northeast the main lithology is shale.
- The small brown spots in the North are the Rotliegend sandstone.
- The pink subcrop in the north is the Zechstein, which consists mostly of rock salt.
- The blue unit in the South is the Altena Group which is mainly shale.
- The small green occurrences in the north belong to the Rijnland and Chalk Groups and are considered to consist mostly of shale.

The Eavor-Loop placement criteria emphasize the potential of the Carboniferous Limestones, and the Rotliegend and Bunter sandstones. Chalk, marl, shale and rock salt are considered less prospective. This means that, in the subsurface model, the largest part of the Upper Carboniferous (shale), the largest part of the Upper Germanic Trias (shale), the Zechstein (salt) the Altena (shale), the Rijnland and Chalk (shale), all present at both the 110 and 90 °C isotherms, should be discarded.

Figure 8 shows, for the same temperature constraints, the corresponding depth. The maximum allowed depth of 4500 meter (depicted in red) is not reached for the 90 °C case, and rarely for 110 °C. The required temperature can be reached at relatively shallow depth (<~2600m) in the southwestern part of the country (Zeeland province), the northern part of Limburg, and around the Lauwerszee, and also in eastern Gelderland and Overijssel.

Although the 3D temperature model provides a useful tool that enables large scale quick screening on temperature, depth and thermal conductivity, it has some drawbacks:

- The lithological content of the main lithostratigraphic units is heterogeneous. Therefore, the presence of a Group unit does not provide decisive information about the suitability of the rocks found at a location for the Eavor-Loop;
- The model lacks information on the thickness of sandstone layers;
- The thermal conductivities in the model are bulk conductivities valid for model cells measuring 1000x1000x200m. As most cells contain a mixture of suitable and unsuitable rocks of varying thermal conductivity, the resulting thermal conductivity is an average not representative of the individual rocks. For instance, a cell containing highly thermally conductive sandstone and low conductivity shale will have a low average thermal conductivity.

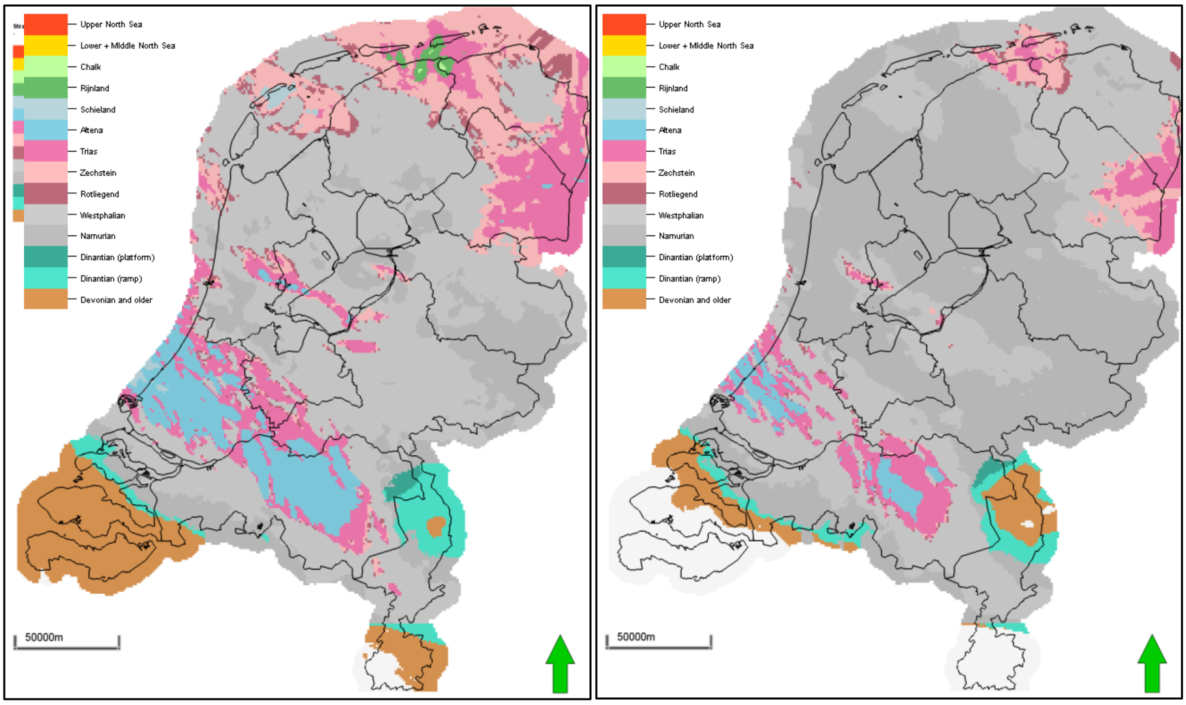


Figure 7 Subcrop of litho-stratigraphic units at the 90 °C (left) and 110 °C (right) isotherms.

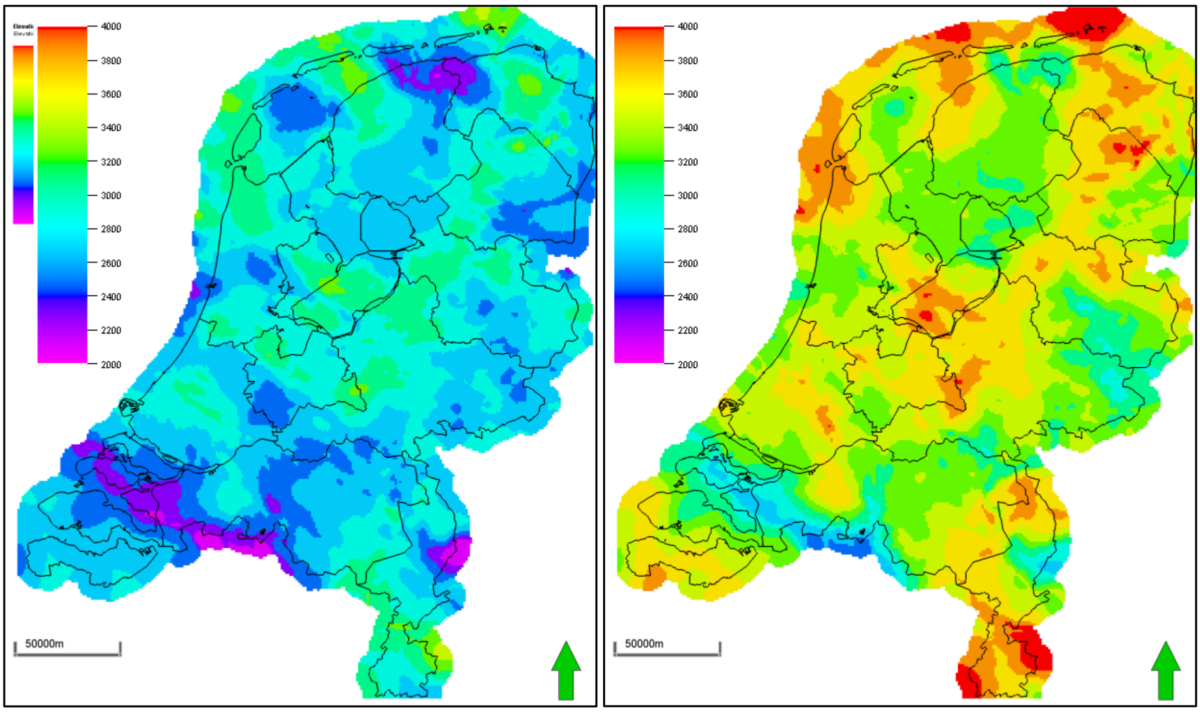


Figure 8 Depth of the 90 (left) and 110 °C (right) isotherms.

3.2. Screening using ThermoGIS

In order to overcome the drawbacks of the 3D temperature model, outlined in the previous paragraph, a second screening was done using the ThermoGIS depth, temperature and thickness data. Figure 12 and Figure 13 show the results of applying the strict (110 °C, 40 meters reservoir thickness and 4000 meters maximum thickness) and stretched (90 °C, 40m, 4000m) criteria per aquifer. Figure 14 shows two overview maps based on Figure 12 and Figure 13.

The following aquifers were studied:

- Upper Germanic Trias: Solling and Röt Fringe Sandstone
- Lower Germanic Trias: Hardegsen, Detfurth and Volpriehausen Sandstone
- Rotliegend: Upper and Lower Slochteren
- Upper Carboniferous: sandstones in the Hunze and Dinkel Subgroups

As mentioned above, various units like Zechstein, the largest part of the Upper Germanic Trias and the Altena, which also occur at depths with sufficient temperature and/or thickness were discarded because of their unfavourable rock types shale, marl, chalk and rock salt. Within the Zechstein various carbonate layers exist (ZEZ1C, ZEZ2C and ZEZ3C), some of which are gas bearing. They occur in a wide area over the Netherlands (Figure 10, limestones in light blue). Their average thickness is small, and they are embedded in rock salt and shales. This makes them less attractive for emplacement of the Eavor-Loop, and therefore they were excluded from further analysis.

Rocks older than the Upper Carboniferous such as the Dinantian limestones and those belonging to the Devonian may be interesting targets but there are several complicating issues:

- The burial depth often exceeds the maximum allowed depth (see left part of Figure 9, 4000 meter depth contour stippled)
- The thickness of the rock layers is largely unknown. This is indicated by the right-hand side of Figure 9. Whereas the top of the Dinantian can be idenfitief on seismic in a large part of the country, except for the northeast (3D seismic) and the south (shallow burial), the thickness of the Dinantian could only be identified on two long seismic lines, one in the offshore and one roughly running from Breda to Lelystad.
- The nature of the rocks is unknown. The Dinantian was drilled in only few boreholes in the Netherlands. Therefore, the rock type is known for specific parts of the Dinantian corresponding to carbonate ramps in the south and platforms in the north (Mozafari et al. (2019)). In between, the rock facies is probably basinal mudstones but this has not been proven.
- Rocks of the Dinantian and Devonian were drilled in two doublets near Venlo. They produced from a fault, but both have been shut down, one after the occurrence of a seismic event. This, and the fact that the depth at which the rocks are within reasonable drilling depth coincide roughly with a part of the Netherlands which has natural seismicity (Roer Valley Graben) makes them less attractive for geothermal production. This does not apply to the southwestern part of the Netherlands and the area north of Winterswijk.

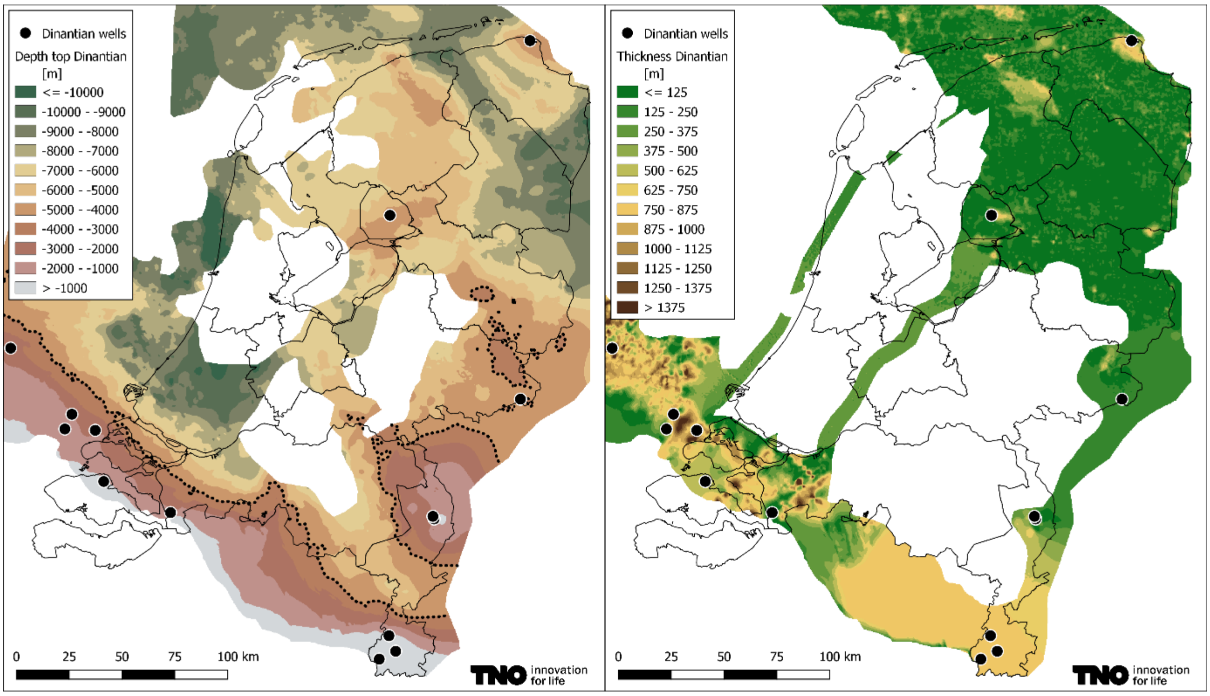


Figure 9 Depth of the top of the Dinantian. Dark green, cyan, blue and purple: Dinantian too deep. White areas: base of the Limburg Group not identified. Source: www.nlog.nl/scan

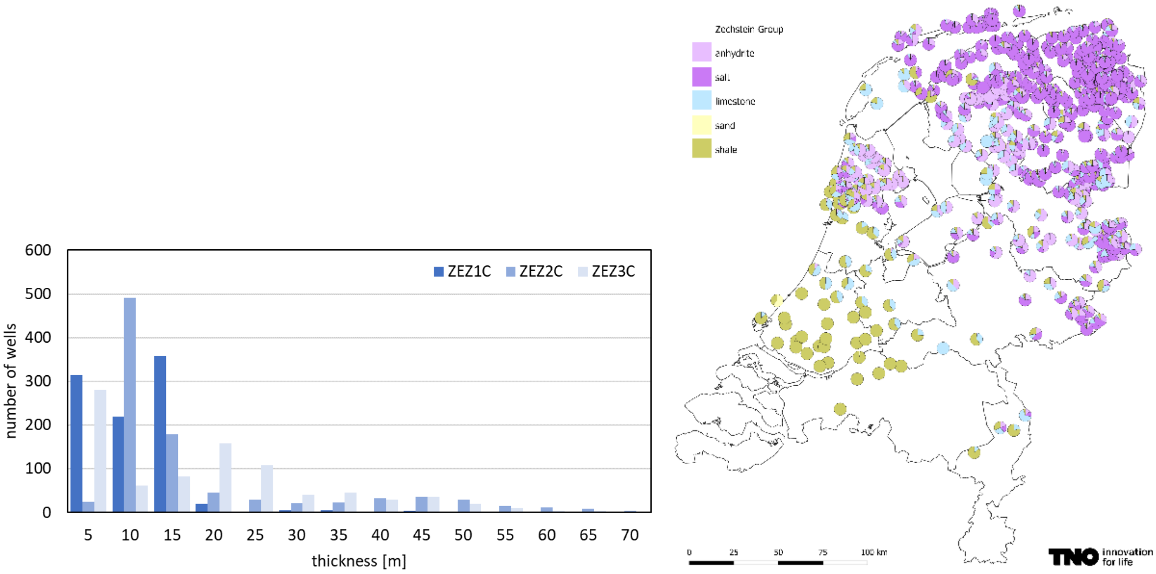


Figure 10 Frequency distribution of thickness of the various Zechstein carbonates in the Dutch onshore (left), and per well lithological composition (right). Source: www.NLOG.nl

The colour coding of Figure 12 and Figure 13 is as follows:

- All three criteria (temperature, depth, thickness) are met
- Blue to green: one criterium not met
- Yellow to orange: two criteria not met
- Red: none of the criteria met

The loop placement potential of the various lithostratigraphic units is determined to a large extent by the structural setting (see Figure 11 for locations and names of structural units). Potential is present in the West Netherlands Basin, the Roer Valley Graben, the Lower Saxony Basin and the Friesland Platform – Lauwerszee Trough – Groningen Platform areas, and possibly in the Gouwzee Trough located within the Central Netherlands Basin.

For the upper left map of Figure 12 this means for instance that although the Basal Solling Sandstone occurs over a large part of the Netherlands, it usually does not meet the temperature nor thickness criterium (orange colour). In the Roer Valley Graben (in North-Brabant) and West Netherlands Basin (South Holland) the formation is buried deeply, and therefore the temperature exceeds 110 °C, but the thickness is still insufficient (blue-green colour). Similarly, the occurrence of the Röt Fringe Sandstone is limited to the Roer Valley Graben and the West Netherlands Basin. Especially in the former region, temperature, thickness and depth are all within the set limits (dark blue colour). In general, the most promising areas are the Roer Valley Graben for the Röt Fringe, all Lower Germanic Trias units except the Nederweert Sandstone, and to a lesser extent the West Netherlands Basin for the same units. The Rotliegend stands out especially in the North aroung the Lauwerszee area. The Upper Carboniferous Dinkel and Hunze Sandstones are of interest in the West Netherlands Basin and the Lower Saxony Basin in the eastern parts of the provinces of Drenthe and Groningen. Here, several gas fields produce of have produced from this unit. The aquifer consists of fluvial sandstones, which means that the lateral extent may be limited and that the net-to-gross (i.e., the ration between sandstone and shale) is low. ThermoGIS estimates the N/G to be~50%. This means that the likelihood is large that an Eavor-Loop drilled in the sandstone will also encounter shale.

Compared to Figure 12 (strict), Figure 13 shows more potential for all units except the Basal Solling Sandstone and the Nederweert, mostly in the same areas as Figure 12. Especially for the Rotliegend, additional potential is indicated in the West Netherlands Basin. One should note that the Rotliegend potential in the northern part of the Netherlands does not account for the presence of the giant Groningen gas field, and other gas occurrences. Similary, gas is found in rocks of Triassic age on the southern edge of the Roer Valley Graben and the West Netherlands Basin.

Figure 14 is a combination of the individual aquifer maps of Figure 12 and Figure 13 where only those areas are indicated where all criteria are met for any of the aquifers. The map bears a close resemblance to the structural elements map of Figure 11.

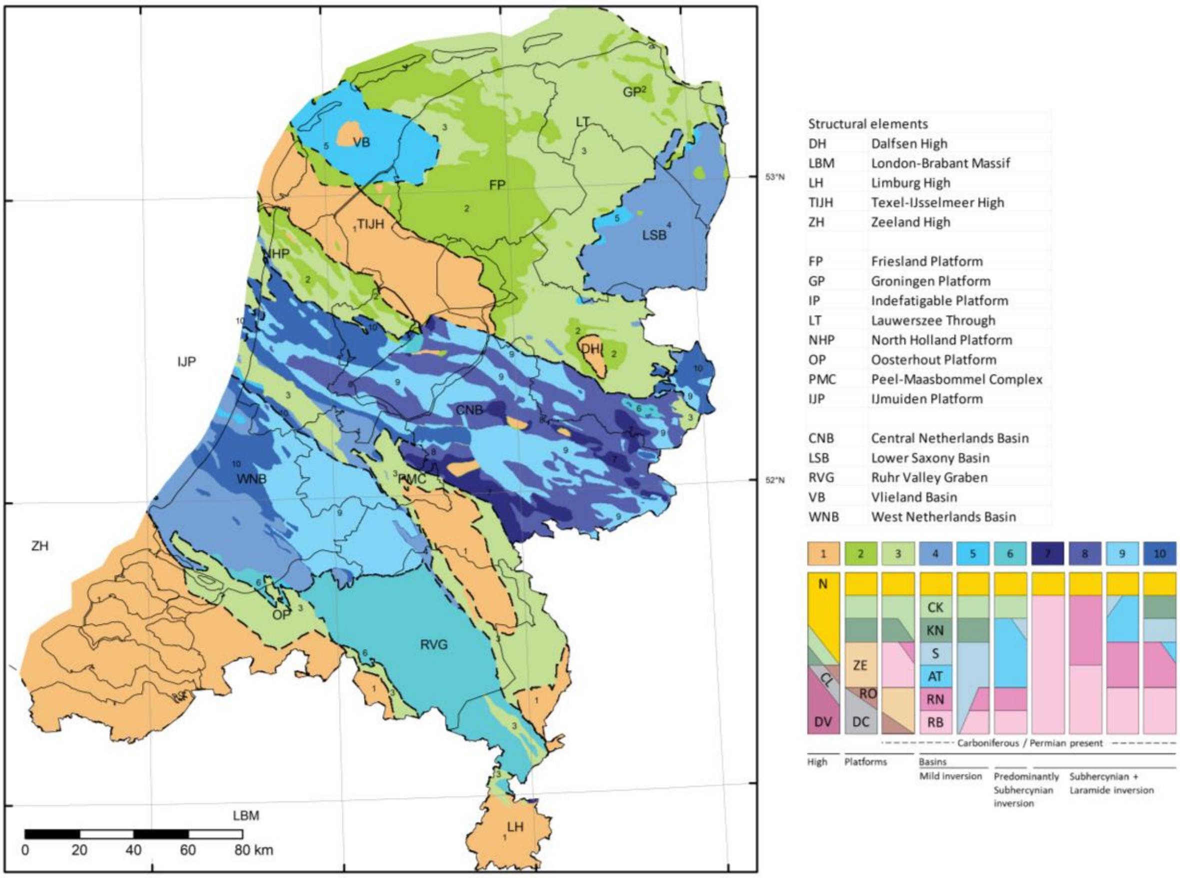
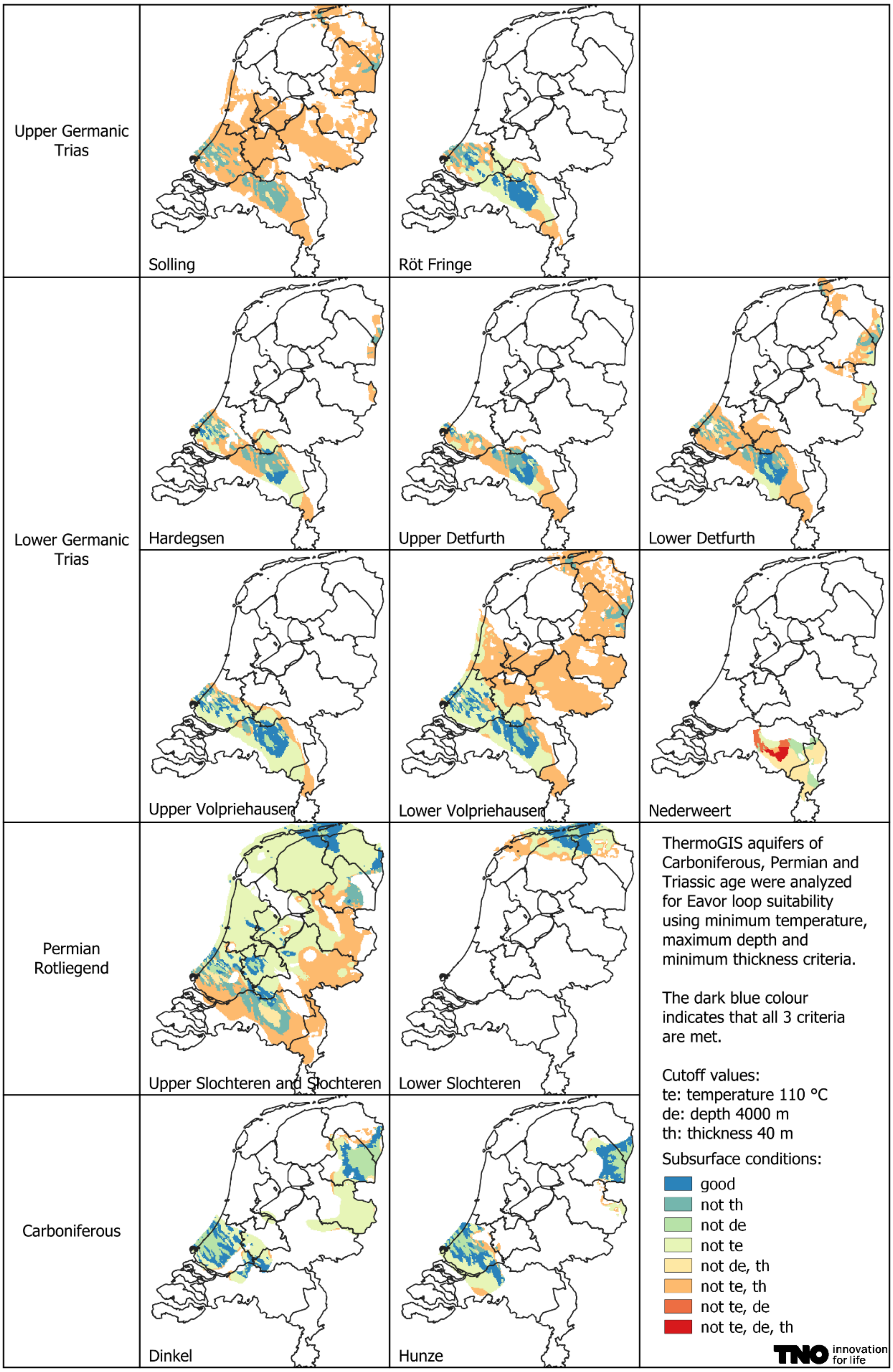


Figure 11 Structural elements of the Netherlands defined using typical lithostratigraphic successions. Source: updated after Kombrink et al. (2012) for DGM Deep v5.



ThermoGIS aquifers of Carboniferous, Permian and Triassic age were analyzed for Eavor loop suitability using minimum temperature, maximum depth and minimum thickness criteria.

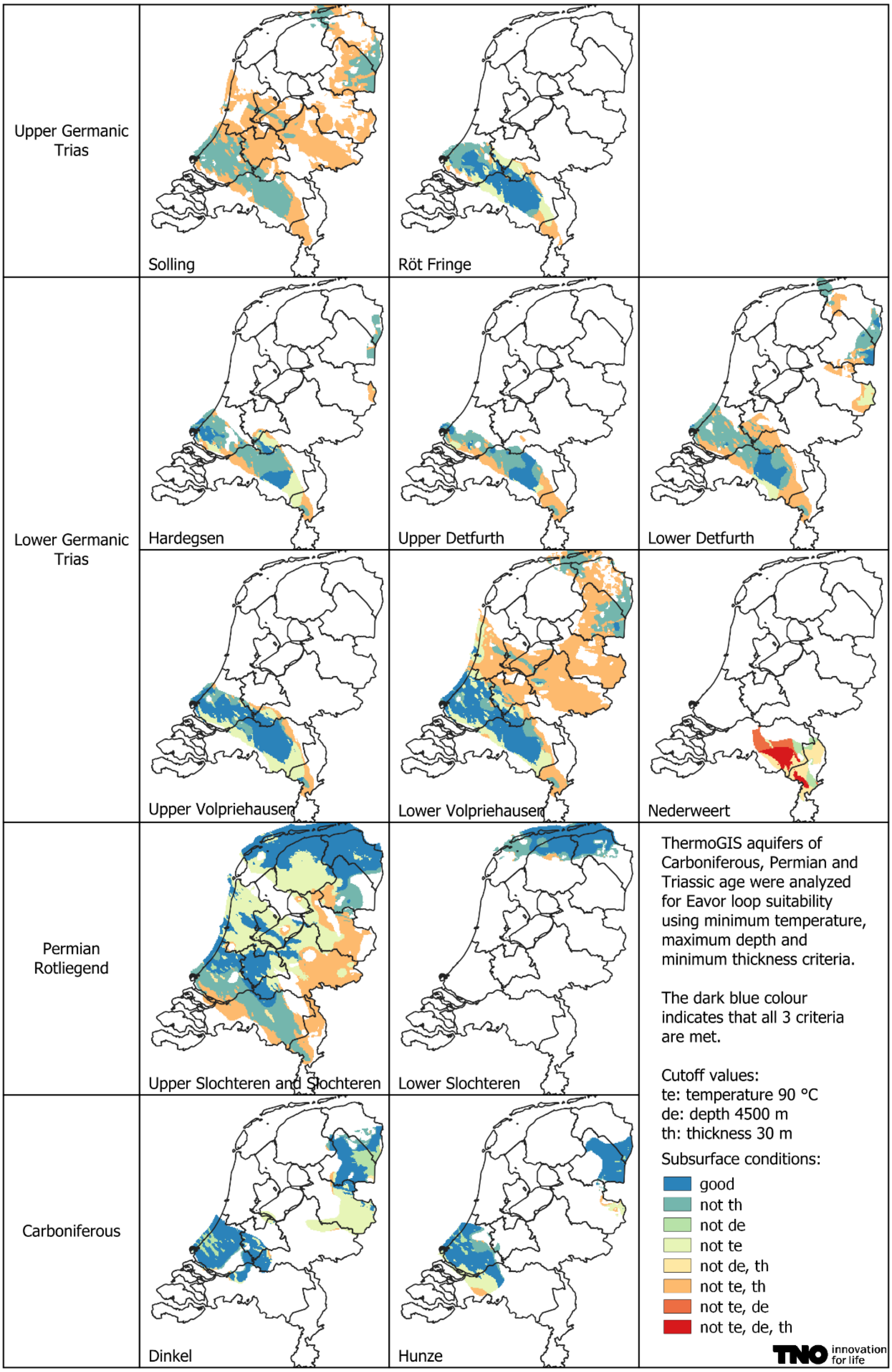
The dark blue colour indicates that all 3 criteria are met.

Cutoff values:
te: temperature 110 °C
de: depth 4000 m
th: thickness 40 m

Subsurface conditions:

- 🟦 good
- 🟦 not th
- 🟩 not de
- 🟩 not te
- 🟨 not de, th
- 🟧 not te, th
- 🟧 not te, de
- 🟥 not te, de, th

Figure 12 Subsurface potential per aquifer for Eavor-Loop based on strict criteria.



ThermoGIS aquifers of Carboniferous, Permian and Triassic age were analyzed for Eavor loop suitability using minimum temperature, maximum depth and minimum thickness criteria.

The dark blue colour indicates that all 3 criteria are met.

Cutoff values:
te: temperature 90 °C
de: depth 4500 m
th: thickness 30 m

Subsurface conditions:
- 🟦 good
- 🟩 not th
- 🟩 not de
- 🟨 not te
- 🟨 not de, th
- 🟧 not te, th
- 🟥 not te, de
- 🟥 not te, de, th

Figure 13 Subsurface potential per aquifer for Eavor-Loop based on stretched criteria.

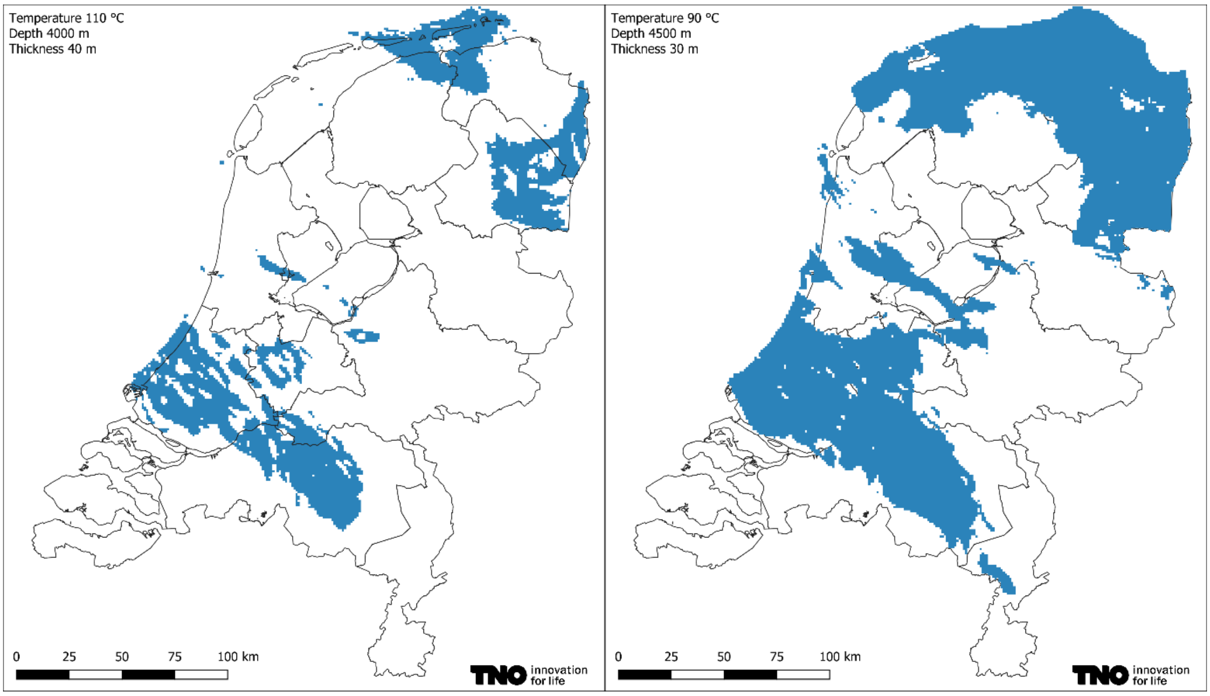


Figure 14 Potential for 'strict' (left) and 'stretched' (right) criteria. Note resemblance to structural elements shown in Figure 11.

3.3. Faults

Faults are important for the Eavor-Loop placement. Faults perpendicular to the loop may have offsets larger than the formation thickness, causing the drilling of unfavourable (instable) formations. For safety reasons the drilling should take place at least 100 meters from faults running parallel to the drilling.

Figure 15 shows the faults from the HIKE database for three of the four lithostratigraphic units that were evaluated. It is possible to identify faults extending down from the Zechstein and Rotliegend into the Carboniferous, but due to the nature of the rocks (shale) it is usually impossible to map them in the Carboniferous strata.

As mentioned in section 2.5, the faults were mapped for regional modeling purposes and therefore not all faults visible on seismic are present in the fault database. Also, the mapping is much more detailed where 3D seismic is available, compared to areas where only 2D seismic is available. Therefore, the maps of Figure 15 should be considered indicative only and used to identify the main fault directions on which the direction of the Eavor-Loop should be determined. A detailed local study based on available seismic data should provide definitive information about the presence of all faults.

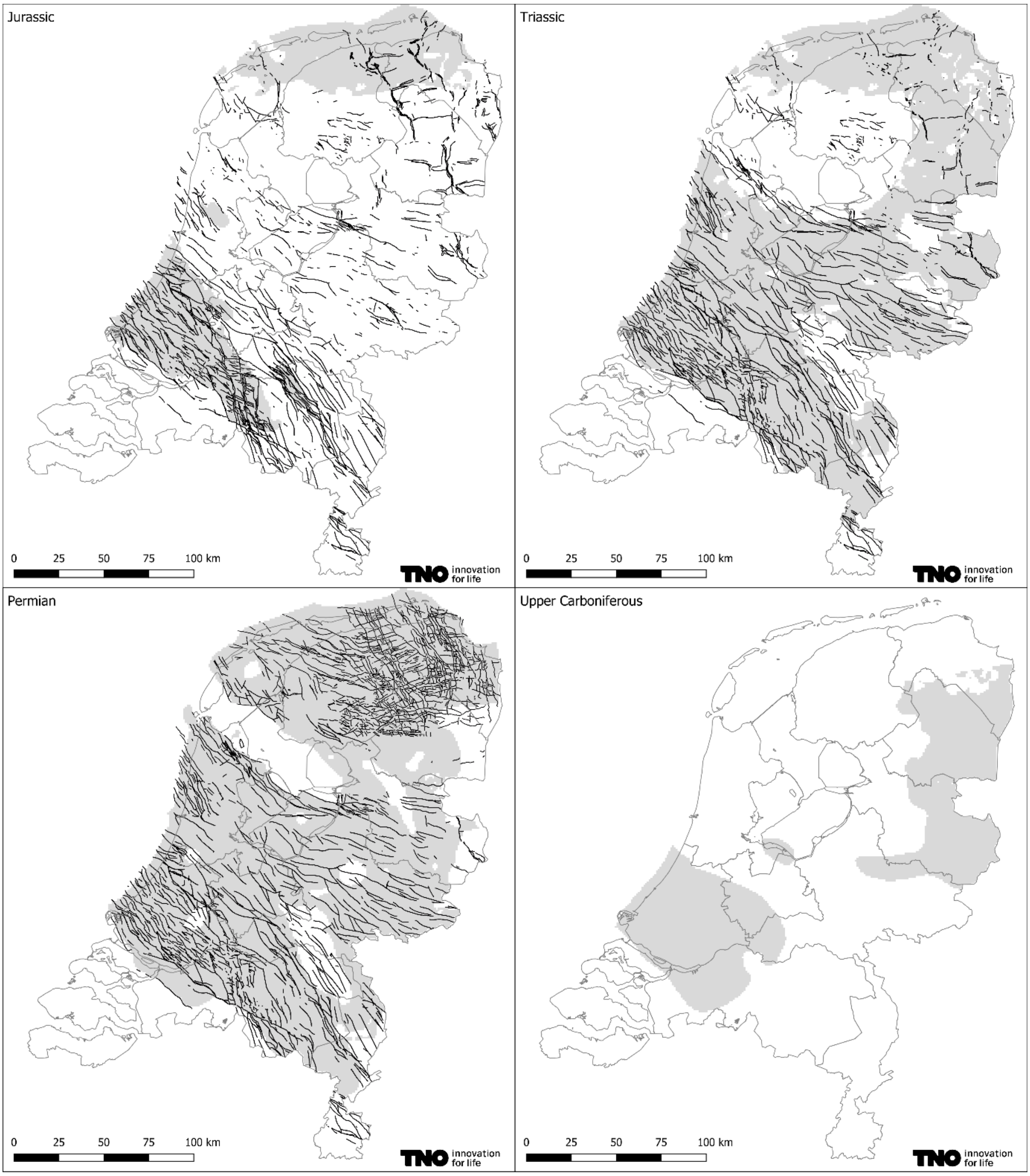


Figure 15 Distribution of mapped faults overlain over the distribution of the aquifers. For the Carboniferous, no faults are available. Note that faults outside the distribution of the aquifer cut the non-aquifer parts of the lithostratigraphic Group. Source: HIKE database.

4. Conclusions

- The most restrictive and therefore most important subsurface criterium for Eavor-Loop development turned out to be the minimum required temperature of 110 °C in combination with sufficient rock strength and thermal conductivity.
- The current maximum depth is only restrictive for older units such as Carboniferous limestones and Devonian sandstones. Of those formations, the lack of data prevents drawing definitive conclusions.
- By applying on the Eavor-Loop placement criteria, to the subsurface of the Netherlands, it is shown that the Permian Rotliegend, and the Lower and Upper Germanic Trias are the most promising formations.
- The minimum thickness of individual layers does not further decrease the applicability of Eavor-Loop over the minimum temperature constraint
- The most favourable conditions are found in the West Netherlands Basin and the Roer Valley Graben, the Lauwerszee Trough and the Lower Saxony Basin.
- Upside may exist in Upper Carbonferous aquifers which are found in nearly the entire Netherlands, but they have a high shale content.
- Older units like the Carboniferous Limestones and Devonian rocks may be interesting too but information about the nature of the rocks is limited. Further, the rocks of these units are usually buried to depths exceeding 4500m.
- Favourable rock types are sandstone and, to a lesser extent, limestone, based on their thermal conductivity and strength. Shale, marl and rock salt are unfavourable.
- Detailed data about the thermal rock properties and rock strength are scarce.
- High quality seismic data are mostly available in the northern part of the Netherlands (Groningen, Friesland, Drenthe, North Holland), and in the southwest (South Holland, western North Brabant).
- Regional scale fault data are available, but they should be used only for a first screening.
- The application of a lower temperature constraint, which might be possible with lower drilling cost and or lower supply temperature requirements for the heat network, increases the extent of the suitable area for the prospective formations. However, this doesn't open up entirely new areas or formations.

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Appendix A. Eavor-Loop placement criteria

Table 2. Eavor-Loop placement criteria for Technical and Economic success at current level of experience

	EL 1.0	**Considerations**
Heat gradient	>30 °C/km	Economics
Formation temperature	>110 °C	Ability to deliver into higher temperature heat networks, but heat pumps can make up the difference
Rock thermal conductivity at ambient conditions	> 2.5 W/m·K	Economics, overall heat output
Formation porosity and permeability	No constraints	The lower the better
Hole stability	Open laterals to be stable at maximum fluid density in the well of 1.2sg – to be estimated from in-situ stress, UCS and well orientation.	Standard circulating fluid has sg of 1.0
Drillability	UCS and abrasiveness not too high	Too High – Low ROP – economics!
Faulting parallel to the laterals	Safe distance away from major faulting >100m	Well placement, geo-hazards
Faulting crossing the laterals	Fault throw must be small compared to formation thickness, max 20% within 500m from the heel.	Assuming knowledge of wellbore position within reservoir is implied. JJ Stacks laterals with radial offset. Combined with formation thickness as a risking factor
Formation thickness	30m (modified JJ) in the whole area.	JJ requires radial buffer room; Mitigate with staggered laterals, reduced offset laterals
Horizontal formation continuity	Min 2500 x 600m (stacked laterals) Ideal 3500 X 1000m	Required space for longest possible laterals (maximum drilling limits) and economical optimization based on TC/Temp/Loop radial separation/Surface constraints.
Suitable formations in the Netherlands	Bunter Rotliegend Dinantian	
Current Drilling constraints (available tools and equipment)		
Depth	4500m	Combined with lateral for max TD max rig capacity.
Lateral length	2000 - 3500m	Subject to TD m md relative to Continental European rig availability
Formation dip	Updip max 5 degr, downdip no limitations	
Minimum Data Availability		
Seismic data	Very important - increasing quality required with decreasing formation thickness	Required to determine depth, lateral extend, thickness

Rock properties	To be obtained from rock cuttings from similar deposits preferably at similar depth.	For conductivity and UCS
In situ stress data	Basic understanding of the local stress fields	Hole stability
Other criteria		
Logistical Execution	Surface location for drilling of 130 x 120m	
Safe distance from vulnerable objects	No separation required. Operation of an EL is safe	Larger distance or temporary evacuation required during drilling of the wells to allow 24hr drilling operation for 6-9months
Interference issues	Drilling through or under water protection and water production areas is completely safe	Drilling through dedicated drinking water aquifers currently not allowed.