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Combined geothermal and dissolved CO_2 storage system – Example of application to a geothermally heated greenhouse area in The Netherlands

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Abstract

This paper explores the concept of combining a geothermal energy system with CO_2 storage. Introducing CO_2 in dissolved form into the cold return stream of a geothermal doublet would lead to inherently safe CO_2 storage, while generating the possibility of an additional revenue stream for the a geothermal operator. Moreover this concept could also provide a solution for smaller emitters, located far from storage sites or transportation facilities, but close to (potential) geothermal systems. It uses a low-cost CO_2 capture technology. Storing CO_2 in dissolved phase by co-injection with the geothermal water, increases storage security and safety compared to supercritical storage. The absence of buoyancy as an upward migration force removes the risk of leakage. Because of this, a caprock is not required and therefore more storage sites become available. This is only true if degassing, both on the short- and the long-term, can be excluded. The design of the entire chain therefore takes into account the solubility limit of CO_2 in the geothermal water at all conditions which occur during the operational phase and beyond. Reservoir simulations were performed on a existing geothermal reservoir in the greenhouse area in The Netherlands to investigate the feasibility of CO_2 co-injection and potential impacts on the geothermal operations and the business case. Results show that, for the conditions considered, no (significant) breakthrough of either the cold front or the dissolved CO_2 are predicted to occur within 30 years of continuous operations. Also, the simulations show that all CO_2 remains dissolved and hence no degassing takes place. An initial cost estimate indicates that with current emission reduction credits the return on investment of the CO_2-Dissolved concept can be achieved within a few years, and is therefore an economically attractive addition for a geothermal operator.

Keywords: Dissolved CO_2; geothermal energy

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1. Introduction

In The Netherlands geothermal energy is one of the key elements of the future low-carbon energy strategy. It plays an important role in increasing the sustainability of the greenhouse sector in the Westland area, which is responsible for close to 4% of the national CO_2 emissions [1] and around 8% of the national gas consumption. Furthermore more than 90% of the houses in the Netherlands are currently connected to the gas network for heating, cooking and hot water. According the roadmap geothermal energy , geothermal energy could provide 25% of the heating demand in order to replace natural gas by renewable heat. In order to realize this ambition the number of geothermal production systems need to grow from 17 today to more than 1000 in the coming decades. Targeting temperatures up to about 100°C at depths of about 3 km, geothermal energy is envisioned to grow to about 175 systems by 2030 and 700 by 2050 [2], part of which in the greenhouse sector. In parallel, greenhouse gas emissions from fossil fuel based power and industry is to be reduced through fuel switching, energy demand reduction and carbon capture and storage (CCS). For the latter technology, storage options will be available offshore only, at least in the short and medium term, implying that access to storage for emission points located away from the coast, or far from CO_2 collection systems, will be difficult.

A recent development provides a link between geothermal systems and CCS and may provide a solution for small-scale greenhouse gas emitters (*ca*. 10 to 150 kt/yr) located at distance from CO_2 pipelines and offshore storage locations. The CO_2-Dissolved system, using an innovative CO_2 capture technology developed in the USA [3, 4], adds dissolved CO_2 to the injected stream of a geothermal doublet. The technology could turn geothermal systems into a CO_2 store, providing an additional revenue stream for the operator in the form of carbon credits†. As the CO_2 remains dissolved at the conditions in the reservoir, a buoyancy force for leakage is absent and CO_2 storage is secure [3, 5, 6, 7]. In general, CO_2-saturated brine is denser than unsaturated formation water and will therefore migrate downwards. As a result, the security of CO_2 storage does not rely on an impermeable caprock, which means that many more formations might have potential as storage sites [6]. Given the expected growth of geothermal systems in The Netherlands, the concept could be a solution for small-scale CO_2 emitters located close to geothermal operations. It would generate additional revenue from European emission allowances (EUA) by storing dissolved CO_2 in the geothermal reservoir. At the time of writing, (August 2018), the price of EUAs is about € 20/tCO_2, and prices are expected to increase.

This paper presents a high-level investigation of the feasibility of the CO_2-Dissolved technology from the point of view of the geothermal operations. For the operator or owner of the geothermal system, the injection of dissolved CO_2 would only be interesting if the geothermal energy production is not compromised, or if it is enhanced. If this is not the case, the additional revenue from the stored CO_2 needs to be high enough to cover potential risks of decreased geothermal potential.

Reservoir simulations were performed for a currently operating geothermal system and greenhouse operator in the Westland, close to Rotterdam, to investigate the impact of dissolved CO_2 on the operations. In accordance to the ambitions of the operator, the setup of the investigated system as used in this paper is that of the current doublet, with an added third well. This new well would be used as injector, the two existing wells would serve as producers. With the new set-up, the current geothermal potential could be doubled. A high level cost estimate for this concept is performed – under the assumption that storing CO_2 in dissolved form can be permitted.

2. Technology, concept and potential

The innovative CO_2 capture technology, 'Pi-CO_2', is currently being developed by Partnering in Innovation, Inc. (USA) with the aim to provide an efficient and low energy alternative to conventional capture technologies for separating CO_2 from post-combustion gases. It basically consists of an absorber installed in a dedicated 300 m-deep

† Assuming that small emission sources will fall under the ETS.

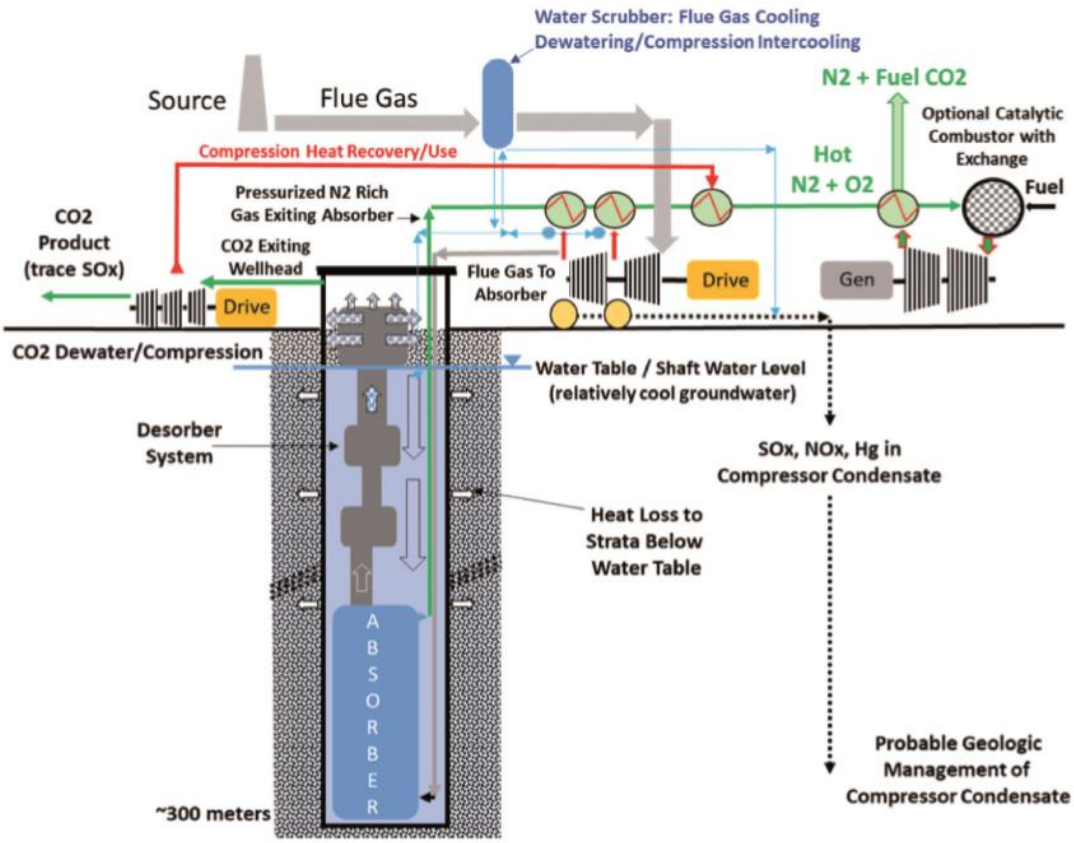

Fig.1. Schematic overview of the Pi-CO_2 capture technology. The hydrostatic pressure of a deep water column is ~30 bar at the bottom. Copyright Partnering in innovation, Inc. (www.pi-innovation.com).

shaft filled with water enabling preferential CO_2 dissolution, undissolved gases (N_2 mainly) being recovered through the return line of the installation (Fig.1). Since the solubility of CO_2 increases with increasing pressure [3], the water column provides optimal conditions (about 30 bar at the bottom) to achieve high CO_2 solubility without additional costs or energy needed for compression.

For the CO_2-Dissolved concept, CO_2 can be dissolved in the injected stream of a geothermal system. Fig. 2 shows an example layout, for a geothermal system delivering heat to a greenhouse in the Westland area of The Netherlands. A CO_2 injection line can be implemented in the injection well of the doublet. The solubility is the key parameter for injectivity and capacity definition. The solubility increases with increasing pressure, and decreases with increasing temperature or salinity. Depending on the specific conditions, several to many injection wells are needed to inject 1 Mt of CO_2 per year, which is much more expensive than conventional storage in supercritical phase in which a rate of 1 Mt/yr can be achieved per well, as evidenced by the Sleipner and Snøhvit projects in Norway. Dual completion and multi-lateral well techniques would be necessary to reduce the number of required injection wells for dissolved CO_2 storage [6]. In the Dutch subsurface, the salinity in the potential geothermal aquifers is in the order of 100,000 to 300,000 mg/l, which results in a CO_2 solubility roughly between 25 and 40 kg/m3. Considering injection rates of 150 to 300 m3/hr, the CO_2 injectivity would be roughly 33 to 100 ktonne/yr.

Hamm et al. assessed the concept in terms of storage lifetime and efficiency, as well as geothermal operations, by hydrodynamic modelling [8]. They included temperature effects but excluded the changes in brine properties related to the dissolved CO_2 or chemical reactivity. They found that in a commercial scale operation, breakthrough of the CO_2

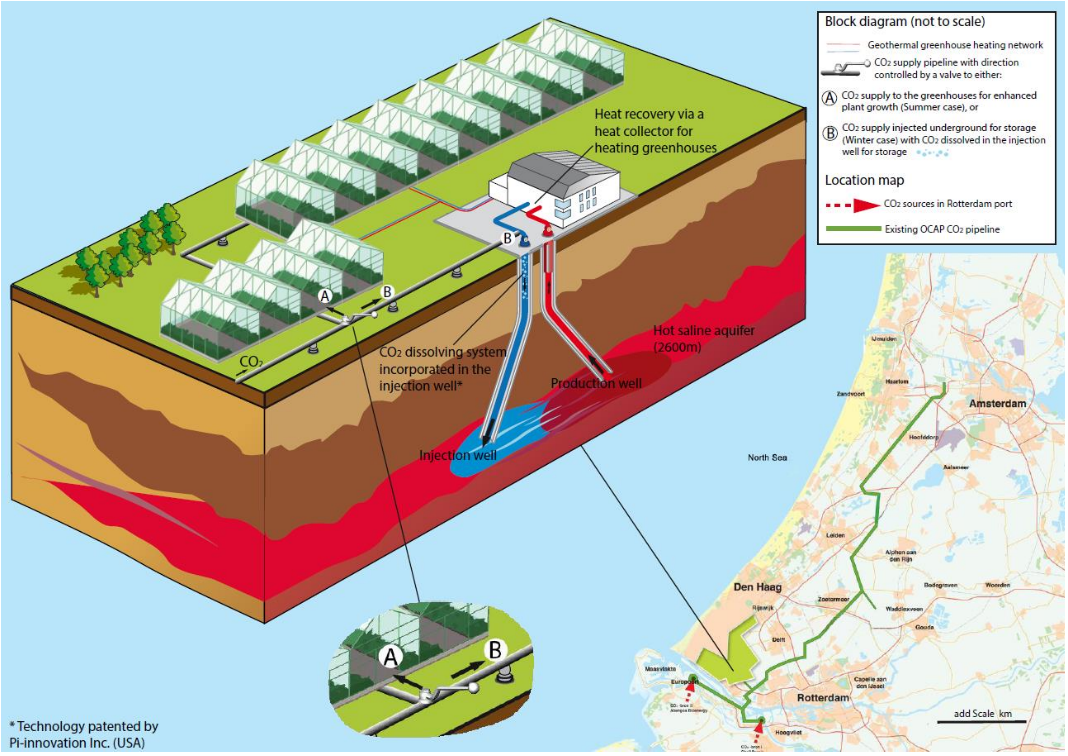

Fig.2. Location of the proposed pilot site in the Westland area in The Netherlands; inset: Switching valve between the CO_2 feeding circuit and injection circuit.

in the production well is between 2 and 15 years, depending on the distance between the injection and production well, and the injection rate. Storage efficiencies are higher for a larger distance between the wells and for lower flow rates [8]. The thermal breakthrough is predicted to be much slower than the breakthrough of the CO_2.

With a reservoir temperature of 70°C and re-injection at 40°C the decrease in production temperature after 30 years of operations was only 0.5°C [8]. An important aspect regarding the injection of dissolved CO_2 is the potential exsolution of CO_2 from the brine upon changes in downhole conditions. In a study similar to Hamm et al. [8], Shariatipour et al simulated the fate of injected dissolved CO_2 [6]. Their study did not focus on integration with geothermal operations but investigated dissolved CO_2 storage for the purpose of increasing storage security. By dissolving CO_2 in brine extracted from the aquifer instead of injecting supercritical CO_2 directly into the aquifer, pressure increase in the reservoir remains limited. Their simulations demonstrated that the saturated brine initially moves upwards as a result of the (limited) pressure gradient, but subsequently sinks due to gravity. No exsolution of CO_2 was predicted, supporting the idea of enhanced security by storing in dissolved phase. The initial upward movement, however, needs to be considered in the design of the system to prevent initial leakage towards overlying formations [6].

3. Reservoir simulations

3.1. Methodology and model description

Reservoir simulations were performed with the TOUGH2N simulator to predict the spatial evolution of the temperature field and the spreading of brine with dissolved CO_2 within the reservoir of a typical Westland geothermal system. Assuming the presence of a geothermal doublet, a third well with twice the diameter of the existing wells, which both will be used for production, was added to the system for injection of the geothermal water and dissolved CO_2, thereby doubling the geothermal potential. The three wells are deviated at depth from a single mother well, with equal distances of 1820 m between them. Perforations are modelled throughout the trajectory of the well within the reservoir, which has a thickness of 540 m, a permeability of 2 Darcy, a ratio of horizontal to vertical permeability (kh/kv, a measure of the vertical layering of a formation) of 5 and a porosity of 0.17. The initial reservoir temperature was set at 88°C and for the temperature of the re-injected water, a value of 38°C was chosen. For a reservoir pressure of 255 bar, this corresponds to an enthalpy of 1.82·105 J/kg. It was assumed that the enthalpy of the injected mixture was equal to that of the pure water. Currently the geothermal doublet produces 43 kg/s of warm water. In the doubled capacity scenario, 86 kg/s (~310 m^3/h) of water with 11 wt% NaCl was injected along the well interval. The amount of dissolved CO_2 was calculated from the solubility of CO_2 in pure water under the pressure and temperature of the reservoir (according to [9]). The impact of salinity was accounted for after [10]. As a safety margin for preventing degassing, dissolved CO_2 concentration was reduced to 75% of the estimated solubility limit at reservoir temperature. This resulted in a CO_2 concentration of 0.032 mass % (0.73 mol/kgw). The addition of CO_2 resulted in a slight dilution of the NaCl in the brine. Simulations were performed with and without the addition of dissolved CO_2 in order to evaluate the potential effect of the CO_2 on the geothermal operations.

3.2. Simulation results

During 30 years of geothermal operations with dissolved CO_2 at a brine injection rate of 86 kg/s, bottom hole pressures do not increase. This is due to the favourable characteristics of the reservoir; its high permeability (2 Darcy) and large thickness (over 500 m). The simulated distribution of dissolved CO_2 after 30 years of operations shows a slight breakthrough at the end of the operation phase, but the concentrations are still very low (Fig. 3).

Fig.4 and 5 show the temperature distribution after 30 years of operations with and without dissolved CO_2. Some minor differences are visible. Yet, in both cases, a temperature breakthrough does not occur. The temperature front remains well behind the dissolved CO_2 front, as expected. Hence, besides a minor breakthrough of dissolved CO_2 at the end of the operational phase, the results suggest that no significant impact on geothermal operations from the addition of CO_2 to the system is expected.

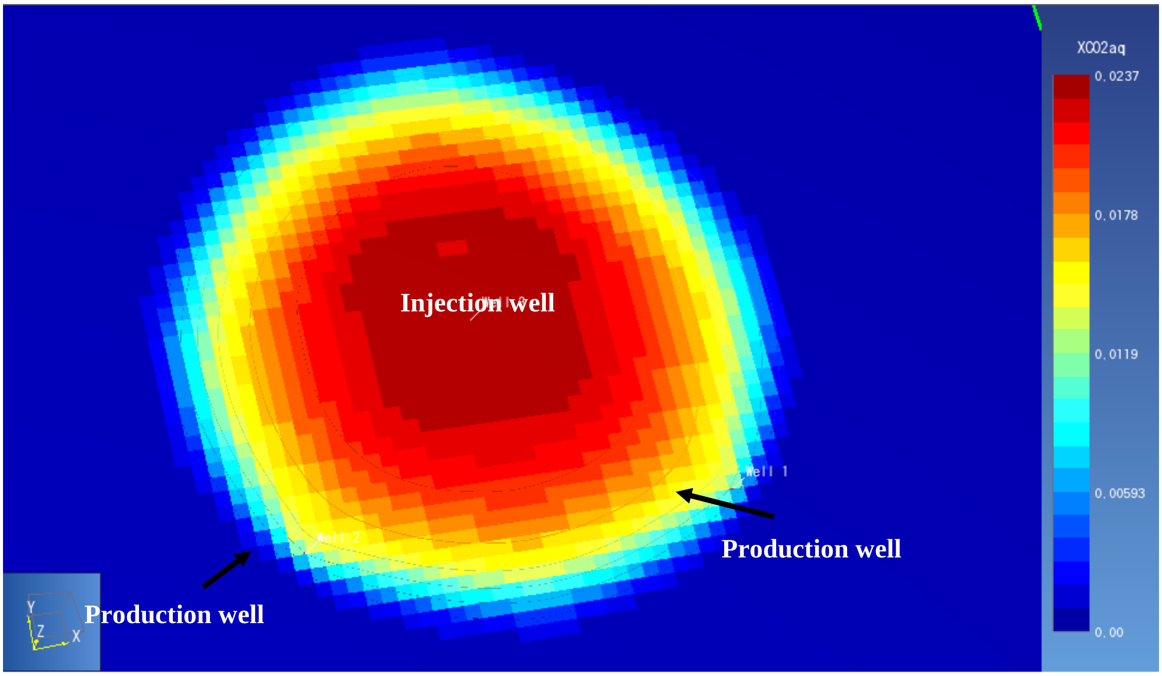

Fig.3. Simulated CO_2 mass fraction in the brine after 30 years of CO_2 co-injection operations.

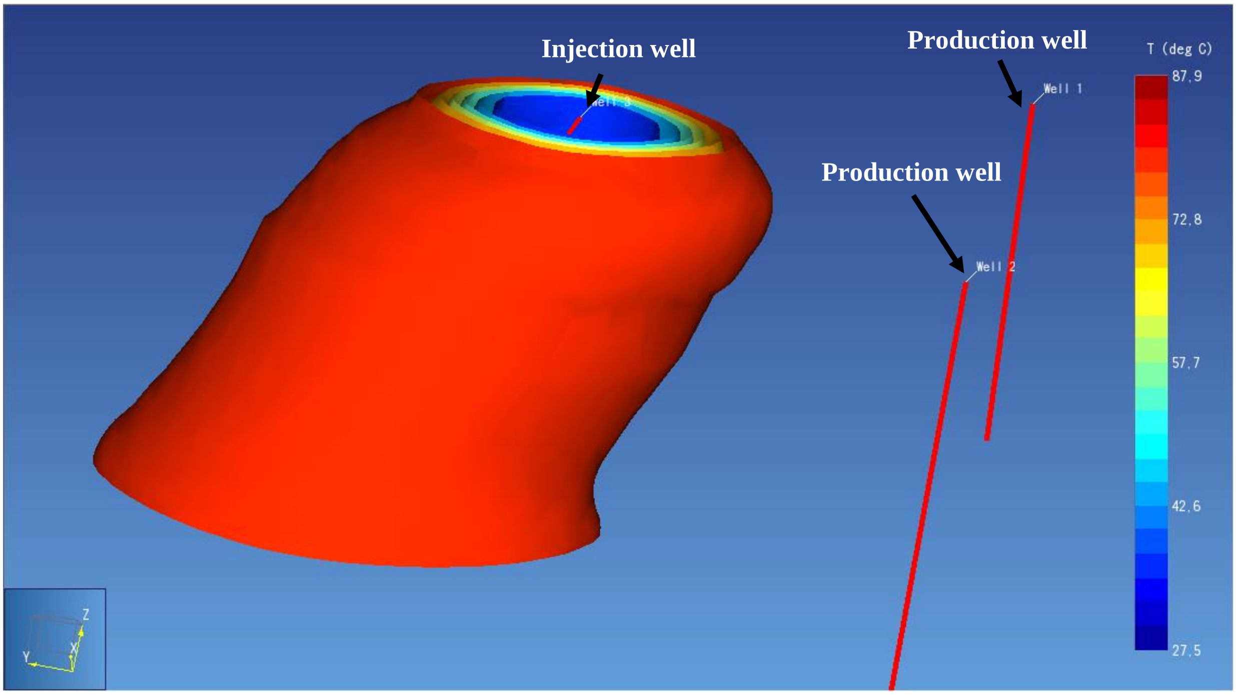

Fig.4. Temperature of the brine after 30 years of CO_2 co-injection operations.

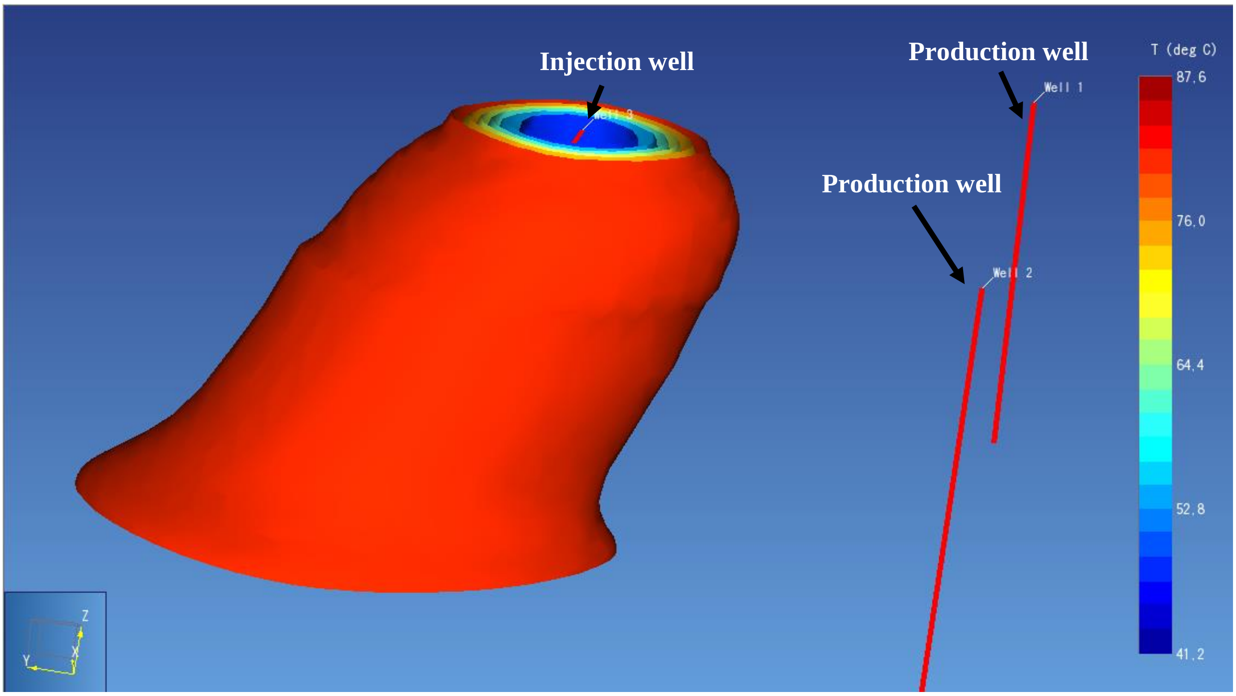

Fig.5. Temperature of the brine after 30 years of conventional operations without CO_2 co-injection.

4. Cost estimate

An initial cost – benefit analysis was done, to assess the attractiveness of the proposed CO_2-Dissolved technology for geothermal system operators. Starting with the benefits, these are only related to the amount of CO_2 stored during operation of the geothermal system. In our scenario, a total of 2.6 Mt of CO_2 was stored in a period of 30 years. Given the solubility of CO_2 under the condition in the reservoir, this is the maximum amount that can be stored during that period for the given injection and production rate and taking into account a safety margin for the solubility of CO_2. It has to be noted that no (significant) breakthrough of either temperature or CO_2 is predicted to occur implying that the system could operate for a long period of time.

In our simulated scenario, an existing doublet is extended with a third well. We assume that the costs for drilling an extra well will be fully covered by the doubled geothermal energy production. We further assume that both existing wells of the doublet will need a workover. A rough estimate of the element costs is given in Table 1. Total costs: M€ 5.6. With an OPEX for the compressor of 59 k€/yr based on 0.1 €/kWh, the operator needs 10 €/tCO_2 for a return on investment within 7 years.

Table 1. Required elements, with cost estimates.

Scenario	Element	Comment	Cost
	CO_2Dissolved down-well hardware	Cost estimated – no firm cost figure available	M€ 0.5
	Compressor	Small compressor to increase pressure from 21 to 30 bar	M€ 0.1
Existing doublet	Surface facilities workover	Workover of existing wells to handle CO_2 rich brine	M€ 1
	Well workover	Required for injector and producers, to handle the CO_2 rich brine	M€ 2 per well
New doublet	Well material costs (high quality steel casing)	Additional compared to conventional well	M€ 0.3 per well
	Surface facilities (high quality materials)	Additional compared to conventional facilities	M€ 0.1

Considering that many new doublets will be developed in The Netherlands, a cost estimate was performed based on the required CO_2 dissolved technology and additional costs for high quality well and surface facility materials (Table 1). Total costs: M€ 1.2. Having similar OPEX for the compressor, the operator only needs 2.7 €/tCO_2 for a return on investment within 7 years. Considering the current European Emission Allowance (EUA) of 21 €/tCO_2 (September 2018), both scenarios but especially the scenario for development of new geothermal doublets, seem economically viable.

5. Conclusions

The following conclusions were drawn:

- At the conditions considered in the study, the density and viscosity changes caused by co-injection of dissolved CO_2 do not significantly affect the temperature evolution of a geothermal reservoir.
- For a typical (thick and highly permeable) reservoir in the Netherlands with relatively large distance between the wells, no significant breakthrough of dissolved CO_2 is predicted to occur within 30 years of operations.
- Based on high-level cost estimates, the return on investment for the CO_2-Dissolved concept can be acceptable at current EUA price levels (September 2018).
- Assuming a further increase of emission credits in the (near) future, the CO_2-Dissolved concept should be considered in long-term CO_2 storage roadmaps as potential emission reduction technology for small scale emitters, provided that small emitters become eligible under the ETS.

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