Final report

ELFO:

Eavor Loop Feasibility for Tilburg (Amer network) and Outlook for application in the Netherlands

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Executive summary

The energy generation and consumption in the Netherlands is slowly but steadily shifting away from fossil fuels towards renewable energy sources, such as offshore wind, and solar, thereby reducing greenhouse gas emissions. In order to improve renewable energy security and affordability, other sources of renewable energy, like geothermal energy, need to become part of the energy mix in the near future. At present, the majority of geothermal wells in The Netherlands are shallow wells, but deeper wells with high power output will be required to make a larger contribution to the overall energy supply. In this light, the ELFO project assessed the feasibility and economic viability of a deep well system: the Eavor Loop, consisting of 12 multi-laterals. The consortium of TNO (independent research institution), Eavor (geothermal energy company), Huisman Geo BV (drilling equipment & research) and EnNatuurlijk (operator of district heating) evaluated the suitability of this technology as primary heat source for city heating networks in the Tilburg area and for possible wider adaption in the Netherlands.

The results of the project contribute to the objective of the TKI Urban Energy scheme for Sustainable Heat Networks and Geothermal Energy (MMIP 4) by demonstrating that an Eavor Loop system for the Tilburg area can be seen as a possible option for a renewable heat source for the existing Amer heat network. Within the current market, deployment of the technology requires CAPEX subsidy and SDE++ guaranteed pricing. However, the study identified the possibility to further reduce drilling costs by 20%, making it commercially viable without CAPEX subsidy.

These conclusions are based on the following ELFO project components:

A **Subsurface feasibility study** on the feasibility of using the Eavor Loop™ technology to extract geothermal heat as a source for the Amer heat network in the Tilburg area. This study focused on the geological and geomechanical interpretation and modelling of the subsurface in an economic context and identified a suitable rock formation for placing the full loop system. A surface screening identified several suitable surface locations from where the base case well design of 12 horizontal multi-laterals could be drilled and operated Unfortunately, the preferred city surface location was unavailable, resulting in the selection of a surface location that posed limitations to the optimal well design at depth. The horizontal length of the laterals therefore had to be shortened from 3,000m to 2,100 m length as the horizontal legs now had to be drilled updip into the reservoir instead of slightly downdip. For the most optimal scenario, the heat output was calculated using the Eavor heat flow model, and the economic feasibility was based on an estimated CAPEX of € 54.5 MM to construct the Tilburg Eavor-Loop™, yielding an annual heat production of 74,000 MWh.

A **Drilling optimisation** desktop study on the design of a more automated and dedicated Eavor Loop rig for more cost-effective drilling and completion that is able to drill 24/7 in urban environments. Given that drilling efficiency (and therefore speed) is the key factor affecting drilling costs for geothermal wells, related parameters such as drill bit design, mud system, power, and rig control precision have been analyzed. A new design of a dedicated rig constructed that involves automated pipe handling and reduction of manual handling of bottom hole assembly components that reduces the time required for mechanical steps when compared to conventional drilling. Furthermore, the new rig design provides more accurate control of drilling parameters, reducing the need to pull out the drill string to replace the drill bit, resulting in significant time reductions. To reduce the required footprint for drilling in an urban environment, a dual activity drilling system (dual-derrick) was compared with drilling by 2 conventional rigs drilling simultaneously. The study concluded that the dual-derrick option is preferred saving costs by 16% and reducing drilling time by 43%.

An **assessment of environmental impact, safety and CO_2 footprint** of Eavor Loop based on numerical simulations over its lifetime. The study assessed the possible occurrence of undesirable effects (i.e.,

leakage, well bore collapse, induced seismicity) and compared the carbon footprint of the Eavor Loop technology with conventional geothermal applications. As part of the evaluation, thermal performance and Eavor Loop construction / operational characteristics were analyzed through a Life Cycle Assessment (LCA) and quantitative assessment of the CO_2 per GJ produced. This showed that Eavor Loop emissions are 20% improved compared to conventional systems, saving over 2kg CO_2-eq/GJ. The thermal response of the Eavor Loop for 30 years at constant flow rate conditions was calculated using a dedicated numerical thermal model. It shows that the Eavor Loop has a long lifetime marked by a very moderate linear decline of the production temperature and power over a lifetime of 10s of years, with minor thermal interference of laterals if placed with a spacing of ca 70 m. Based on the thermal simulations, stress changes were analyzed with a semi-analytical approach, assessing underlying sensitivities. Results indicated that potential leakage due to issues with borehole-stability and reactivation of pre-existing faults is not likely to be risks for safe operation of the Eavor Loop over its full life-time.

A **system integration** study of the Eavor Loop in the district heating network of Tilburg (Amer) involving the evaluation of two main components: 1) physical connection to the existing grid with the technical capacity to handle the thermal energy generated by the Eavor Loop, and 2) simulation of heat demand and temperature profiles to determine the feed-in capacity of the loop ensuring the quality of heat delivered to customers. The physical connection between the Eavor Loop and the heat grid was defined as a connection point in the existing grid and a new connection pipeline. The technical design has been modeled with Sishyd and a concept budget has been made, with increasing accuracy in later project phases. Two simulations have been completed to understand the impact of the Eavor Loop on heat grid temperatures: one by EnNatuurlijk using historical data, and one by TNO using the Design Toolkit software. The simulations by TNO show that a temperature drop of the network mainly occurs in high heat-demand periods and that the heat grid part “Kraaiven” is most affected if no measures are taken. Note that the simulations were based on a theoretical model at feasibility stage and more detailed modeling and optimisation is required to increase simulation model confidence.

Evaluation of the **wider implementation of the Eavor Loop technology in the Netherlands**. The study determined the subsurface potential for the Eavor Loop in the Netherlands by comparing subsurface conditions to Eavor's placement criteria. These criteria were divided into three subsurface categories: those specific to the formation, those specific to the location, and those specific to the local situation (e.g. characteristics that vary locally and cannot be studied using a national scale data base). The study concluded that the most favorable conditions for Eavor Loop placement occur in the West Netherlands Basin, Ruhr Valley Graben, Lauwerszee Trough, and the Lower Saxony Basin, where older units like the Carboniferous Limestone and Devonian rocks are of interest but for which limited information is available. These units are usually buried to depths exceeding 4500m.

Overall, the ELFO project has demonstrated that the Eavor-Loop™ is a more attractive geothermal production technology than conventional systems from a societal and environmental perspective. It is a closed loop, highly controllable system that does not depend on a permeable reservoir and has no environmental interaction with the subsurface or CO_2 emissions while in production. To achieve deployment of the technology at a large scale in a cost-effective manner, dedicated rigs, like those evaluated in this project, are required to drill these types of wells in an urban environment. Only with further innovations to improve drilling speed and cost-reductions, like those identified from this project, the technology is economically viable for large scale deployment.

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Glossary of key terms

Aquifer	A body or layer of permeable rock which can contain or transmit water, for example a sandstone layer.
Borehole collapse	A shear-type wellbore failure that occurs at low wellbore pressures when tangential stress becomes large, ultimately resulting in failure. Rock fragments fall off the wellbore wall, often leaving an elliptic borehole shape due to the stress concentration effects described above.
Break out or fracturing	Borehole breakouts / fractures are stress-induced enlargements of the wellbore cross-section. When a wellbore is drilled, the material removed from the subsurface is no longer supporting the surrounding rock. As a result, the stresses become concentrated in the borehole wall. Break outs occurs when these stresses exceed the required to cause compressive failure of the borehole wall.

Casing	A lining that is installed in a well once it is drilled that surrounds the well entirely. Casing is typically a hollow steel pipe that lines the inside of the wellbore to support the well, as the raw sides of the well would collapse in without support.
Doublet	A pair of two wells drilled next to each other into the same aquifer, and enabling hot groundwater to be pumped up through one well, while the cooled-down water is injected back into the same aquifer through the other well.
(Drilling) Mud system	Also called drilling fluid, aids in the process of drilling a borehole into the subsurface. It is used to lubricate the drill bit and transport drill cuttings to the surface.
Dual-derrick rig	Large, load-bearing structure from which the hoisting system and therefore the drill string is suspended. The derrick provides the height necessary for the hoisting system to raise and lower the pipe. A dual-derrick rig contains 2 of derrick structures as part of a single rig, which allows drilling of 2 wells simultaneously.
Eavor Loop (EL)	A new type of deep geothermal system (at ca 3-4 km depth range) which eliminates or mitigates many of the issues with traditional deep geothermal systems.
Fractures	A crack or surface of breakage within the subsurface. Wellbore tensile (or open mode) fractures occur when the minimum principal stress on the wellbore wall goes below the limit for tensile stress.
Geomechanics	The study of how soils and rocks deform in response to changes of stress, pressure, temperature, and other parameters. This science is central to understanding how drill bits remove rock, characterizing borehole stability, predicting the stability of perforation tunnels, and designing and monitoring stimulation programs.
Induced seismicity	Non-tectonic (i.e., non-natural) earthquakes that result from human activities that alter the stresses and strains in the subsurface
LCA	Life-Cycle Assessment. A systematic methodology used to calculate the environmental impacts, by quantifying and comparing the effects of a product, system, service or geographical entity, in the case of the ELFO project the assessment of the Eavor Loop as part of the Tilburg/Amer Heat network.
LCM	Lost Circulations Material refers to additives introduced to the drilling fluid when there are signs of inadvertent returns or the loss of drilling fluid into the formation. Lost circulation materials are intentionally introduced into the mud system to stop the flow of drilling fluid into a thief zone or a weak formation.
Multi-lateral well	A horizontal well constructed with more than one productive lateral branching off a main wellbore.
SCU	Shear capacity Utilisation. SCU is used to quantify the risk of shear failure (for example on an existing fault plane, e.g. fault criticality). SCU is between 0 (no risk) and 1 (rock is at shear failure).
Target Formation	Sedimentary layers suitable for heat extraction by Eavor loop.

Temperature Gradient	The rate of temperature change with respect to increasing depth in Earth's interior. As a general rule, the crust temperature rises with depth.
(Thermal) conductivity	A property that describes how well a material can transfer heat. A material with high thermal conductivity allows heat to pass through it easily, while a material with low thermal conductivity resists heat flow.

1. Nederlandse samenvatting

De energieopwekking en -consumptie in Nederland verandert langzaam maar gestaag van fossiele brandstoffen naar hernieuwbare energiebronnen, veelal door groei van wind- en zonne-energie. Om de energiezekerheid en betaalbaarheid van hernieuwbare energie te verbeteren, zouden ook andere bronnen, zoals geothermische energie, een groter deel moeten gaan uitmaken van de energiebalans in de nabije toekomst. Om een grotere bijdrage te kunnen leveren aan de totale energievoorziening zullen vooral diepe putten, die een hoog vermogen kunnen leveren, nodig zijn.

Om nieuwe en innovatieve ideeën rondom geothermie (sneller) van de grond te krijgen, heeft het ELFO-project de technische en economische haalbaarheid van zo'n diep, innovatief geothermisch systeem beoordeeld: de Eavor Loop, een put bestaande uit 12 multi-laterals. Het consortium van TNO (onafhankelijk onderzoeksinstituut), Eavor (geothermische energiebedrijf), Huisman Geo BV (boorapparatuur & onderzoek) en EnNatuurlijk (warmtebedrijf) heeft de toepasbaarheid van deze technologie als primaire warmtebron voor stadsverwarmingsnetwerken geëvalueerd voor de regio Tilburg alsmede voor een bredere toepassing elders in Nederland. De uitkomsten van het project dragen bij aan de doelstelling van de TKI Urban Energy regeling voor Duurzame warmtenetten en Geothermie (MMIP 4) door aan te tonen dat het haalbaar is om een Eavor Loop-systeem in de regio Tilburg te ontwikkelen als een hernieuwbare warmtebron voor het bestaande Amer-verwarmingsnetwerk. Binnen de huidige markt is de technologie alleen economisch haalbaar met een CAPEX-subsidie en gegarandeerde SDE++-prijzen. De studie voorziet dat er een mogelijkheid is om de boorkosten verder te verlagen met 20%, waardoor het commercieel wordt zonder CAPEX-subsidie.

Om tot bovenstaande bevindingen te komen, heeft het ELFO-project de volgende aspecten geëvalueerd:

Een **ondergrondse haalbaarheidsstudie** heeft het gebruik van de Eavor Loop™-technologie om geothermische warmte te extraheren als bron voor het Amer-warmtenetwerk in de regio Tilburg beoordeeld door middel van geologische en geomechanische interpretatie en modellering van de ondergrond in een economisch context. De ondergrondse haalbaarheidsstudie heeft een geschikte gesteenteformatie geïdentificeerd voor het plaatsen van het volledige loopsysteem dat voldoende vermogen kan leveren. Het basisontwerp van het systeem bestaat uit een verticale put tot ongeveer 3,5-4 km diepte met daaraan 12 horizontale multi-laterals van 3,000m lengte elk. Dit ontwerp kon helaas niet gerealiseerd worden omdat de voorkeurslocatie in de gebouwde omgeving niet beschikbaar bleek voor het plaatsen van de put en de operationele activiteiten. Om toch dezelfde gesteenteformatie aan te kunnen boren vanaf een andere locatie in de gebouwede omgeving, moest de lengte van de multi-laterals worden verkort naar 2,100m doordat de laterals nu enigszins updip (omhoog) geboord moeten worden in plaats van horizontaal/iets naar beneden. Desalniettemin levert dit aangepaste scenario een jaarlijkse warmteproductie van 74.000 MWh. De geschatte CAPEX om de Tilburg Eavor-Loop™ te bouwen bedraagt 54,5 MM €.

Een studie naar **optimalisatie van boortechnieken en nieuwe boorinstallaties** heeft geresulteerd in het ontwerp van een kosteneffectief, semi-geautomatiseerd en toegepaste boorinstallatie voor de Eavor Loop dat 24/7 ingezet kan worden in stedelijke omgevingen. Factoren die de boorefficiëntie beïnvloeden, met name de snelheid van boren, zijn geanalyseerd en geoptimaliseerd door veel processen te automatiseren. Tevens is er optimalisatie gedaan in het nauwkeurig controleren en aanpassen van boorparameters, waardoor de noodzaak om de boor vaak te vervangen wordt verminderd en hierdoor dus tijdwinst te behalen valt. Een belangrijke verbetering ten opzichte van bestaande (geothermische) boortechnieken, is het gebruik van een dual-derrick boorinstallatie, waardoor de alle apparatuur op een kleinere plek geïnstalleerd kan worden en daardoor dus gemakkelijker te plaatsen is in een stedelijke omgeving.

Een evaluatie van de **milieueffecten, veiligheid en CO_2-voetafdruk** van de Eavor Loop op basis van numerieke simulaties laat zien dat ongewenste effecten (zoals lekkage, instorting van de boorput, geïnduceerde seismische activiteit) uit te sluiten zijn en bevestigde de lage CO_2-voetafdruk van de Eavor Loop-technologie in vergelijking met conventionele geothermische toepassingen. Als onderdeel van de evaluatie werden thermische prestaties en de bouw- en operationele kenmerken van de Eavor Loop geanalyseerd door middel van een Levenscyclusanalyse (LCA), alsmede een evaluatie van geproduceerde CO_2 per GJ. Hieruit bleek dat de Eavor Loop-emissies 20% lager zijn in vergelijking met conventionele systemen, waardoor meer dan 2 kg CO_2-eq / GJ wordt bespaard. De thermische respons van de Eavor Loop gedurende 30 jaar bij constante debietomstandigheden is berekend met behulp van een gespecialiseerd numeriek thermisch model. Op basis van de thermische simulaties werden spanningen geanalyseerd met een semi-analytische benadering, waarbij de onderliggende gevoeligheden werden beoordeeld. Dit gaf aan dat de stabiliteit van de boorput (en mogelijke lekkage) en het potentieel voor reactivering van bestaande breuken geen risico vormen voor een veilige werking van de Eavor Loop over de volledige levensduur.

De simulaties laten zien dat de Eavor Loop een lange levensverwachting heeft en dat er geen uitputting van de bron plaatsvindt. De warmteoverdracht tussen bron en Eavor Loop systeem vindt plaats door de thermische gradient van het relatief koude boorgat en de omgevingstemperatuur. De sterkte van de warmteoverdracht is lineair afhankelijk van dat temperatuurverschil, en blijft relatief constant na het eerste jaar/maanden, met een geringe afname (typisch <10%) over de levensduur van 20-30 jaar. Ook over langere tijd blijft dat karakter van afvlakkende afkoeling in stand tot ca 100 jaar. Op langere termijn zal verdere afkoeling kunnen optreden door thermische interferentie van de laterals, maar dit is niet meer dan een paar graden en verwaarloosbaar klein. De grootste warmteoverdracht vindt plaats bij de instroom van de laterals waar het temperatuurverschil tussen het de vloeistof in het boorgat en temperatuur in het reservoir het grootst is.

De **systeemintegratiestudie van de Eavor Loop in het stadsverwarmingsnetwerk** van Tilburg (het Amer netwerk) laat zien dat het mogelijk is om de warmtecapaciteit van de Eavor Loop fysiek op het bestaande netwerk aan te sluiten. Tevens concludeert de studie dat een temperatuurdaling van het netwerk voornamelijk optreedt in perioden met een hoge warmtevraag en dat het warmtenetwerkgedeelte "Kraaiven" het meest wordt beïnvloed als er geen maatregelen worden genomen. Let op dat de resultaten van deze studie met zorg moeten worden behandeld, omdat het gebaseerd is op een theoretisch model in de haalbaarheidsfase en er meer gedetailleerde modellering en optimalisatie vereist is.

Om de **bredere implementatie van de Eavor Loop-technologie in Nederland** te beoordelen, is het potentieel van de Nederlandse ondergrond geëvalueerd aan de hand van geologische voorkeurscondities voor het plaatsen van een Eavor Loop system. Zo is er naar verschillende criteria gekeken die specifiek zijn voor de gesteenteformatie, voor de locatie of specifiek voor de lokale situatie. De studie vond dat de meest gunstige condities voor Eavor Loop-plaatsing werden gevonden in het West-Nederlandse Bekken, Ruhr-vallei Graben, Lauwersee Trog en het Neder-Saksische Bekken. Oudere gesteentelagen zoals de Carboon-kalksteen en Devoon gesteenten zijn erg interessant en mogelijk van belang om verdere uitrol van de technologie te verbreden. Helaas is er maar beperkte informatie over deze lagen beschikbaar, mede door de diepte (>4500m) waarop ze te vinden zijn. Verdere exploratie naar en kenniswerving van deze diepere lagen via boringen, (seismische) data acquisitie, interpretatie en modelleringen zou een completer beeld geven van de mogelijkheden voor deze vorm van geothermie.

Ondertussen is het ELFO-project voor Tilburg doorgegroeid naar de FEED-fase. Partners ENN, EBN en Eavor werken aan de plannen voor deze fase op basis van de uitkomst van de haalbaarheidsstudie zoals in dit eindrapport omschreven. De resultaten van WP1 en WP 3 zijn gebruikt voor het succesvol aanvragen van een NWN-subsidie ("Nieuwe Warmte Nu") en voor de SDE++ aanvraag. Tevens heeft de ELFO-studie aangetoond dat veiligheids- en milieurisico's goed onder controle zijn. Vanwege een juridisch geschil met de gemeente Tilburg is een nieuwe exploratievergunning nodig (en aangevraagd) om verdere activiteiten uit te voeren.

Contact

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De verschillende werkpakketrapporten zijn via de TKI-Urban Energy gratis te downloaden.

2. General

2.1. Introduction

Currently the main sources for renewable energy in the Netherland are offshore wind and solar energy. These sources of energy are being developed with great pace. The downside of the technologies is that they only provide power when there is wind or sunshine. To be able to provide a more consistent renewable energy supply and shave off the peaks, geothermal energy can become a larger player in the energy mix in the near future. In general, geothermal energy can be described as sustainable heat extracted from the subsurface through wells that can be used to heat houses, buildings or green houses. The most conventional method is to pump up hot water, circulate it through a heat network and return into the rocks once cooled. The majority of current geothermal wells are shallow wells (~ 500 mtr) that are used as temporary storage systems to collect energy in summer periods and extract heat in colder periods. To be able to make a larger contribution to the overall energy supply, geothermal wells with high power output will be required at competitive costs levels with other renewables.

The success of such deeper geothermal systems is strongly dependent on the geological parameters and heat flow at depth, as well as its economic viability. Nevertheless, geothermal energy has been attracting a lot of attention in the Netherlands as a sustainable energy source. The sector has experienced strong growth since its first success in 2007, with more and more market players becoming active and bringing innovations to this relatively young energy sector.

One of these innovations is a novel multi-lateral well design that can extract heat independent of the quality of the source rock (e.g., the aquifer) as the design is based on a closed-loop system. Where conventional systems require a relatively permeable aquifer to allow for sufficient and constant flow of the hot water through the rocks into the well bore, the Eavor-Loop™ technology can be operational in much tighter rocks as it is not dependent on water flow for heat exchange, thereby unlocking vast amounts of geothermal energy from impermeable rocks otherwise not suited for geothermal energy.

However, for commercial development in the Netherlands this novel technique needs to prove its feasibility and requires assessment on (1) lowering the costs for drilling, (2) environmental safety and sustainability, and (3) optimised performance for heat networks.

Therefore, the ELFO project (**E**avor **L**oop **F**easibility for Tilburg and **O**utlook for application in the Netherlands) is aiming to evaluate the feasibility of the Eavor-Loop™ multi-lateral well system.

2.1.1. The Eavor-Loop

The Eavor-Loop™ (EL in short) is a new type of deep geothermal system that comprises of a series of connected horizontal well sections (e.g. multi-laterals) drilled to a depth range of around 3-4 km, and eliminates or mitigates many of the issues with traditional deep geothermal systems. The technology has been demonstrated in a pilot in Canada but has not yet been commercially exploited.

The key difference relative to existing geothermal technology is that it is a completely closed-loop: it is simply a buried-pipe system, akin to a deep radiator or heat exchanger. Where conventional geothermal systems do rely on fluid flow through the rock layers, it also is associated with pumping up dissolved salts and other elements, resulting in corrosion, local clogging and other side effects which potentially reduces the efficiency of the system over the lifetime.

As the water in the Eavor Loop system doesn't come in contact with the rock layers, corrosion and clogging of the pipelines in the system and heat network are not common which contributes to the longevity of the systemin contrast to conventional systems.

The Eavor Loop technology is scalable and independent of the permeability of aquifers or hydrothermal flow capacity. This makes it possible to utilize these systems in areas without suitable reservoir conditions for conventional geothermal energy without the need for and high-risk exploration and therefore extends the overall geothermal resource base. Its scale-up is based on standardised wells which means it is less dependent on the availability of specialised resources. There are several types of Eavor-Loop™ configuration which depend on overall setting, application and surface locations (Figure 1). The ELFO project will focus on the feasibility of the James Joyce design only.

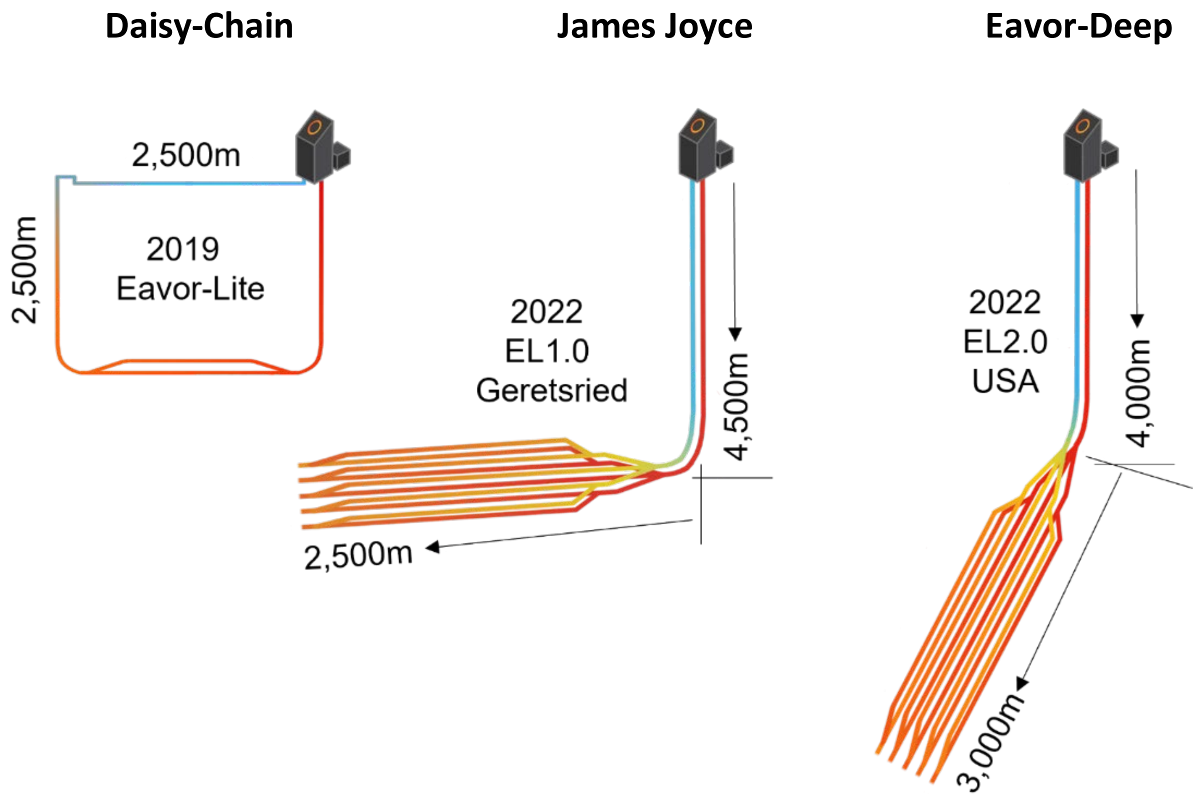

Figure 1: Schematics of different Eavor-Loop™ (EL) designs with indicative depth & length ranges and multi-lateral design. The Daisy-Chain configuration was demonstrated in a Canadian Pilot (2019). The James Joyce configuration is the proposed design for the ELFO project. The Eavor-Deep design is currently being drilled in the USA.

An Eavor-Loop™ has remarkably consistent and predictable output over long timeframes, as demonstrated in the pilot project in Alberta, which is now fully operational. As heat is extracted from the earth, the radius of the temperature affected area around the wellbore expands; beyond this radius the reservoir is still at virgin temperature. The radius size is a logarithmic function of time and the lateral wellbores have minimal interference with each other if spaced properly. Therefore, decline is addressed by calculating the effective radius and specifying lateral spacing requirements for the project to ensure minimal wellbore interference.

Computational Fluid Dynamics (CFD) analysis has also been performed on analogue Eavor projects to validate and predict the thermal interference between laterals. A simplification showing an element of symmetry with four laterals with 65 m horizontal spacing and 75 m vertical spacing is shown in Figure 2 below, after 10 years of operation.

The CFD analysis shows that lateral interaction will not materially impact the project output over the 30-year project life.

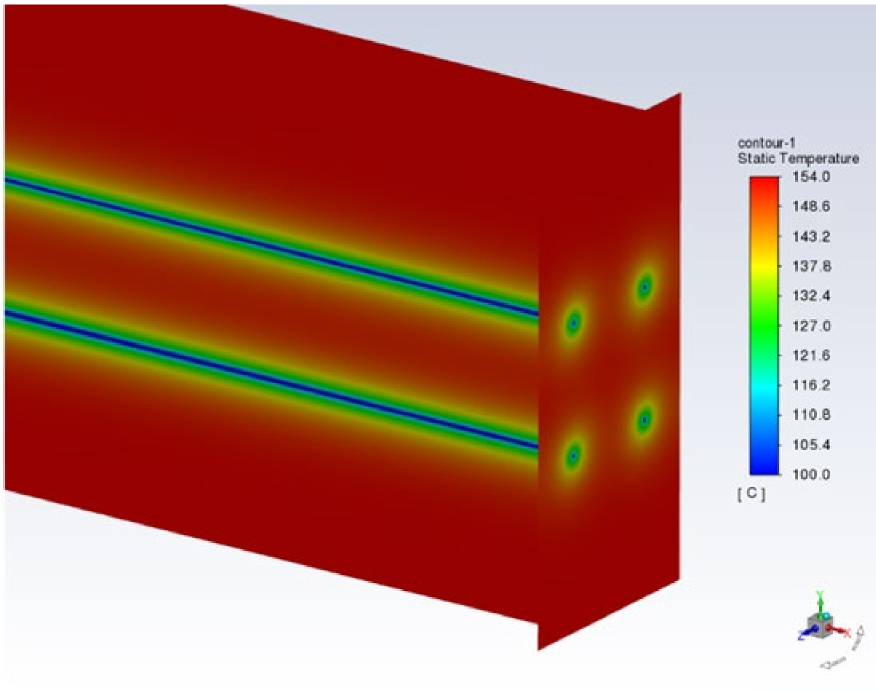

Figure 2: CFD example showing lateral interaction after 10 years of operation, based on 75m and 65m vertical and lateral spacing, respectively

The James Joyce EL design comprises a multi-lateral system, consisting of 12 semi-horizontal laterals. The horizontal spacing between the laterals is 65 meters. The well is constructed with two drilling rigs operating simultaneously from the same surface location. First, the 2 vertical well sections are drilled close together, and intermediate casing is cemented in place for both wells according to standard oil and gas industry practice. Then, two deviated wellbores are drilled out of each standard vertical cased hole and intersecting at the toe of each horizontal section. This process is repeated until all 12 multi-lateral wellbores are intersected. The vertical spacing between this top and bottom lateral of a single loop is 75 meters. The laterals are completed with a sealant called RockPipe^{TM} that ensures there is no leakage from the well bores into the surrounding rock formations. After well construction, the drilling fluid is displaced with a working fluid designed for improved thermodynamic and operational performance.

In order to commercially introduce this Eavor Loop system into the Netherlands, a number of hurdles need to be overcome:

- Demonstrate that the technique can be applied commercially for the delivery of heat for subsurface and surface condition in the Netherlands
- The cost for drilling has to decrease: Currently this is the biggest factor in the economical evaluation. For the proposed EL design more than 65km of well section has to be drilled. For reference, a standard geothermal doublet system at similar depth only consists of 6-8km of well bore. The Eavor Loop involves long, horizontal open hole well sections, which are not conventional. The implications for environmental safety and sustainability have not been addressed so far in the Netherlands.
- The performance characteristics of the Eavor Loop for heat delivery and options for optimisation of design for heat network system integration need to be accurately mapped out

and understood (i.e., the radiator as well as circulation is significantly different to conventional geothermal systems).

2.2. Objectives

The main objectives of the ELFO project are 1) to assess the feasibility and applicability of the Eavor Loop (EL) technology as the primary heat source for the Amer heat network in Tilburg and 2) evaluating the possibilities for wider adaptation in the Netherlands. The following sub-objectives are addressed:

1 Assess subsurface suitability in the Tilburg Area for construction of an EL (James Joyce design), and prognose associated heat delivery as a function of subsurface and (design) engineering parameters.
2 Design a dedicated rig set-up for cost effective drilling and completion of the proposed EL, such that the drilling can be carried out at lower costs on a 24/7 basis in the urban environment.
3 Assess environmental impact, safety and CO_2 footprint of the EL based on numerical simulations over its lifetime, capable of ruling out undesirable effects (i.e., leakage, well bore collapse, induced seismicity), and validating low carbon footprint compared to conventional geothermal applications.
4 Develop an optimised EL design and optimise operational parameters for integration in Amer heat network, based on the heat demand, temperature levels, and overall business case.
5 Provide an outlook for EL in the Netherlands, including best practices and a roadmap for use in similar and different geological settings.

2.3. Project partners & roles

The ELFO consortium has the following partners:

Partner	Type of organisation	Role
Eavor Europe	Geothermal technology company	WP1 & 5 lead Eavor's focus is on the applicability of the Eavor Loop in the Tilburg area and the Netherlands.
EnNatuurlijk	Heating company (“warmtebedrijf / leverancier”)	WP4 lead Responsible for the system integration aspects (integration of the Eavor loop in the Amer network)
Huisman Geo	Drilling company	WP2 lead Responsible for the design of drilling rigs that will be required for economically viable and large-scale construction of Eavor loops across the Netherlands.
TNO	Research institute	Project coordinator & WP3 lead TNO will conduct the overall project management, geology and the environmental risks such as induced seismicity, leakage and the CO_2 footprint of the system and supports the study for wider adaptation in the Netherlands

The consortium partners have been carefully selected such that the whole value chain involved in developing a geothermal energy project is represented to assess the Eavor Loop concept: Technology provider and operator (e.g. Eavor), Drilling company and operator (e.g. Huisman), environmental risk & well bore integrity assessment, fundamental and industrial research (e.g. TNO) and the end user (e.g. EnNatuurlijk – the Amer network).

2.4. Duration

The initial project duration was one year, from 01.11.21 till 01.11.22, however the project was extended by 3 months till 31.01.23.

2.5. Overview technical scope

The ELFO project scope is setup in five Work Packages, in accordance with the five objectives listed in section 2.2. In addition, WP6 deals with project management and overall coordination.

The work scope is designed to evaluate and mature the applicability of the Eavor Loop technology at a site-specific location in the Tilburg area. As such, it integrates complex systems and their interfaces by focusing on subsurface, drilling, and safety aspects while optimising this system into the existing Amer heat network.

The activities per Work Package are given below:

WP	Work plan item	Responsible
1	**Feasibility study of subsurface of Tilburg area for Eavor Loop**	**Eavor**
1.1	Obtain seismic data	Eavor
1.2	Review and interpret seismic data (Bunter depth map, thickness map, fault locations, offsets and uncertainties)	Eavor
1.3	Determine bottomhole location EL	Eavor
1.4	Review well data logs & core	Eavor
1.5	Determine regional stress field	Eavor
1.6	Model stress changes due to cooling	TNO
1.7	Subsurface peer review	Eavor/TNO/EBN
1.8	Determine ROP range for drilling of lateral	Eavor
1.9	Basic well design based on offset wells	Eavor
1.10	Modelling of optimum thermal output	Eavor
1.11	Determine economics	EBN
2	**Optimised drilling rig design and drilling practices**	**Huisman**
2.1	Optimise tripping in/out process in cased holes, aiming at 30% time reduction	Huisman
2.2	Investigate the effect of tripping in/out speed in open hole laterals	Huisman
2.3	Analyse cost benefit of deployment of dedicated rigs and crews (simultaneous drilling; 24/7 operations)	Huisman
3	**Environmental impact & safety**	**TNO**
3.1	Determine regional stress field	TNO
3.2	Induced seismicity: Semi-analytical modelling of reservoir stress changes due to cooling	TNO
3.3	Well leakage modelling w/ thermo-mechanical models	TNO
3.4	Evaluation of COP - towards end of project	TNO
4	**System integration EAVOR in district heating**	**ENN**
4.1	Select tie-in point(s) for Eavor loop	ENN
4.2	Operating hours, including full-load equivalent, per year for the EAVOR loop system. Given its technical specifications (e.g. temp & flow) and input WP 1 - 3	ENN

4.3	Calculate steady state EL output	Eavor
4.4	Review options for optimum use of EL source	TNO
4.5	Conceptual design of the EAVOR system tie in, in the existing heat grid	ENN
4.6	Calculate output for non-steady state operation	Eavor
4.7	Multiple scenarios for future temp & demand optimalisations- also non-steady state operation	ENN
4.8	Stakeholder orientation regarding de surface location and benefits to the future growth of the heat system	ENN
5	**Outlook for NL and dissemination**	**Eavor**
5.1	Evaluation of suitability of EL for current and future district heating potential (incl greenhouse and industry heat demand), in similar and different geological settings in NL	TNO
5.2	Technological learning curve perspective	Eavor
5.3	Webinar showcasing the Tilburg feasibility study and NL outlook	Eavor

3. Results and discussion

3.1. Summary

This chapter describes the technical scope, results, potential bottlenecks and recommendations of each Work Package (Figure 3) at a high level, with details where required. The reader is referred to the dedicated Work Package reports for more detailed information regarding scope, methodology, assumptions, results and conclusions.

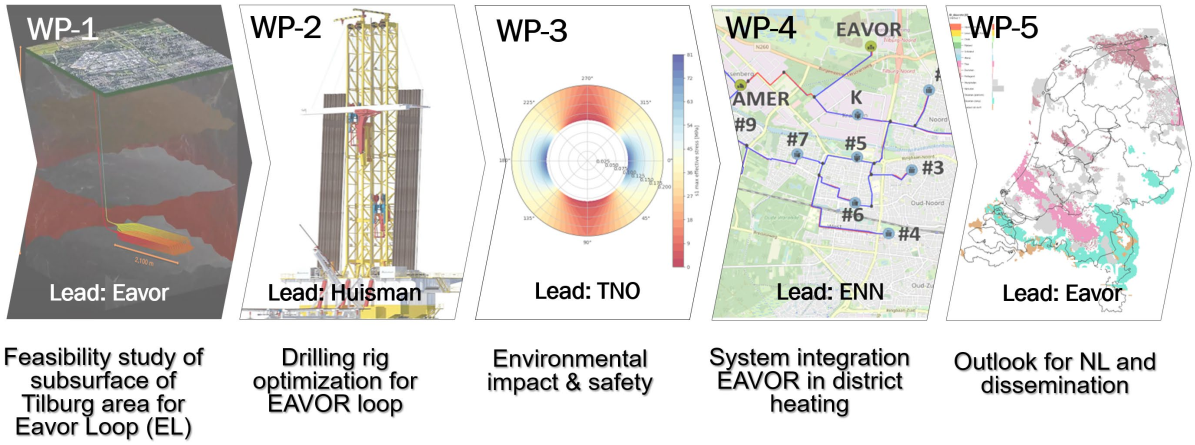

Figure 3: the 5 work packages (WP's) and their leads

3.2. WP1: Subsurface feasibility study of the Tilburg area

The goal of WP1 was to assess the feasibility of the use of Eavor Loop™ technology for the extraction of geothermal heat to be used as a source for the Amer heat network. The work included a thorough geological and geomechanical interpretation of the subsurface in the Tilburg area in the Netherlands, to assess suitability of the geological conditions both from a drilling perspective and from a heat delivery point of view. In addition, the subsurface feasibility was evaluated in an economic context.

The first criteria which applies to any geothermal development in the Netherlands involves the selection of an area with available 3D seismic and a heat network with sufficient capacity for utilization of a new geothermal heat source.

The 3D seismic survey in the Tilburg area was interpreted and depth corrected with standard geophysical interpretation tools. Faults and target formation tops were identified within uncertainty ranges. The available seismic survey unfortunately did not cover the full area of interest as identified by the extent of the heat network, which limited the optimisation of the placement of the loop, which was further exacerbated by the restrictions in suitable locations in this area. Eventually, one location for a complete loop (of 12 laterals) was selected taking into account the limitations in the area. The lateral length is limited in this case due to the fact that from the selected location the laterals will have to be drilled updip in a Southward direction, following the dip of the target formation. Updip drilling limits the maximum length of the laterals to approximately 2100m due to drilling mechanics. Longer laterals would make the project more economic, due to restrictions on potential other available locations, these could not be considered.

The temperature gradient and the relevant formation properties of the target Triassic Bunter sandstone formation in the selected region was investigated based on offset well data. The temperature gradient was confirmed to be better than expected at 35 °C/km. The conductivity of the Bunter was measured as well as the unconfined compressive strength. The conductivity was also a bit better than expected and the formation strength is sufficient for the stability of the open-hole laterals throughout the productive life of the loop as shown by modelling of the near well bore stresses.

The drilling plan for the vertical wells was constructed based on available information from nearby offset wells. Combining the knowledge of the wells drilled with the new requirements for EL resulted in a concept casing design and time and cost estimate. For the drilling of the laterals in the target Bunter formation the rate of penetration and the bit life were estimated by comparing rock hardness with the results from the hard rock drilling research at Utah Forge. The estimates were judged to be manageable.

The heat output was calculated with the Eavor heat flow model. The current inlet temperature of the Amer heat network at 120 °C is quite high in the wintertime (95°C in the summer). This temperature is not often needed but the old network is not able to withstand quick temperature changes. This high inlet temperature is not good for the efficiency of the loop, as it requires a low circulation rate. This problem can be overcome by the use of a heat pump to boost the outlet temperature by taking more heat out of the return flow. The optimum capacity for a 30-year flat profile was derived to be 9.1 MW in summer months and 7.1MW in winter months.

The economic feasibility is based on an estimated CAPEX of 54.5 MM € to construct the Tilburg Eavor-Loop™, yielding an annual heat production of 74,000 MWh. OPEX is estimated at 162k €/year and electricity demand of 660 kW to power an on-site heat pump to meet the heat network demand. The project is eligible for subsidized energy pricing through the SDE++ program.

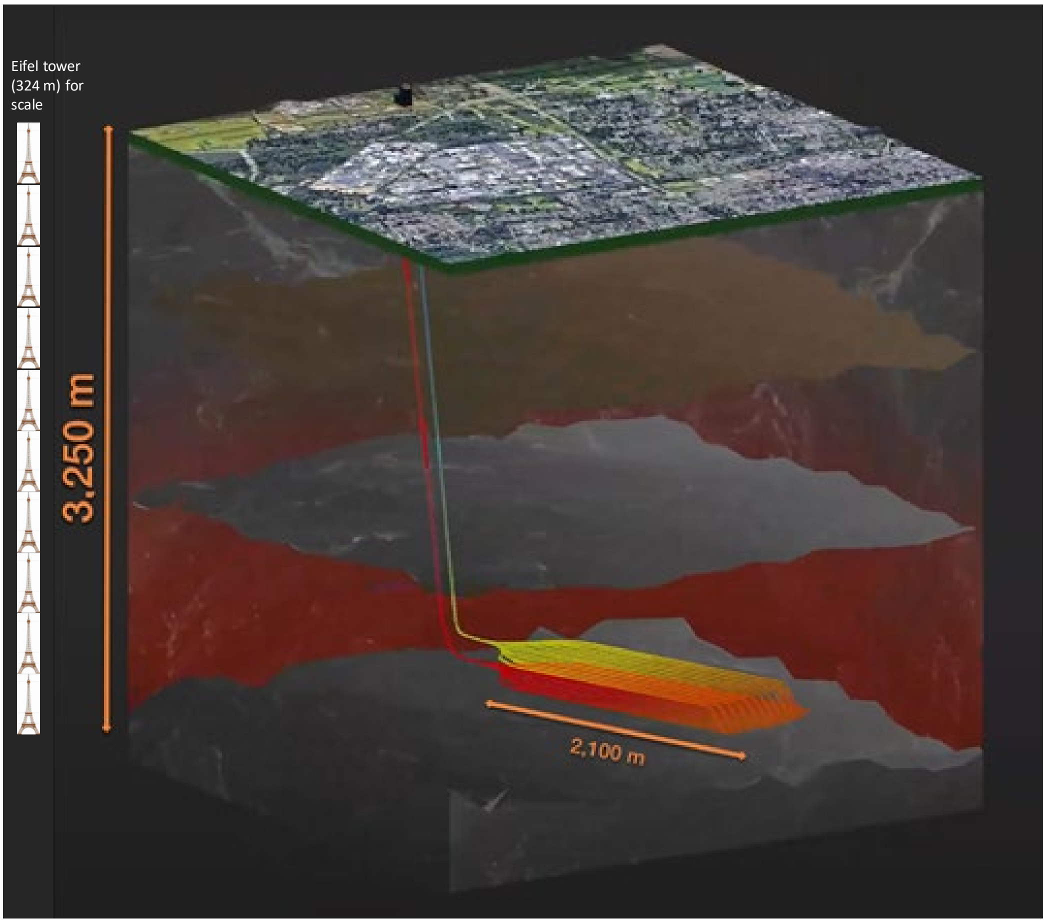

Figure 4: Stylised schematic of the Eavor-Loop™ planned near Tilburg. For perspective purposes, the size of the Eifel Tower is shown on the right; the Eavor Loop system is planned at a depth of 10x the height of the Eifel Tower.

3.3. WP2: Optimised drilling rig design & drilling practices

The work conducted as part of WP2 has the aim to design a dedicated and more automated Eavor Loop rig for cost effective drilling and completion such that the drilling can be carried out on a 24/7 basis in the urban environment. In order to achieve this, various parameters that affect the efficiency of drilling, have been analysed to improve the most costly activity of delivering the geothermal well; the drilling activities.

The drilling speed is influenced by factors such as drill bit design, mud system, available power, and the control precision of the rig. An automated rig can save time by automating the pipe handling process and reducing manual handling of bottom hole assembly components. Additionally, the automated rig can provide accurate control of drilling parameters, reducing the number of times the drill string needs to be pulled out to replace the drill bit. Therefore, the use of a dual derrick rig as a cost and time-saving method for drilling the Eavor Loop well system was considered and compared to the use of two conventional drilling rigs.

The dual derrick system has the ability to drill two wells simultaneously with only one floor crew, resulting in a smaller crew size and cost savings of around 16%. Combining two rigs into one system also results in a much space requirements for the required drilling site, meaning a. The required space to accommodate a dual derrick compared to two conventional rigs is approximately 40% less. The smaller footprint for the dual derrick set-up is of great significance for the ability to drill EL systems in dense urban areas.

In case there is no dual derrick rig available or when there is not enough space for two conventional rigs, a single conventional rig set-up was also considered. It was found that this set-up would be less efficient due to a lack of automation, resulting in additional time per well, a larger crew and half the capacity of the dual derrick system.

The dual derrick system can complete a project in 170 days compared to 300 days for the conventional rig, resulting in a cost savings of 19% and a time savings of 43%.

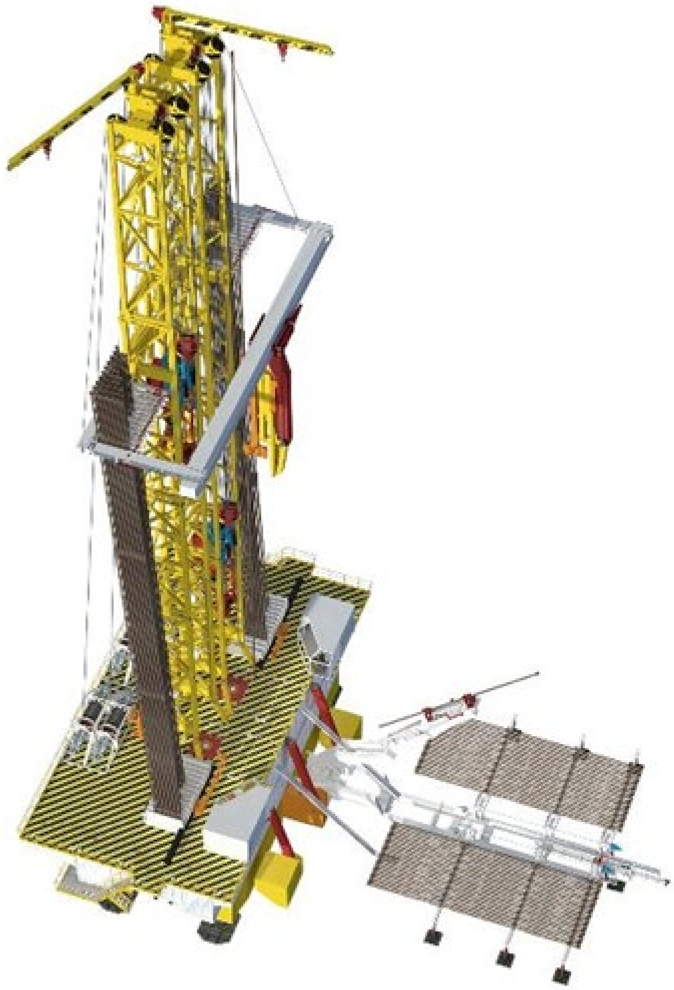

Figure 5: InnoRig XL90D dual derrick: two rigs with one combined floor and pipe handling system

3.4. WP3: Environmental impact and safety

Work Package 3 covers the assessment of environmental impact, safety and CO_2 footprint of the Eavor Loop (EL) based on numerical simulations over its lifetime, capable of ruling out undesirable effects (i.e., leakage, well bore collapse, induced seismicity), and validating low carbon footprint compared to conventional geothermal applications. The methodological approach includes the following steps

- Input well path trajectory, well completion and EL operational conditions (i.e., flow rate, inlet temperature) for the Tilburg Case study as well as relevant subsurface data and interpretation, thermo-mechanical properties have been adopted from the results of WP1 and WP2 of ELFO.
- EL loop performance and near well bore thermal response, based on thermal simulation
- Stress response as a function of the predicted near well bore thermal response, superposed on the in-situ stress.
- Analysis of Borehole stability and potential for fault reactivation.
- Subsequently, based on the thermal performance and EL construction and operational characteristics, LCA analysis (Life Cycle Assessment) and quantitative assessment of the CO_2 per GJ produced has been done.

The layout of the well system is based on key well survey points which have been defined by Eavor, which consist of 12 laterals, each about 70m apart. For the operation of the Eavor Loop it is assumed that inlet temperatures will be ~60°C and flow rate of 60 kg/s with the assumption that the water density at 60°C is 1000 kg/s. A dedicated numerical thermal model has been used to calculate the thermal response of the Eavor Loop for 10 years at constant flow rate conditions. The grid sizes in radial direction have been chosen such that the logarithmic value of the cell centers radial coordinates is linearly increasing from sub cm-size at the well bore to few meter size a radial distance of 70 m, which is sufficient to fully cover the transient heat flow over the simulated lifetime. The predicted thermal power is in excess of 7 MWth.

The simulations indicate that the Eavor-Loop has a long lifetime marked by a very moderate linear decline of the production temperature and power over a lifetime of 10s of years, with minor thermal interference of laterals if placed with a spacing of ca 70 m (Holmes et al., 2021, Van Wees, 2021)

Based on the thermal simulations, the stress changes were analyzed with a semi-analytical approach and the following was concluded:

Borehole stability:

- The borehole wall upon cooling of the EL is stable, except for less than 1 cm of the wall at the entry of the laterals, marked by a Shear Capacity Utilization (SCU) close to or slightly exceeding 1 indicative for frictional instability (in horizontal direction) and strong tensile stresses of -14 MPa (in vertical direction).
- The likelihood for tensile failure is dependent on the actual tensile strength which can be estimated from Cohesion values. For the Triassic drilled in Tilburg, cohesion may not be higher than 3-6 MPa. Therefore, it will create tensile cracks and break-out under the ca 14Mpa tensile stress, which are limited to the first 1 cm of the borehole wall. In the analysis we did not consider the impact of Eavor's proprietary Rock-pipe, which will be placed on the walls of the open hole laterals to seal off the formation from the fluids inside the EL. This could change the rock parameters at the wellbore face, and can to some extent affect the cohesion, friction, and tensile strength.
- The thermal effects, responsible for the tensile fracturing will manifest itself very early in the Eavor Loop lifetime, possibly already during drilling when mud circulation is causing borehole wall cooling. The fracturing can therefore already occur during the drilling process. Stress effects of thermal cooling do not noticeably increase over time after the first month of operation. Consequently, the breaching of Rock-Pipe, after the first month of operation is unlikely. The early use of Lost Circulations Material (LCM) and Rock-Pipe to plug the crack tip can prevent further propagation of potential fractures. Rock-Pipe can be reapplied throughout the life of the Eavor-Loop™.

Potential reactivation of faults:

- Stress effects have been calculated up to 70 meters from the well bore based on the predicted temperature response at 120 months and have been tested for stability on pre-existing fracture favorably aligned in the (locally rotated) stress field, adopted a cohesion of 0.
- The results show Shear Capacity Utilization (SCU) for pre-existing fractures leading to failure only in the very close vicinity of the borehole (<10 m radius). The associated reactivated fault areas would be relatively small and most likely not result in seismicity which could be felt at surface – unless stress changes are able to trigger theoretically larger events, albeit at much lower probability.

Sensitivities:

- The results for potential fault reactivation are very sensitive to the in-situ stress assumptions. Adopting a higher horizontal stress gradient of 17 MPa/km instead of the base case 15 MPa/km, results in more stable predictions, both in terms of SCU for fault reactivation, as well as tensile stresses at the bore hole wall, positively affecting borehole stability.
- The sensitivity to fault reactivation has been analyzed for a higher estimate of the friction angle of pre-existing faults (in line with the range given in Table 1). This results in reduced SCU values, preventing shear failure for existing faults. Well bore stability is still prone to high tensile stresses.
- Lower injection temperature will result in larger cooling of the well bore, in particular at the bore hole wall. In order to test the sensitivity to lower injection temperature, the injection temperature was reduced from to 40°C. Consequently, this resulted in more accentuated bore-hole instabilities and a potentially larger instable zone for frictional reactivation of pre-existing faults, further away from the borehole.

Subsequently, based on the thermal performance and EL construction and operational characteristics, a Life Cycle Assessment (LCA) and quantitative assessment of the produced CO_2 per GJ heat produced has been conducted and a comparison with a conventional geothermal doublet system was made:

- the emissions (kg CO_2-eq/GJ) of the EL loop are ca. 20% less compared to a conventional geothermal doublet system, saving over 2 kg CO_2-eq/GJ. In more detail, the emission related to system construction is slightly higher than a conventional doublet, given that much longer sections are drilled. However, the operation-related emissions are characterized by reduced pumping power and absence of formation gas compared to a conventional doublet system, which over the lifetime of operations offsets the increase related to construction.

Table 1: Parameters used in the Tilburg Case study

parameter	value	unit	remarks
target formation	Triassic		
laterals			
lateral length (times two)	2180	m	see well survey points (WP3 report)
start depth	3450	m	see well survey points (WP3 report)
end depth	3125	m	see well survey points (WP3 report)
lateral dip	-7.8	degrees	see well survey points (WP3 report)
number of laterals	12		
horizontal spacing laterals	65	m	maximum lateral extent is 325 m from the main lateral
vertical spacing laterals	75	m	return is deepest located 32.5 m below specified depths, inlet is located 32.5 m above specified depths
Build Up Rate (deg/30m)	6		

diameter wells	8.5	inch	
thermal properties/model			
typical porosity	7	%	Tilburg area Triassic core plug porosities are in the range 6-10%, ~7% on average. 'Good' reservoir zones have 8-13% (5-26 mD), 'poor' zones 7-8% (0.06 – 0.5 mD) (BP report 'Sedimentology and reservoir quality of the Middle and Upper Bunter Formations')
conductivity laterals	3	W m-1 K-1	Limberger et al., 2019. The P3 petrophysical properties database (Bär Reinsch & Bott 2020) has average bulk thermal conductivities for Triassic sandstone (measured in Germany so likely comparable with the Netherlands) between 2.8 (fine sandstone) and 3.6 (coarse sandstone). 'Average' sandstone has 3.0. The latter is in line with Limberger. Chris Dalby core data measurements on Triassic sandstones (relatively nearby wells Werkendam, Waalwijk Noord, Steelhoven) has average 4.2 for horizontal, saturated.
conductivity vertical sections	2.25	W m-1 K-2	
rock heat capacity	3	MJ K-1 m-3	Limberger et al., 2017
fluid heat capacity	4.18	kJ K-1 kg-1	water
temperature model	Gies et al., 2021		See WP3 report **Error! Reference source not found.**
mechanical parameters			
Young's modulus	20	GPa	lab experiments (range 21 -25 Gpa)
Poisson's ratio	0.2		lab experiments (range 0.05-0.16)
linear expansion coefficient	1.50E-05	K-1	lab experiments (range 0.9-2E-5)
cohesion	20	MPa	lab experiments (range 26-41 Mpa)
friction angle	31	degrees	lab experiments (range 29-40 Degree)
in-situ stress			
SH (maximum total horizontal stress)	21	MPa km-1	oriented in direction of the lateral azimuth ~150, stress report wUP
sh (minimum total horizontal stress)	15	MPa km-1	stress report wUP, perpendicular to lateral
sv (vertical total stress)	22	MPa km-1	stress report wUP
hydrostatic pressure	10.6	MPa km-1	brine

3.5. WP4: System integration of Eavor Loop into district heating

This Work package focused on the optimisation of the Eavor Loop (EL) design towards district heating network integration, showcased for the Amer network. The Eavor loop contains many engineering and operational parameters, which need to be tailored for system integration in heat networks.

The system integration of the EAVOR Loop in the district heating network consists of 2 sub-work packages:

1. Physical connection to existing grid with the technical capacity of absorbing the EAVOR loop heat
2. Simulation of heat demand profiles and temperatures to determine the capacity feed-in of the loop without a negative impact on the quality (temperatures) of the heat delivered to the customers.

The physical connection between the EL and heat grid consists of a connection point in the existing grid and a new connection pipeline between the Eavor inlet and the existing grid (Figure 5). The technical design has been modelled with Sishyd software. The connection point has been identified by comparing the most logical (geographical) options, which resulted in one most logical connection point. For the technical design are based on the technical requirements received from the EAVOR loop. One important output of the design is the diameter of the connection pipeline. With the concept design a concept budget could be made. The accuracy of the budget will increase in the upcoming project phases.

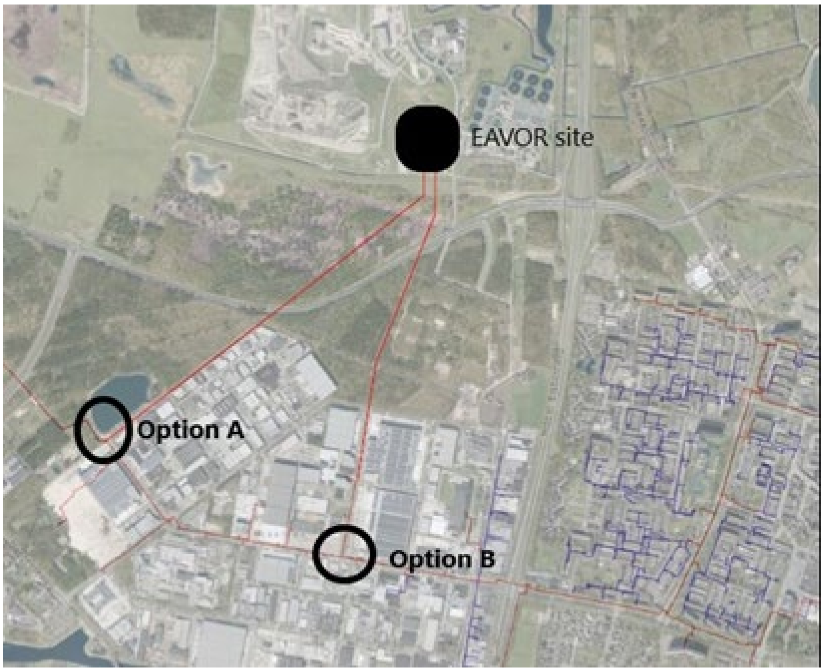

Figure 6: Grid connection options

For the simulation of demand and temperatures two approached have been used. EnNatuurlijk has modeled the heat demand for the EAVOR loop with historical data (hourly basis) of the heat grid and taken into account that there always needs to be a minimum capacity from other heat sources to avoid the cooling down of the transport grid to these other sources. The current temperature regime of the heat grid has mostly been treated as a given. Still, lowering the supply and return temperature reduction will be an important point of attention and topic for further optimalisation. For a next phase of the project future scenario's for optimalisation can be considered in the project valuation.

Besides the historical simulation, another simulation has been done by TNO using the Design Toolkit software. With this software several scenarios have been explored to understand the impact of the EAVOR loop in the heat grid temperatures. Overall, it shows that a temperature drop of the network mainly occurs in high heat-demand periods and that mainly the industrial area "Kraaiven" is subjected to a potential temperature drop if no measures are taken.

3.6. WP5: Outlook for wider implementation in the Netherlands

A short study was conducted in which the 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 for the entire county of the Netherlands. The general Eavor Loop placement criteria were fine-tuned during the feasibility study (WP1) to address commercial application of the technique in the Netherlands.

The criteria can be divided in three categories:

1) Criteria which are a function of the specific formation:
   - Rock thermal conductivity: minimum 2.5 W/m.K
   - Hole stability: consolidated formation, no reactivity with water
   - Drillability (abrasiveness/UCS)
   - Porosity/permeability: no restrictions

2) Criteria which are a function of the location at regional scale:
   - Temperature gradient: minimum 30 °C/km
   - Formation minimum temperature: minimum 110 °C
   - Depth maximum: 4500 meter
   - Thickness minimum: 30 meter

3) Criteria that are very specific to the local situation and which cannot be studied using national scale databases:
   - Layer dip angle versus drilling orientation
   - Stress data
   - Faulting (parallel and crossing, defining layer continuity and maximum possible lateral length).

The most restrictive and therefore most important subsurface criterium for EL development turned out to be the minimum required temperature of 110 °C in combination with sufficient rock strength and thermal conductivity.

The criteria which are specific to a formation were compared to the lithological column of the Netherlands. This resulted in the identification of the competent sandstones, siltstones and carbonates from Jurassic age and older as most favourable candidates: the Bunter sandstones, Rotliegend sandstones, Dinantian carbonates and possibly the Devonian sandstones. Of the latter two there is insufficient data in the database to include them in an automated search.

For these lithologies it was investigated where they are present at the right depth to reach the minimum temperature but not too deep for them to be out of reach for existing drilling technology. A set of maps were generated based on data from various sources, see Figure 7 for the final map where all criteria are favourable.

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.

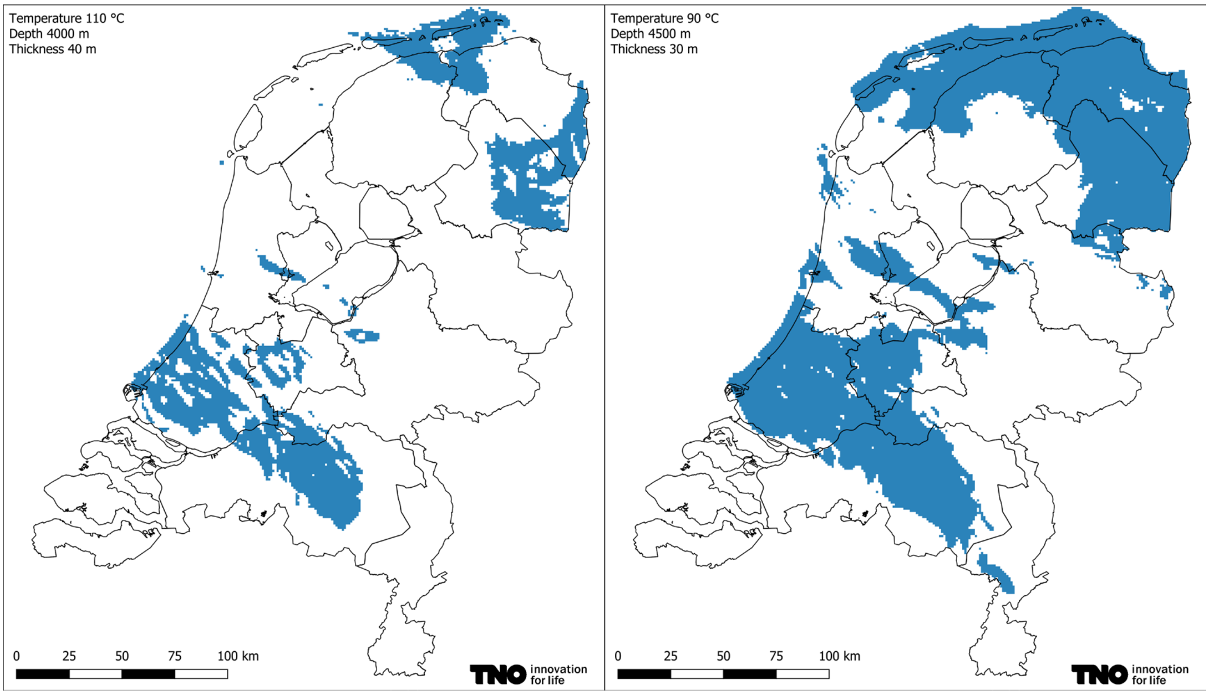

Figure 7: prospective areas (in blue) or so-called sweet spots where all criteria deem favourable for EL development. Left figure shows strict criteria, while right figure shows more relaxed (or loosened) criteria, resulting in larger prospective areas.

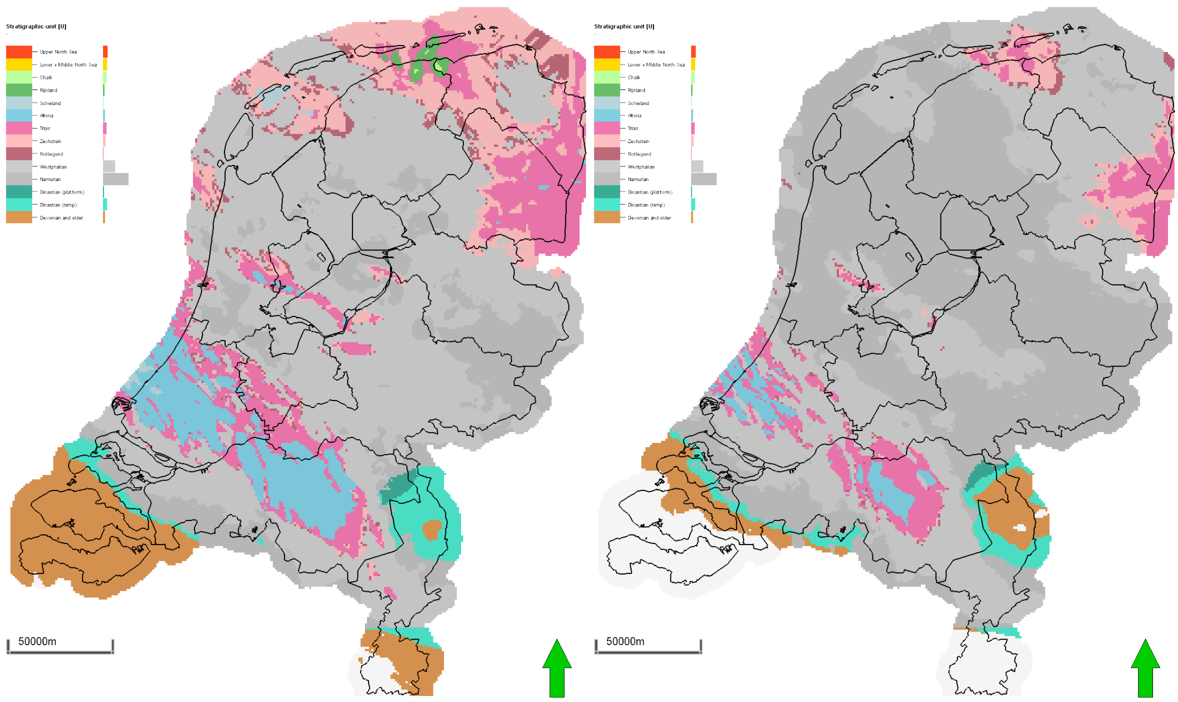

Figure 8: Subcrop of litho-stratigraphic units at the 90 °C (left) and 110 °C (right) isotherms

Figure 8 shows the lithology at the depth corresponding to the current formation temperature cut-off of 110 °C and for a potential future lower cut off 90 °C. From these maps it is clear that in large parts of the Netherlands the most prospective layers i.e., Bunter (pink colour/Trias) and Rotliegend sandstones (brown-pinkish colour) are too shallow. From the Dinantian and Devonian prospective layers there is insufficient data to be able to prepare reliable maps.

A formation thickness of less than 30m is another important restriction that has been evaluated using various data sources. Only the ThermoGIS database has the required granularity to screen for this criterium on the basis of the individual members. This criterium turned out not to limit the potential area more than the minimum temperature.

The conclusion from WP 5 is that the most favourable conditions for EL placement are found in the West Netherlands Basin and the Ruhr Valley Graben, the Lauwerszee Trough and the Lower Saxony Basin (see blue area in Figure 9).

Older units like the Carboniferous Limestone and Devonian rocks may be interesting too but information about the nature of the rocks is limited. Furthermore, the rocks of these units are usually buried to depths exceeding 4500m.

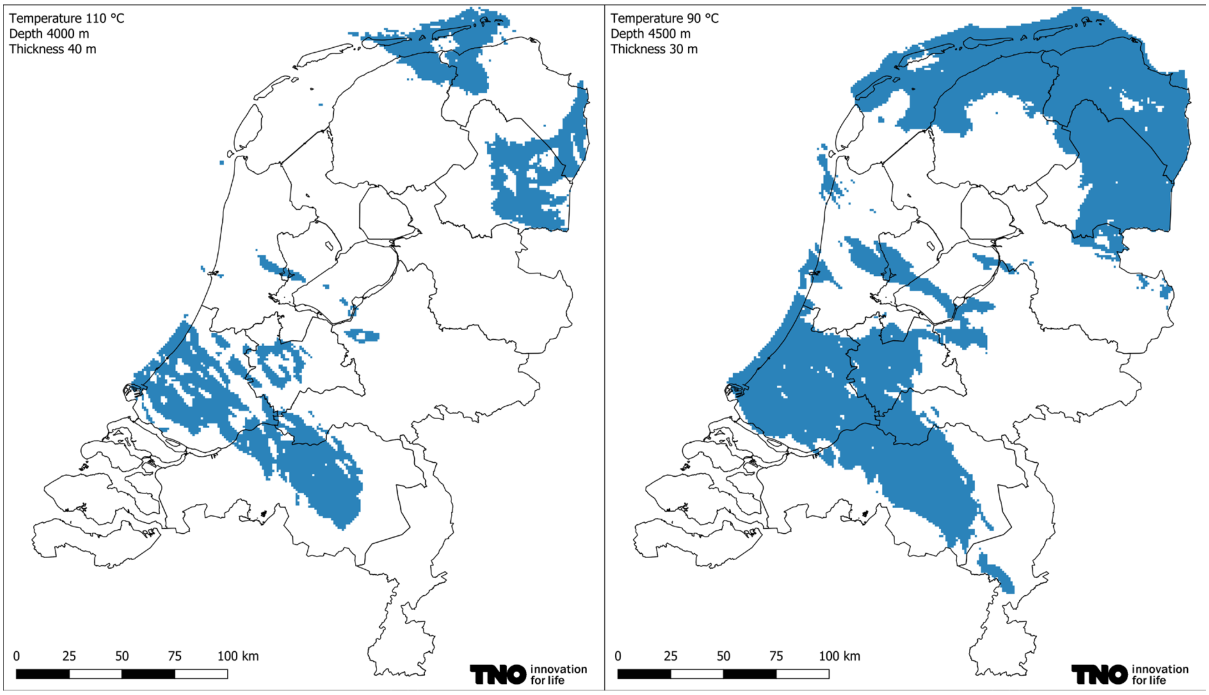

Figure 9: prospective areas when combining all selection criteria. Left: base-case criteria, right: loosened criteria.

3.7. KPI table

KPI	Omschrijving
TRL at completion, main category	Industrial Research: TRL: 6; demonstrating the (technically & economically) feasible drilling & implementation of the EL technology in the Amer heat network.
TRL at completion, subcategory	• Feasibility study of Tilburg subsurface area for EL: can not be expressed in TRL level as standard available technology was used. • Laboratory testing of conductivity rock properties (fundamental research): TRL 2. All other lab experiments are proven technology. • Optimise drilling rig design & practices for EL: TRL 8 • Validation of environmental impact, safety and CO_2 footprint of EL: TRL 8 to 9

KPI	Omschrijving
Project success	• Optimised EL design and operational parameters for integration to Amer heat network: TRL 8 to 9 • Outlook for wider implementation of EL in the Netherlands: not suitable for TRL classification • EL multilateral technology: TRL 8 to 9 1. The project has been completed in accordance with the original scope. All milestones have been achieved
Follow up	The project can be seen as the precursor of the NieuweWarmteNu project currently being developed.
Number of peer-reviewed publications	0
Number of expected peer-reviewed publications	0
Number of non-peer-reviewed publications	1 (at Geoconvention, Calgary, 2023), more publications expected
Number of submitted patents & doi's	0
Number of granted licenties	NA
Number of prototypes	NA
Number of demonstrators	This project entails the demonstration of new technology in a specific area. The project has shown the feasibility of the demonstration and planning is ongoing to conduct the project.
Number of spin-offs/ spin-outs	The results of this project have been used for SDE application as well as for exploration license renewal.
Number of new or improved products/technologies/services	- ,
Impact	Within the current market, the technology is only economically viable with CAPEX subsidy and SDE++ guaranteed pricing.

4. Conclusions and recommendations

4.1. Conclusions

The overall conclusion is that the project has resulted in determining that an Eavor Loop system for the Tilburg area can be seen as a possible option for a renewable heat source for the existing Amer heat network.

The sub- conclusions are:

- The Eavor-Loop™ has a long lifetime marked by a very moderate linear decline of the production temperature and power over a lifetime of 10s of years, with minor thermal interference of laterals if placed with a spacing of ca 70 m.
- Suitable subsurface conditions for Eavor-Loop™ development have been identified resulting in a potential 13 MWth Eavor-Loop™ capacity. However, restrictions in available surface drilling locations in urban areas resulted in suboptimal loop design and depth. In this case the length of the laterals is limited to 2100m because they are planned to run slightly updip and have a therefore result in a reduced Eavor-Loop™ capacity of 9MWth in the summer months.
- Extensive modeling of the stress changes as a result of the gradual cooling and operation of the Eavor-Loop™ is not expected to induce seismicity or to reactivate existing faults. The modelling also indicated that the open-hole laterals will be stable over time.
- The connection with the heat network is complicated by the fact that this old network requires an inlet temperature of 120°C in the winter months. An optimisation was carried out with the outcome that a heat-pump will be needed to boost the temperature in the winter. Lowering the district heating network temperature in the winter is possible and should be pursued. This will increase the thermal capacity of the Eavor-Loop™.
- The possibility to start and stop the Eavor-Loop™ and use all its daily capacity during peak hours is valuable but was not quantified in this study.
- The base cost estimate has been prepared assuming the use of existing drilling rigs and available technology. Under these conditions, the application of the EL is considered economic, but only if CAPEX subsidy and SDE++ subsidy is taken into account. By comparison, a 20% reduction in drilling cost can be achieved by using a semi-custom dual derrick Huisman drilling rig. A cost saving of this magnitude would make this project commercial without CAPEX subsidy.
- Eavor-Loop™ development is not possible everywhere in the Netherlands due to restrictions in minimum required temperature (110 °C) in combination with sufficient rock strength and thermal conductivity.
- The presence of the Carboniferous formation over a large portion of the depth range suitable for EL developments. The Upper Carboniferous is overall quite shale and coal rich, this not a viable target for the current versions of the Eavor-Loop™ technology. The Lower Carboniferous Dinantian platform carbonates do hold some potential and could be derisked throughout the Netherlands with seismic data acquisition and deep exploration drilling programs

4.2. Recommendations

The following research questions and recommendations for further work are identified at project closure:

- **WP1: extend laboratory work**
  - General: design and build an experimental set up that can accurately measure thermal conductivity from core samples.
  - For Tilburg area: provide thermal conductivity from rock samples, construct thermal conductivity "logs".
  - For Tilburg area: determine the tensile strength (Brazilian test)
  - Extend rock property measurements for relevant rock formations present elsewhere in the Netherlands
  - Determine correlation between rock properties and drilling ROP

- **WP2: enhanced automation**
  - Utilise AI to optimise & automate drilling process with a focus on drilling speed and mud parameterisations.

- **WP3: fault modeling**
  - For Tilburg area: model fault rupture scenarios based on stochastic assumptions of pre-existing fault geometry and properties. This can be done effectively with linear elastic fracture models. Sense-check the expectation that potential fault rupture is very limited in space (non-felt magnitudes) and unlikely to occur.
  - For Tilburg area: map active vs. non-active faults and their effect on the mechanical reactivation response.

- **WP4: heat usage optimisations**
  - In depth assessment and optimisation of use of heat pumps, and added value of seasonal heat storage in combination with EL

- **WP5: update & refine**
  - Evaluate the potential of Dinantian formation through data collection, interpretation, and modelling.
  - Update the findings based on outcome of follow-up research questions.

5. Project execution

The ELFO project was coordinated by TNO, with each consortium partner leading a dedicated work package. Monthly Project Management Board meetings ensured for regular exchange of information, status updates and provided the opportunity to flag issues. Additional technical meetings within and across work packages allowed for in depth technical discussions and alignment, though more integration meetings could have resulted in improved communication about use of parameterization, assumptions and required input data. All participants were committed to collaborate and considering the project was fully online, engagement of partners was good.

The project was concluded with an in-person close-out meeting, with consortium partners and stakeholders attending from the Netherlands, Germany and Canada.

5.1. Technical & organisational issues

The geographical spread of the participating organisations in the Consortium is spanning across 2 different time zones, with the majority of the Eavor workforce being located in Calgary (UTC -6 or -7 hrs). Workshops, Management Board Meetings and Work Package meetings were therefore scheduled in the CET afternoons, to allow for as much as possible time overlap for communication and collaboration. This proved to be a very effective approach and the transnational time zone challenge was easily overcome.

Minor technical challenges were faced during the laboratory experiments in the iM4RockLab of TNO Applied Geosciences in Utrecht for measuring mechanical properties of the claystone rock samples. Unfortunately, it was not possible to extract intact cores from the claystone ELFO_3.

Due to the complexity of accurately measuring thermal conductivity, it was decided to use analogue data as published by Dalby et al 2018.

5.2. Changes in project plan

Several Work Packages suffered from delays in project execution due to COVID-19 related illnesses. Therefore, additional time was required, and a 3-month project extension was granted by TKI to ensure delivery and integration of results between all Work Packages. The project scope has not been amended.

5.3. Knowledge transfer

The final reports for each Work Package are publicly available, describing the details of the work conducted, as well as the findings, conclusions and recommendations.

The results from the laboratory experiments on deriving mechanical rock properties conducted by TNO on core plugs are made available thought the DINO / NLOG portal.

At the moment of writing this report, a webinar is being planned for the Dutch public to raise awareness about the technique as an alternative to conventional geothermal systems and more specifically about the Tilburg case study.

Several abstracts have been submitted (or are being constructed) to disseminate the project results at international conferences for wider visibility.

6. Contribution to research area

6.1. TKI Urban Energy MMIP's

The results of the ELFO study have contributed to the goals of TKI Urban Energy for sustainable heat networks and Geothermal systems (MMIP 4) by demonstrating feasibility of the Eavor Loop (EL) technology as a renewable heat source for the Amer city heating network in Tilburg. The complexities, uncertainties and risks regarding system integration, safety, environmental impact of the geothermal system and reduction of CO_2 emissions have been identified and evaluated. It can be concluded that the Eavor Loop system can be constructed safely in the deep subsurface of the Tilburg area, with very low risk of induced seismicity, no leakage to the environment, and reduced CO_2 emissions compared to conventional geothermal systems. Additionally, the study has demonstrated that the Eavor Loop system can be integrated into the relatively old Amer city heat network, locating the optimal tie-in point. It shows that a temperature drop of the network mainly occurs in high heat-demand periods and that mainly the industrial area "Kraaiven" is subjected to a potential temperature drop if no measures are taken. A heat-pump will be needed to boost the temperature in the winter to avoid temperature drops. The optimum capacity for a 30-year flat profile was derived to be 9.1 MW in summer months and 7.1MW in winter months, with a yearly heat production of 74.000 MWh.

6.2. Dutch economy

6.2.1. Eavor Loop Market

Implementation of the Eavor-Loop™ as one of the key geothermal techniques in the Netherlands, faces several commercialization challenges. These include achieving low drilling costs while being dependent on factors such as reservoir temperature and lithology for sufficient heat transfer, but also to ensure drillability of the well laterals and safe operation and production throughout the well's life-time. The goal is to construct a rig that can be financed out of the project at a lower cost than existing systems, with Huisman R&D initially being the main financial contributor to its development.

The ELFO study demonstrates that the Eavor-Loop™ is a more attractive geothermal production technology than conventional systems from a societal and economic perspective. It is a closed loop, highly controllable system that does not depend on a permeable reservoir and has no environmental interaction with the subsurface or CO_2 emissions. The combined results from WP1 to WP4 show that it is feasible to implement the Eavor Loop system into the current heat network of Tilburg, considering geological, technical, and economic parameters and sensitivities as well as their safety and environmental aspects.

Additionally, WP5 shows that there is potential for the Eavor Loop to be developed in other regions in the Netherlands where traditional systems cannot be applied due to the absence of immature, but it has been successfully demonstrated in a pilot in Canada, and another initiative code named 'Eavor-Deep™' spud September 2022, which is considered the deepest and hottest geothermal well in history.

The ELFO project shows that the Eavor Loop technology has potential for both direct heat applications and production of electricity at locations lacking sufficient underground permeability, like the Tilburg area. To achieve this potential on a large scale, dedicated rigs would be required, which are equipped of drilling these types of wells in an urban environment in a cost-effective manner 24/7. Therefore, WP2 focused on designing a new semi-automated dual-derrick rig and drilling procedures to provide efficient, safe, and environmentally friendly Eavor-Loop™ drilling. Current estimates show that ~40% time and 16-20% of costs savings can be achieved during drilling of an Eavor Loop well through automation of tripping, dual-derrick system and faster pipe adding. The automation of many processes, including the use of a dual-derrick instead of a single rig, also leads to reductions in crew size and therefore overall costs. Optimisations to the currently developed dedicated rig are identified that could enable even faster uptake of the technology.

6.2.2. Financial

The ELFO study has succeeded in demonstrating commercial feasibility of drilling the first loop in the Netherlands, the Tilburg area. In parallel with the ongoing ELFO study, and SDE++ subsidy application was being conducted to put the ELFO results into practice and proceed to the FEED stage to ultimately construct the Eavor Loop Technology as part of the Amer heat network in Tilburg.

The study provided a more accurate estimate of the capital cost of 54,5MM € (instead of the assumed 46MM € at project start) with a unlevered IRR of 8% (instead of the assumed 6.1%) over the project's life time of 30 years. The technology is expected to become more cost-effective with economy of scale and innovation, and eventually will not need any subsidy. The drilling of the loops will create several times more employment than the fossil drilling industry, and the manufacturing of advanced drilling systems will also create significant growth in employment.

6.2.3. Business case end-user

In the (near) future, end users of heat, like city heating systems and greenhouses, can no longer be expected to use biomass for new heat applications. Thereby making geothermal heat the only alternative for mid and high temperature applications. In areas with good permeability in the underground, conventional geothermal is more economic. However, with Eavor-Loop™ generated geothermal heat, it should be possible for city heating systems to become completely CO_2 neutral at an affordable cost for customers.

6.3. Strengthening Dutch knowledge position

The technological thresholds that must be overcome for the Netherlands is proving the technology in the Dutch sedimentary subsurface and to start a learning curve that will lead to a capital cost level at which an Eavor Loop system can be developed without the need for subsidy. Therefore, the ELFO study focused on the several aspects related to these technology thresholds; a suitable subsurface able to produce sufficient heat while maintaining operational safety, optimised drilling processes, system network integration and applicability elsewhere in the Netherlands for wider adaptation.

6.3.1. Subsurface feasibility

The subsurface feasibility research as carried out for the ELFO project has contributed to a robust prediction of the subsurface near the City of Tilburg, indicating favourable conditions for deployment of an Eavor Loop system in the Lower German Triassic sandstone rich Volpriehausen, Detfurth and Hardegsen members. Given the low uncertainty on Heat in Place it is possible to predict energy yield with relatively high confidence. An expected energy yield of 9.1 MW in summer months and 7.1 MW in the winter months and an approximate annual production of 74,000 MWh of clean baseload heating into the Amer heating network

6.3.2. Improved understanding of heat transfer, borehole stability and life-cycle footprint of closed loop geothermal systems

Dedicated numerical thermal models have been designed and optimised for the purpose of the ELFO study with parameterisation applicable to the Tilburg subsurface and operational assumptions of the

Eavor Loop design. The approach is the first in its kind for these type of closed loop systems and shows the practical usage of the simulation and sensitivity results with robust predictions of stable borehole conditions, no to low risk of fault reactivation and the impact when lowering the injection temperature.

The Life Cycle Analysis has improved our understanding of the emission characteristics (kg CO_2-eq/GJ) of the Eavor-Loop™. The study shows that these are ca 20% improved compared to a conventional geothermal doublet system, saving over 2 kg CO_2-eq/GJ.

6.3.3. Improved drilling processes

The Eavor Loop is an alternative technique to extract heat from low to non-permeable rock compared to other methods like closed loop systems in a single vertical well or Enhanced Geothermal Systems (EGS). The EGS method is marked by hydraulic fracking but due to the risk of induced seismicity and the current political and public debate on this topic, its applicability in the Netherlands is doubtful.

The current market onshore drilling rigs are dedicated to the oil and gas market, with modifications made to adapt to the geothermal application, providing semi-efficient rigs. However, drilling of Eavor Loop systems is new to the geothermal market and these semi-efficient rigs will be even less efficient to drill Eavor Loop systems. The study conducted in WP2 by Huisman B.V., a custom-built drilling equipment specialist, has shown that innovation can lead to optimsed, dedicated drilling rigs and improved (automated) drilling procedures to improve efficiency, safety and consistency when drilling Eavor Loop well systems.

6.3.4. ELFO use case for Design Toolkit; a heat system integration tool

The Design Toolkit, as developed during the WarmingUp Project (MOOI call), has been used evaluate the operational dispatch of the Eavor Loop in the Amer heat grid as well as to demonstrate its applicability (and limitations) in this Tilburg use case. The study highlighted several complexities and struggles when using existing data (e.g. data loading of the heat network grid, requirements to simplify the heat network to limited number of clusters, availability of detailed heat demand profiles), but it also showed its value by quantifying the flow distribution based on the heat demand of all consumers and heat production characteristics of the Eavor Loop. It provided valuable insights into the optimisation of a city heat network, and how to best mitigate for temperature drops or stagnation of flow within the network. The knowledge obtained during this use case can be used to improve functionality of the Design Toolkit.

6.3.5. Improved understanding of applicability elsewhere in the Netherlands

Overall, the ELFO study has resulted in improved knowledge about the suitability of the Tilburg subsurface for deployment of an Eavor loop system from well placement & integrity perspective, drilling perspective and heat transfer perspective as well as highlighting favourable regions elsewhere in the Netherlands for an Eavor Loop placement. While data availability was found scarce (particularly for the deeper and older Carboniferous Limestone and Devonian rocks), areas worth investigating more are found in the West Netherlands Basin, the Roer Valley Graben, the Lauwerszee Trough and the Lower Saxony Basin.

7. Spin off

The Eavor Tilburg project has progressed to the FEED stage. Partners ENN, EBN and Eavor are working on the plans for this stage based on the outcome of the feasibility study. The results of WP1 and WP 3 were utilized for the successful application of a NWN subsidy and for the SDE ++ application. Due to a legal dispute with Tilburg a new exploration permit was required, and the results of WP 3 were used to show that safety and environmental risks are well under control.

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