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## Recovery Factor of Geothermal Resources

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### ABSTRACT

Geothermal resources are often exploited by multiple independent operators with potentially conflicting objectives. As a result, exploration licences are issued on a first-come, first-served basis. Alternatively, doublet deployment could be based on a regional masterplan that aims to optimise heat recovery, which is common-practice in the hydrocarbon industry. This study compares the impact of geothermal well deployment following those two different approaches on (1) recovery efficiency, (2) Net Present Value and (3) its CO<sub>2</sub> footprint. We conduct heat transfer simulations of exploitation of Lower Cretaceous Sandstones in the West Netherlands Basin. This Hot Sedimentary Aquifer is the main target for ongoing geothermal exploitation in the Netherlands. In the simulations, doublet wells were deployed following the ‘first-come, first-served’ doublet deployment, which is based on the location of two currently active doublets. In addition, simulations are conducted in which doublets are deployed with a hypothetical, regional coordinated, optimised ‘masterplan’ approach. Results of this study indicate that there is significant scope to optimise doublet density and recovery efficiency of geothermal heat when doublets are deployed in a regionally coordinated ‘masterplan’. This is because with a ‘first come, first served’ approach, doublet placement and design mainly aims to meet targets of individual operators and remaining space might be too small for new operators leaving much of the resource untapped. Optimisation of doublet deployment and licensing is required to make geothermal a more significant player in a future low-carbon energy mix. Firstly, this would require new tailor-made geothermal subsidy schemes that promote deployment optimisation over the ‘first come, first served’ deployment. Secondly, it requires tailor-made legislations that accommodate for increased interference between operators that is inevitable with denser doublet deployment. Finally we show that geothermal exploitation has a very low carbon footprint, highlighting its value to meet low-carbon energy targets. This study could assist in the development of realistic geothermal exploitation targets and the development of required financial and legislative support schemes to promote more efficient use of the enormous amounts of geothermal heat.

### 1. INTRODUCTION

The Netherlands hosted one of the fastest growing geothermal industries in the past decade. Some 18 doublets (injector-producer well pairs) with a combined capacity of 221 MW<sub>th</sub> were realised since 2007 (Provoost et al., 2019). Heat In Place estimates indicated that there is still significant scope for further expansion (Kramers et al., 2012) and ambitious targets have been defined by the government and government agencies for the future role of geothermal energy in the Netherlands to reach a 30 PJ/yr heat production rate from geothermal resources (Schoof et al., 2018). Considering that the current doublets produce approximately 3 PJ/yr (Provoost et al., 2019), approximately ten times more doublets have to be realised. So far, doublets have been realised by individual operators with one or few doublets and deployment and licencing has been based on a ‘first come, first served approach’. This is common for various types of geothermal exploitation, ranging from Aquifer Thermal Energy Storage (ATES) to high enthalpy geothermal electricity production (e.g. Bloemendal et al., 2018; Tureyen et al., 2015). Often doublet design is based on the individual heat requirements of the individual operators and based on engineering judgement. In contrast, hydrocarbon resources are typically developed by a single operator utilizing a field development plan that aims to optimise recovery from the entire resources, instead of the performance of individual wells. Willems et al., (2017a,b) showed that the well and doublet spacings can be reduced depending on the design lifetime in homogeneous reservoirs. Considering heterogeneous reservoirs, Crooijmans et al., (2017) and Babaie and Nick (2019) also illustrated that the well spacing can be reduced compared to what has been implemented in the Netherlands (~1500 m). This study investigates the scope of optimisation of heat recovery of geothermal resources. This is done by numerically simulating exploitation of a low-enthalpy resource in the West Netherlands Basin with three different deployment strategies. We quantify the Net present Value (NPV), Levelised Costs Of Heat (LCOH) and carbon footprint of the currently used ‘first come, first served approach’ with optimised deployment strategies whereby deployment of doublets is coordinated according to a regional masterplan and investments for surface facilities are shared by neighbouring operators. The CO<sub>2</sub> footprint is analysed utilising a life cycle assessment of greenhouse gas emissions developed by McCay et al. (2019). The aim of this study is to indicate that there is significant scope for optimisation and a need to update legislation a subsidy schemes to meet the ambitious targets for geothermal energy production, not only for the Netherlands but world-wide.

## 2. METHOD AND DATA

### 2.1 Aquifer model and thermal flow modelling

Numerical production simulations were used to compare recovery efficiency with three different deployment scenarios in a simplified homogenous aquifer model the Lower Cretaceous Nieuwerkerk Formation in one fault block in the West Netherlands Basin (Figure 1). The model consisted of a horizontal 100 m thick homogeneous sandstone layer, which was confined between 300 m impermeable over- and underburden layers providing thermal recharge. Two of the four boundaries of the model were formed by faults, derived from the WNB structural analysis of Duin et al., (2006). The aquifer properties were assumed isotropic. The aquifer permeability and porosity were 1000 mD, and 20%, respectively. The permeability of the confining layers was 10 mD and 10%, respectively. Other aquifer properties including heat capacities, and heat conductivities were derived from Willems et al., (2017c). Element size ranged from 0.3 m to 40 m in the aquifer layer and from 40 m to 300 m in the confining layers.

For thermal flow modelling, the energy balance was solved for a rigid medium fully saturated with water, with thermal equilibrium between the fluid and solid phases:  $\partial/\partial t (\rho C_r T) + \rho_w C_w \nabla \cdot (\mathbf{q} T) - \nabla \cdot (\lambda \nabla T) = 0$ , where  $t$  [s] is time,  $T$  [K] is the temperature,  $\rho$  [kg/m<sup>3</sup>] and  $C_r$  [J/(kgK)] are the temperature independent mass density and specific heat capacity, respectively. Subscripts reference to the rock- ( $r$ ) and water ( $w$ ) phase.  $\lambda$  [W/(mK)] is the thermal conductivity tensor. The thermal conductivity is equal to  $\lambda_{eq}I + \lambda_{dis}$ , and the volumetric heat capacity is described in terms of a local volume average. Where  $\lambda_{dis}$  is the thermal dispersion tensor and  $I$  the identity matrix.  $\mathbf{q} = -K\mu \nabla h$  is the Darcy velocity vector, with hydraulic conductivity  $K = k_i \rho_w g / \mu$ , where  $k_i$  [m<sup>2</sup>] is the sandstone or shale permeability,  $g$  gravitation acceleration and  $\mu$  the temperature dependent viscosity. We utilised the empirical viscosity temperature dependency of Mercer and Pinder, (1974). The production simulations yield a pressure development and production temperature development over time for each well. The difference between injection and production pressures for each doublet ( $\Delta P$ ) was used to estimate pump energy losses:  $E_{pump} = (Q \Delta P) / \epsilon$ , where  $Q$  is the production rate and  $\epsilon$  the pump efficiency of 60%. The produced power ( $E_{prod}$ ) was estimated by:  $E_{prod} = Q \rho_w C_w \Delta T$ , in which  $\Delta T$  is the difference between injection temperature (35°C) and production temperature. The net energy ( $E_{net}$ ) is the sum of  $E_{prod}$  and  $E_{pump}$ . A more detailed description of the aquifer model and the thermal flow modelling can be found in Willems and M. Nick, (2019).

### 2.2 Doublet deployment scenarios

Three doublet deployment scenarios are considered in which 3, 9 and 16 doublets exploit the aquifer, respectively. All doublets are connected at the surface with a heat distribution grid to cover production down time for maintenance or repairs. The length and costs of this heat grid depends on the well spacing ( $L$ ) and the doublet distance ( $dx$ ). In scenario 1 and 2, injector and producer well pairs are drilled from one surface location. We assume a vertical drill section of 1200 m and a deviated one to Total Depth (TD) of 2200 m. The well length of the deviated section is calculated as the hypothenuse remaining 1000m to TD and half of the well spacing ( $L$ ). In scenario 3, we assume that two doublets are drilled from one drill pad. This slightly increases well length compared to scenario 2 but reduces required investments for the surface facilities and the length of the surface heat grid.

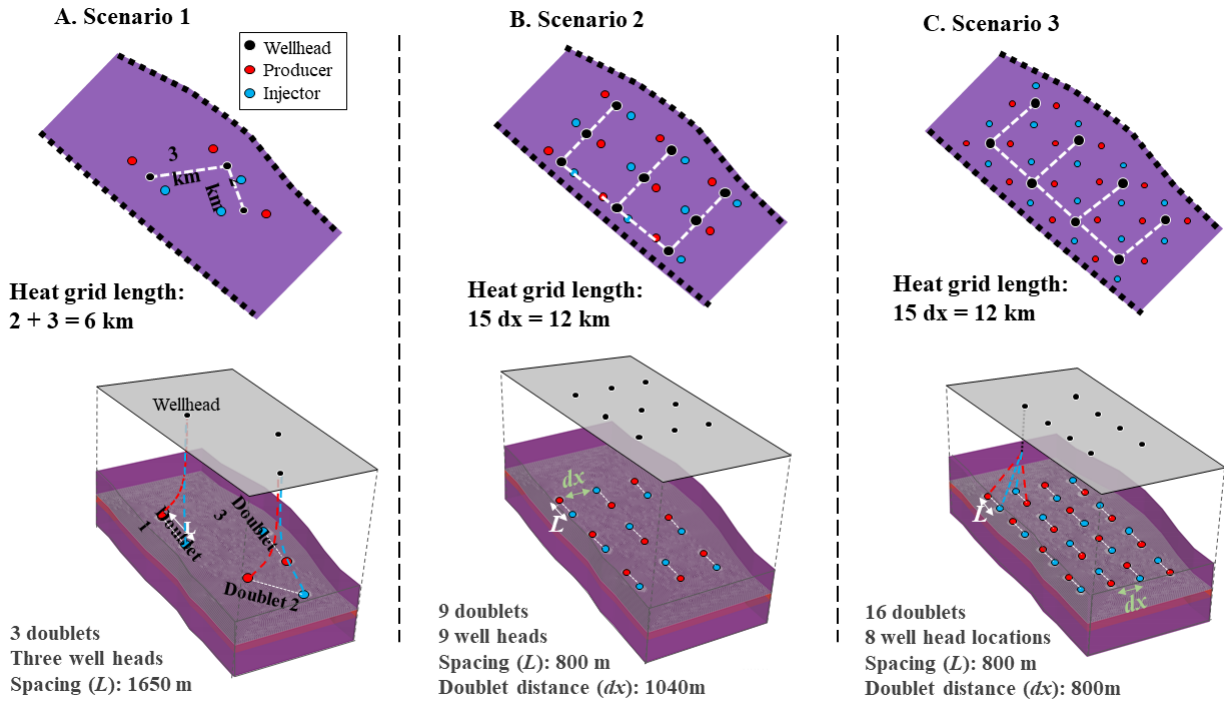


Figure 1: First row: Schematic map-view of the surface heat grid network (white dashed lines) length for three doublet deployment scenarios. It is assumed that operator that exploit multiple doublets need to invest in surface heat grids to sell their heat. Black dots indicate the wellhead surface locations. Second row: well trajectories are only shown in scenario 1 and the well intersection with the aquifer indicated by the red and blue dots. Black dots indicate the surface location of the wellheads (i.e. the surface termination of a wellbore) of the different doublets.

### 2.3 Levelized Cost of Heat

The Levelized Cost of Heat (LCOH) was determined for each doublet deployment scenario, using equation 1 following Daniilidis et al., (2017):

$$LCOH = \frac{\sum_{t=1}^n \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_{net,t}}{(1+r)^t}} \quad (1)$$

$CAPEX_t$  and  $OPEX_t$  are the respective total Capital and Operational expenses in year  $t$ , which are derived from Table 1,  $r$  is the discount rate and  $E_{net,t}$  is the cumulative generated amount of heat in year  $t$ , which is derived from the production simulations. ESP replacement is considered for each doublet every five years in the OPEX estimate. A thirty-year period is chosen because this is a minimal lifetime many operators hope to achieve. To calculate annual income, the annual heat production is multiplied by the heat price and the feed-in tariff subsidy that is only available for 15 years in the Netherlands. Net income is obtained by subtracting the OPEX and CAPEX from the net income. The Net Present Value of the different exploitation scenarios is obtained by summarising the discounted net income over the thirty-year lifetime, following the approach by Van Wees et al., (2012).

**Table 1: Economic parameters for the LCOH calculations based on (Daniilidis et al., 2017; Wees et al., 2010)**

Economic parameters	
Electricity price for operations	8 EUR/ GJ
discount rate ( $r$ )	7 %
Heat price	7 EUR/ GJ
Feed-in tariff (year 1 to 15)	8 EUR/ GJ
CAPEX	
Well costs	2 M€/km
Drilling location costs	1 M€
ESP	0,80 M€
Gas separator	0.21 M€
Heat Exchanger	0,10 M€
Geological risk insurance (Mijnlieff et al., 2013)	0.69 M€
Surface heat distribution network	1000 €/m
<i>CAPEX scenario 1</i>	39 M€
<i>CAPEX scenario 2</i>	108 M€
<i>CAPEX scenario 3</i>	183 M€
OPEX	5 % of Capex/y
Base energy price (2015)	0,052 EUR/ kWh
correction price (2015)	0,019 EUR/ kWh
contribution SDE+	9,17 EUR/ GJ

### 2.3 Carbonomics

The lifetime direct and indirect CO<sub>2</sub> emissions for the three scenarios (shown in figure 1) have been estimated using the Life Cycle Analysis for Heat-only Geothermal projects, developed by McCay et al. (2019). This analysis takes into account the most likely significant factors to emissions as a direct result of the geothermal development, such as diesel combustion from the drilling rig, as well as the indirect emissions, such as the manufacture of the steel borehole casing.

#### 2.3.1 Inventory Analysis

This section details the main processes involved in the construction and operation of the geothermal development which lead to the most significant CO<sub>2</sub> emissions. This is typically known as the Inventory Analysis of a Life Cycle Analysis and aims to clearly detail key assumptions and approximations. McCay et al. (2019) suggest that land use change can be a significant factor in geothermal developments. This is when virgin soils are disturbed and the carbon embedded in the soil reacts with oxygen in the air to produce CO<sub>2</sub>, such land use change can have surprisingly high emissions when high carbon soils are disturbed (Bond et al., 2014; Nayak et al., 2010). Because the study area discussed in this paper, however, is the West Netherlands Basin where soil is already disturbed, we assume that CO<sub>2</sub> emissions from land use change are insignificant.

Each of the three scenarios uses different layouts of surface heat grid pipes (Figure 1) to connect the doublets in each deployment scenario. Here, we follow Fröling et al. (2004) values of 380 kg of CO<sub>2</sub> emissions per 12 m section of pipe. Most of which is associated with the manufacture of the steel within the pipe. The main emissions from drilling boreholes comes from the diesel

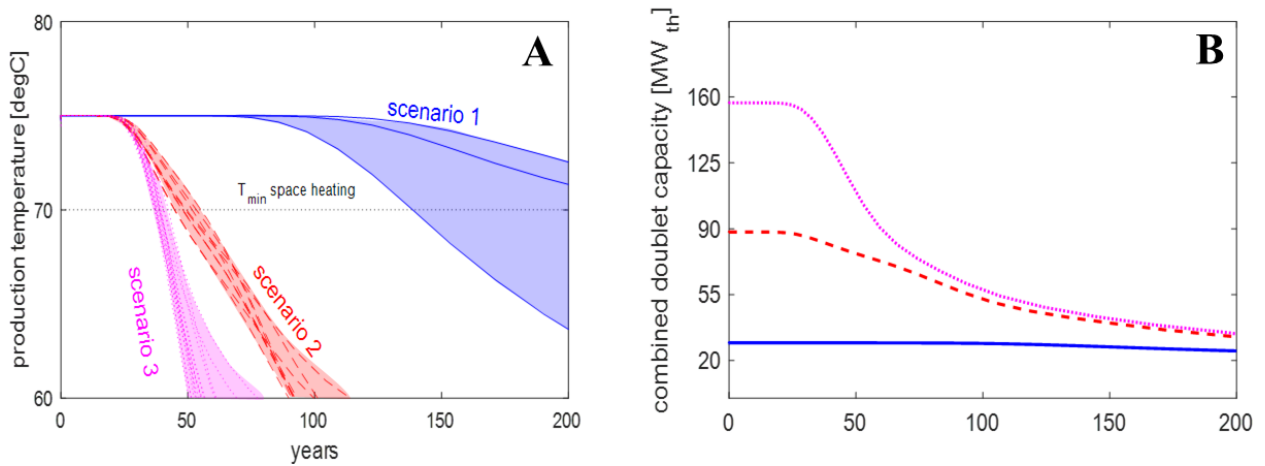
combustion required to power the drill rigs. We follow Bradley (1987) value of drill rig diesel consumption of around 157.7 litres per hour, and an emissions factor of 2.63 kg (CO<sub>2</sub>e) per litre of fuel combusted. Although there is no definite time that a borehole takes to be drilled, due to geological risk factors while drilling, we follow McCay et al. (2019) in using a general figure of 1500 working hours to drill boreholes between 2-2.5 km depth. Geothermal boreholes will be cemented and cased in steel the manufacture of both materials emitting large amounts of CO<sub>2</sub>. The exact layout and amount of materials used depends upon the geological and hydraulic conditions. We follow McCay et al. (2019) general well layout of well design used 17 1/2" casing to ~100 m, then 13 3/8" casing to ~500 m, then 9 5/8" diameter casings to line the production zone. We adopt this as the standard design assuming the production zone begins at 2100 m and a steel production liner with screens is lowered to the total depth of 2200 m. This is approximately 2600 m of casing and liner per borehole. We calculate the embedded carbon in the steel of the casing using an upper bound estimate of Yu et al., (2015) and WorldSteel (2016) of 2.7 t(CO<sub>2</sub>e)/t(steel). For cement we assume 900 kg(CO<sub>2</sub>e)/tonne (Salas et al, 2016). Drilling also requires water, which we assume 5000 m<sup>3</sup> is consumed per well and that indirect CO<sub>2</sub> emissions for water consumption and for water treatment and disposal are 0.34 kg(CO<sub>2</sub>e)/m<sup>3</sup> and 0.71 kg(CO<sub>2</sub>e)/m<sup>3</sup> respectively (DEFRA, 2018). During operation, the main source of emissions is from the power required for the hydraulic pumps. The pump losses are estimated as 60 kW per doublet for scenario 1 (3 doublets) and 50 kW per doublet for scenario 2 (9 doublets) and scenario 3 (16 doublets). The power is assumed to come from the Dutch electrical grid which is still has a significant amount of fossil fuel production, as such the carbon intensity of powering the pumps is estimated at around 500 kgCO<sub>2</sub>e/MWh<sub>e</sub>. We have also used a different scenario of 200 kgCO<sub>2</sub>e/MWh<sub>e</sub> to test the sensitivity to a decarbonising power grid over the project lifetime. The project lifetime for estimated direct and indirect CO<sub>2</sub>e emissions is 30 years. Each doublet is also assumed to produce 10 MW<sub>th</sub> with an 80% capacity factor. In all three scenarios the emissions from the power required to pump the geothermal fluids are the highest source of CO<sub>2</sub>e emissions, with the other significant factors also being the diesel combusted to power the drill rigs, and the indirect emissions from the steel and cement manufacturers.

**Table 2: Calculated CO<sub>2</sub> emissions in each doublet deployment scenario and associated assumptions.**

Activity	Scenario 1 Assumption	Scenario 1 emissions (t(CO <sub>2</sub> e))	Scenario 2 Assumption	Scenario 2 emissions	Scenario 3 Assumption	Scenario 3 emissions
Heat Pipe Construction surface grid [m]	6000	192	8000	256	12000	384
Drill Rig Transport	1 drill rig on site	15	1 drill rig on site	15	1 drill rig on site	15
Drill Rig Operation (hrs of drilling)	9000	3728	27000	11,185	48,000	19,885
Drilling Water [m <sup>3</sup> ]	30,000	31.5	90,000	94.5	160,000	168
Well Casing [m]	15,600	4212	46,800	12636	76,800	22464
Borehole Cement [tonnes]	1200	1080	3600	3240	6400	5760
Pump Power [500kg/MWh <sub>th</sub> /doublet]	60 kW	18,922	50 kW	47,304	50	84,096
Pump Power [200 kg/MWh <sub>th</sub> /doublet]		7569		18,922		33,638
Total Emissions [tonnes CO <sub>2</sub> e] High Carbon Power		28,257		74,158		131,444
Total Emissions [tonnes CO <sub>2</sub> e] Low Carbon Power		16.904		14,191,200		80,986
Heat Produced [MWh <sub>th</sub> ]		4,730,400		14,191,200		25,228,800
Emissions Intensity [kg CO <sub>2</sub> e/MWh <sub>th</sub> ] High Carbon Power		6.0		5.2		5.2
Emissions Intensity [kg CO <sub>2</sub> e/MWh <sub>th</sub> ] Low Carbon Power		3.6		3.3		3.3

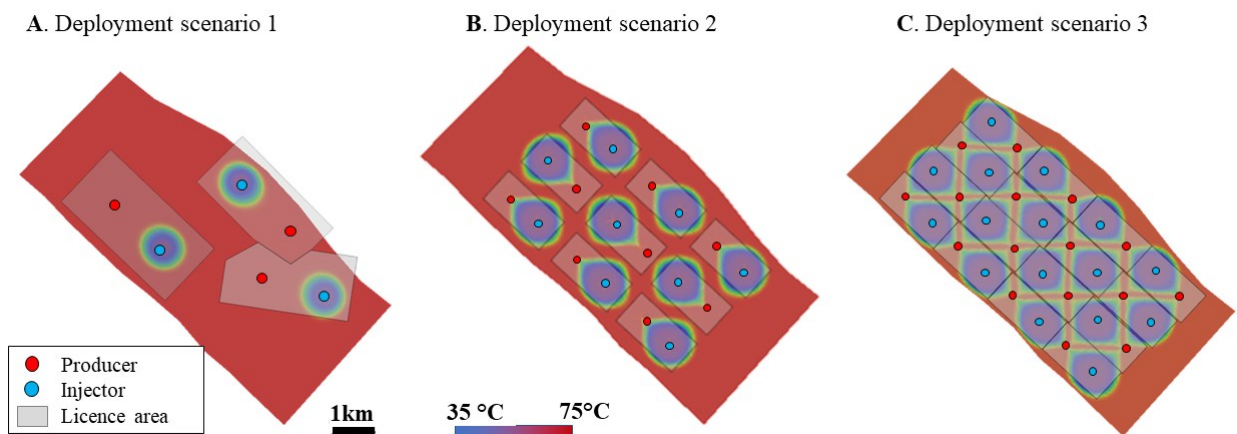
### 3. Results

The numerical production simulations suggest that the current approach to doublet deployment (scenario 1) with well spacing distances of more than 1500 m lifetime of the doublets could exceed over a century (Figure 2-A). It might take between 150 to more than 200 years for the production temperature to drop below the required temperatures for space heating, which is 70°C according to Limberger et al. (2018). This range is a result of the proximity of one of the doublets to a no-flow boundary in the model. Increasing doublet density in deployment scenarios 2 and 3 advances thermal breakthrough time and a faster reduction of the production temperature thereafter. Nevertheless, thermal breakthrough does not occur before 30 years, not even in scenario 3. Figure 2-B highlights that by increasing the doublet density, the heat production capacity could be increased significantly. The range variation in the speed of production temperature reduction is due to slight variations in well spacing of several tens of meters and proximity to other doublets and no flow boundaries.

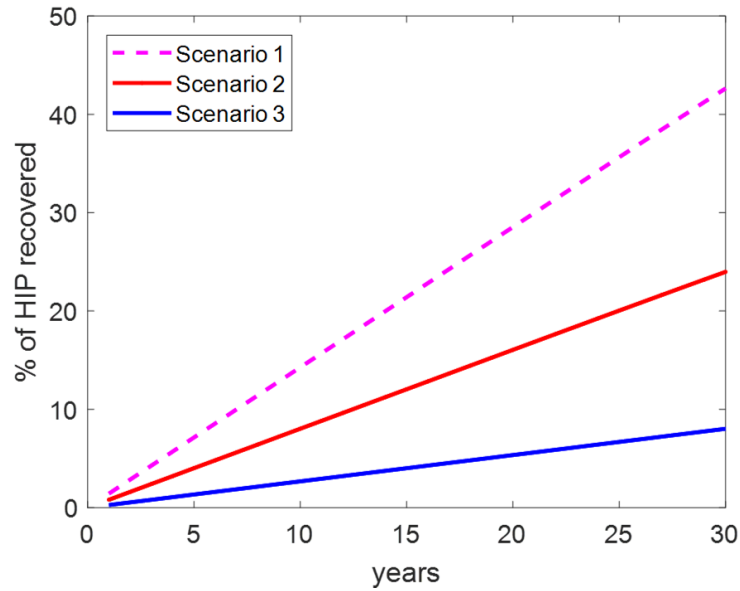


**Figure 2: (A) production temperature development in doublet deployment scenario 1, 2 and with a constant production rate of 200 m<sup>3</sup>/h. The injector-producer spacing in scenario 1 is 1600m and in scenario 2 and 3 this spacing is 800 m for each doublet. Each line represents the production temperature development of a single doublet.**

Figure 3 shows the difference in production temperature after 30 years of exploitation for each deployment scenario. The higher doublet densities in scenario 2 and 3 results in a much more efficient heat extraction, compared to scenario 1. With the small remaining space in between the licence areas in scenario 1n and 2, it will be challenging to fit new doublets. Therefore, much of the available heat will remain untapped, especially in scenario 1. Some 40% of the estimate HIP could be recovered utilising deployment scenario 3 in 30 years, while this would be slightly less than 10% in deployment scenario 1 (Figure 4) .



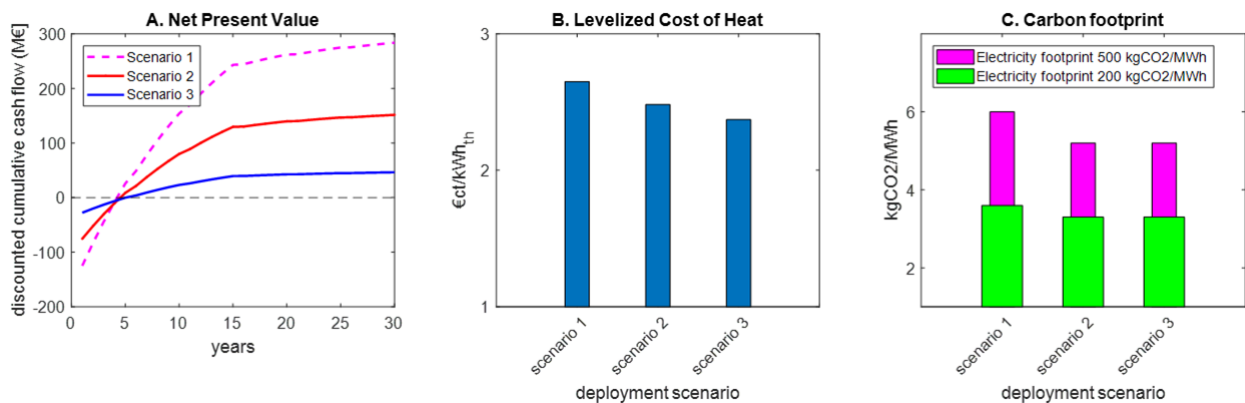
**Figure 3: Map view of the temperature distribution projected on a horizontal slice in the aquifer after 30 years of exploration. Grey polygons indicate the licence areas equal to:  $L \times 2L$ , in which  $L$  is well spacing.**



**Figure 4: Cumulative heat production over time, expressed as percentage of the estimated heat in place for all three deployment scenarios.**

Figure 5 presents the impact of upscaling and optimizing doublet deployment on Net Present Value (NPV), Levelized Cost of Heat (LCOH) and the Carbon footprint of geothermal exploitation. With the current ‘first come, first served’ deployment approach (Scenario1) the NPV is much lower than in the optimised scenarios two and three because of the increased heat income, but also because of higher expenses per doublet, as is presented in Table 1. The difference in LCOH for scenario 2 and 3 is a result of the CAPEX reduction that was obtained by drilling two doublets from one surface location. Please note that our NPV estimation is a coarse approximation that does not consider risks, personnel hours and unforeseen downtime. Also, in our production simulations, exploitation starts at the same moment for each doublet, while in reality development of all the infrastructure could take years. Our financial estimations are therefore intended for relative comparison between the different deployment scenarios only.

In terms of carbon emissions, all three scenarios produce heat which is significantly lower emissions than an equivalent fossil-gas boiler (which would produce emissions of around 200 kgCO<sub>2</sub>e/MWh), ranging from 6 to 3.3 and 3.3 kgCO<sub>2</sub>e/MWh in scenario 1,2 and 3 respectively. Scenario 2 and 3 produce a significant amount more heat but without such high corresponding carbon costs in construction, as such scenario 2 and 3 result in slightly lower emissions than scenario 1. Scenario 2 and 3 have equal CO<sub>2</sub> footprints because pump power per doublet is equal in both scenarios and CO<sub>2</sub> expenses as a result of the larger number of doublets increases proportional to the produced heat.



**Figure 5: Impact of different doublet deployment scenarios on (A) discounted cumulative cashflow and Net Present Value, (B) Levelized Cost of Heat and (C) carbon footprint for the current Dutch carbon footprint of electricity of 500 kgCO<sub>2</sub>/MWh and a hypothetical future decarbonised electricity grid scenario of 200 kgCO<sub>2</sub>/MWh.**

## CONCLUSION AND DISCUSSION

Our simulations show that the total number of doublets and the recovery efficiency could be increased significantly in our study area, when they would be deployed based on a regionally coordinated masterplan approach. In contrast, doublets are currently often designed and deployed based on ‘first come, first-served’ basis by independent operators. We show that this could lead to sub-optimal use of the available space (low sweep) and leave most of the available heat untapped. This is because doublets use unnecessary large injector-producer spacing and are located where heat consumers are. Unfortunately, especially in the early phases of the rise of a new energy technology, larger utility companies and governments are not inclined to commit to high upfront investment that are required for heat recovery optimisation. As a result, the industry develops ‘bottom-up’ by small scale operators. Therefore, a major challenge for geothermal development is to quantify the value of geothermal heat for a region or country that would justify large ‘top-down’ investments to promote optimisation of geothermal energy exploitation, for example by creating tailor-made subsidies and legislation. We show that these are required because currently deployment optimisation would only lead to marginal financial performance under current licencing and subsidy schemes.

In this study we also made a first step towards quantification of the value of geothermal energy by quantifying its carbon footprint, which is significantly lower than most other renewable energy techniques. In all three doublet deployment scenarios in our simulations, carbon emissions associated with powering the hydraulic pumps are the highest contributor to the overall carbon intensity of the produced heat. A power grid with lower carbon emissions significantly reduces the emissions intensity of the heat produced, as can be seen in the comparison between the 500 kgCO<sub>2</sub>e/MWhe and the 200 kgCO<sub>2</sub>e/MWhe scenarios. This shows how vital it is for a sustained effort to ramp up the renewables contribution to the Dutch power grid, as a decarbonised power grid facilitates wider decarbonisation efforts. Sourcing low carbon steel and cement or utilising carbon casing could be possibilities in the future, but currently are not commercially available. However, any design which minimises the quantity of steel and cement required by MWh<sub>th</sub> of heat produced by a geothermal system could significantly reduce the associated indirect emissions of the project. All three deployment scenarios have associated carbon emissions which are less than McCay et al. (2019) estimated for a deep geothermal project in Scotland. McCay et al. (2019) suggested that the Scottish geothermal project had lifetime emissions which were compatible with an effectively zero carbon society. This suggests that all three scenarios presented in this paper are also compatible with a future zero carbon society, although scenarios 2 and 3 do have slight advantages in lower carbon emissions per MWh<sub>th</sub> but producing significantly more amount of heat than scenario 1.

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