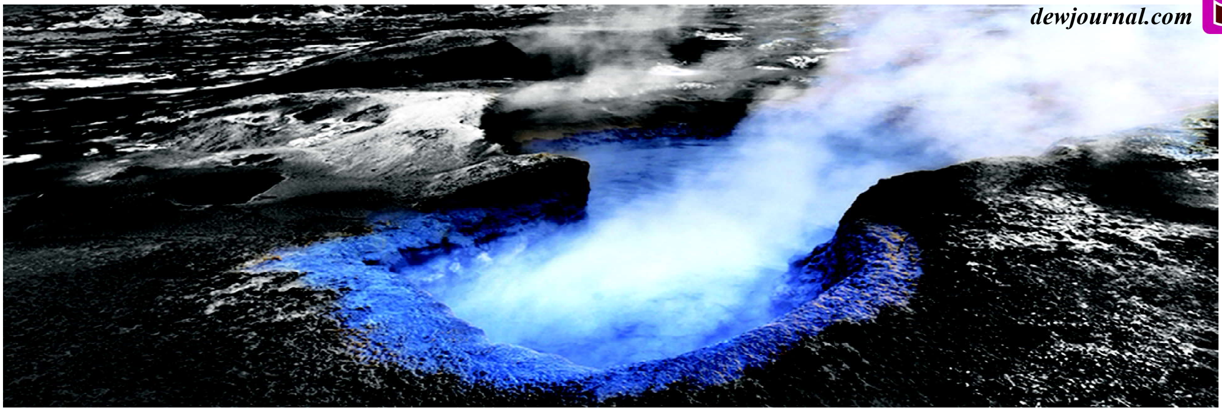
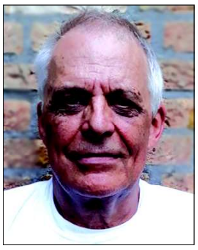


LUC concept: A game-changer for low-enthalpy geothermal developments

Andre Mol



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Here we introduce a Low Unit Cost (LUC) method for low-enthalpy geothermal projects, enabling economic development of geothermal energy from lower-quality aquifers in smaller-scale projects. The LUC method is a robust combination of project management, and best-practices in well engineering, production technology and reservoir management. In countries such as The Netherlands, low-enthalpy geothermal energy is a renewable source of energy for heating, and industrial processes such as drying. For financial reasons, conventional geothermal projects must produce high flow-rates, which is only possible from high-quality (thick, porous and permeable) aquifers. This limits the applicability of conventional geothermal energy to high-cost (subsidized) projects in areas which contain high-quality aquifers in a narrow depth range, *and* a corresponding high, concentrated heat demand.

This article describes the LUC methodology on the basis of two examples from The Netherlands: one for domestic heating and one for heating commercial greenhouses. The examples have not yet been implemented but the peer-reviewed figures presented in this paper are considered representative for LUCs in the Dutch market. In addition, this paper briefly discusses absorption cooling (refrigeration using heat), a much less known use of geothermal energy and likely more applicable outside the Netherlands (due to the moderate Dutch climate). The authors are convinced that LUC is applicable in all countries with a similar market for low-enthalpy geothermal energy for both heating and cooling.

The authors aim to deliver clean, renewable energy (heat) in The Netherlands, without government subsidy, at a unit-cost of € 5/GJ_{th} (current unit-cost is € 25/GJ_{th} based a gas-price of € 0,4/m^3). To reach this ambition we need a new paradigm for geothermal developments. Conventional projects aim to maximize profits per individual project. As government subsidies in The Netherlands are tied to energy production, there is an incentive to produce with high flow rates and to operate under high pressures with matching injection rates. This results from the fact that these conventional systems are

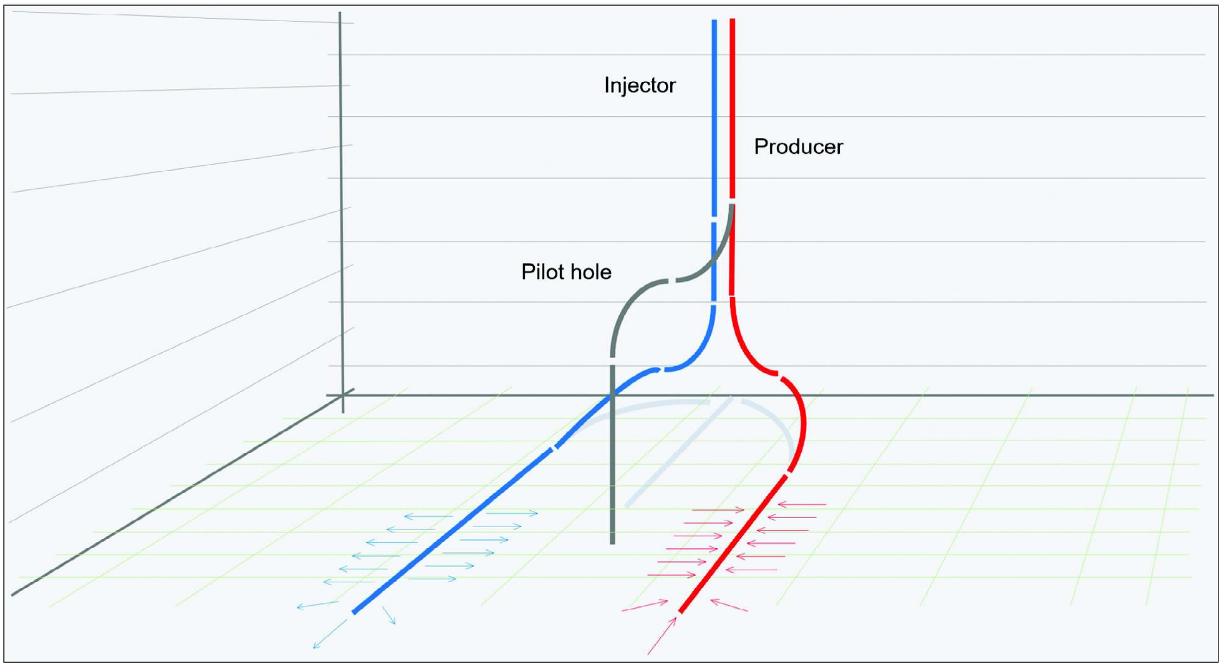

Fig.1 LUC concept – installation geometry (illustrative, not to scale).

mass-balanced: high injection rates result in high fluid velocities. Apart from erosion of the installation, this practice also increases the risk of induced seismicity (earthquakes). Instead of the conventional approach of maximizing profits, the authors argue that LUC projects can better balance the following questions:

- How much thermal energy (heating) is actually needed at surface and at what temperature?
- How can the heat potential (MW_{th}/km^2) from a suitable aquifer be optimized?
- What design can connect the aquifer to the demands in a safe and cost-effective manner?

Delivering heat at € $5/GJ_{th}$ without the need of government subsidy can only be achieved if these questions are addressed in a true exploratory fashion with a portfolio logic, where drilling is the business enabler.

LUC de-risking methodology

Each LUC project starts by drilling a pilot hole. This exploratory well is drilled with an S-type geometry that drills near vertical through the reservoir target (Figure 1). The well is logged while drilling and flow-tested afterwards. The static and dynamic testing provides valuable information about the drainage area and production behavior of the aquifer. That conclusive "in-situ" data is a requirement for decision making in the project. If the project is continued, the pilot hole will be plugged back and an optimized horizontal side-track is drilled and landed in the aquifer. Most likely this well will be completed as the production well and an injector well will be drilled parallel to this producer. The geometry of both wells, the spacing between them, and the length in the aquifer, is based on the acquired test results. The economic viability of a continued project is near-certain if, by this point, the test results have proved that the required production rates can be obtained at the desired low pressures (low operating costs). However, the project can be stopped if the test results show that the required production rates and the economics cannot be achieved. If this happens, then only a modest investment (15-20% of the success-case) has to be written off.

The Low Unit Cost method is a robust combination of project management, and best-practices in well engineering, production technology and reservoir management

In LUC projects, we would aim to maximize the CoP (Coefficient of Power) of the geothermal system. The CoP is the ratio of the geothermal power produced divided by the power used to operate the geothermal system. Simply said, the thermal energy divided by the electrical energy needed to run the ESP and injection pumps. Furthermore, it is good business to minimize the overall costs over the life-span of the system (20-30 years). Consequently, LUCs are implemented with highest-quality materials, the logic being that the geothermal implementation should result in cheap heat (over its entire lifespan) and not cheap wells. The higher initial development costs are more than compensated by lower operating costs. Also, the financial exposure of LUC is much lower than the exposure of a conventional system. In a conventional implementation, the well-design is fixed and the financial exposure (downside) of a failed project equals the total CAPEX. With LUC, the design is not fixed but determined after extensive well-testing in the pilot hole. At this exploration milestone, a project can be stopped if the aquifer characteristics are below the minimum requirements, and hence outside the expected range of uncertainty. The financial exposure up to this milestone is a relatively small part of the LUC CAPEX, which in turn is considerably smaller than the CAPEX of a conventional project.

Refrigeration using geothermal heat – absorption cooling

Cooling is typically not associated with geothermal energy, yet the practice of absorption-cooling is well known and understood. The process is very energy intense, hence only in case of excess heat or seasonally available (free) heat without offtake can absorption-cooling be economical, a welcome "side effect" of low enthalpy geothermal development. This cooling potential can also be considered as a way of compensating for large seasonal differences between peak- and low-demand. This way, uptime hours of an LUC system can be increased considerably, further improving the overall economics of LUC projects.

Low Unit Cost (LUC) is applicable in all countries with a similar market for low-enthalpy geothermal energy for both heating and cooling. Instead of the conventional approach of maximizing profits, the authors argue that LUC projects can better balance the following questions:

- How much thermal energy (heating) is actually needed at surface and at what temperature?
- How can the heat potential ($\text{MW}_{th}/\text{km}^2$) from a suitable aquifer be optimized?
- What design can connect the aquifer to the demands in a safe and cost-effective manner?

LUC Benefits

In summary, LUCs have a number of distinct benefits over "typical' larger-scale developments:

- Development costs and risks are lower;
- Smaller and modular drainage areas in the aquifer, hence installations can be placed closer together and the heat can be harvested optimally on a regional scale;
- Induced seismicity is mostly avoided because: a) there is less uncertainty about the aquifer after extensive production testing in the pilot hole; b) horizontal wells reach the desired inflow performance at much lower pressures than deviated wells; and c) LUC projects are economical at modest temperatures meaning a reduction in induced stress caused by heating-up of cold injection water;
- Low production rates and modest temperatures allow for the development of reservoirs that would otherwise not be considered clean, renewable and economic heat sources for clients with moderate heat-demand (1-3 MW_{th});
- The footprint is small and the environmental impact is limited because: a) waste streams are smaller; and b) LUC installations are very compact with most of the surface facilities below ground in a multi-purpose cellar that is part of the LUC concept.

LUC examples: firstly, an exploration play-enabler and secondly an appraisal style development

The viability of LUCs is illustrated on the basis of two examples, both currently in the planning phase.

The first example is a prospect with a high dose of exploration elements. It describes a case for developing a 3,6 MW_{th} geothermal installation for domestic heating in

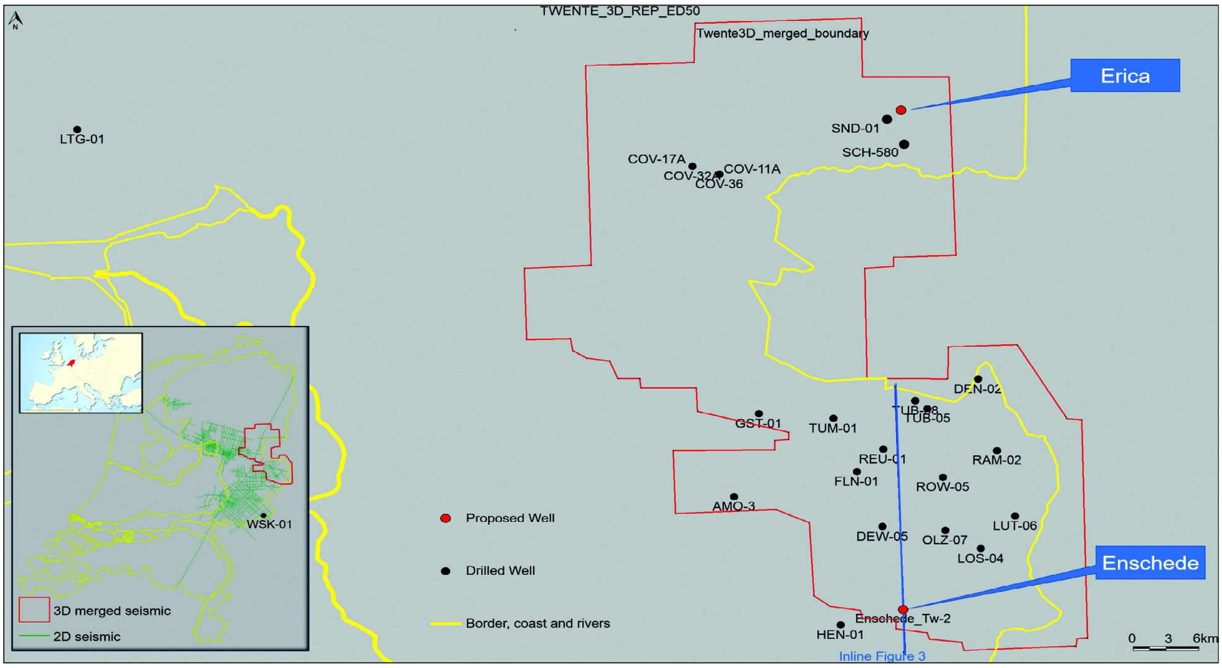

Fig.2 Study area in eastern Netherlands.

the city of Enschede, Eastern Netherlands (Fig. 2, Veenstra et al., 2020). The target is the Late Carboniferous Tubbergen Sandstone Formation at ca 1,500-2,200 mTVD (Fig. 3). The Tubbergen Formation consists of alternating sandstones and claystones / shales and rare coal beds with variable extent and thickness. The overall net-to-gross of the Tubbergen Formation in the Enschede area is ca 50-60%. The sandstones are fine- to very coarse-grained, occasionally up to pebble size and moderately sorted. The sandstones occur in (amalgamated) channel fills of ca 5-30 m thickness with a maximum sandstone thickness of about 50 m. The best prospective reservoirs show blocky gamma ray patterns and reach porosities of 20% and 200-300 mD matrix permeability. The formation shows its best and thickest development (ca 700 m at 1500-2200 mTVD) to the North of

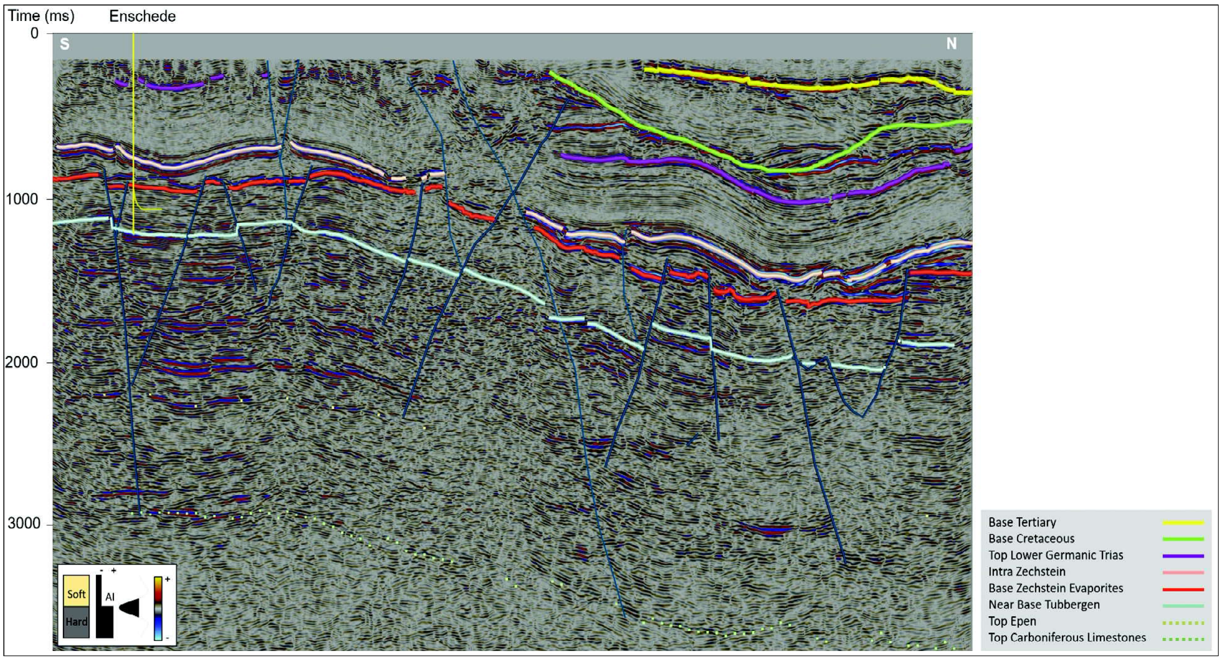

Fig.3 Seismic inline through the virtual well location “Enschede”.

Table-1. Key commercial parameters of two representative, conventional geothermal systems and the two LUC examples discussed.

Parameter	ACL-project	HAL-project	LUC Enschede	LUC Erica
CAPEX (€ x10^6)	25[1]	22[1]	6.5	3.6
OPEX (% of CAPEX)	3% (estimate)	3-5%[1]	< 2%	3%
Power (MW_{th})	14	7	3.6	1.5
CoP (coefficient of power)[2]	10-15	15	20	25
Depth (mTVD – vertical)	1,900	2,200	1,700	1,500
Aquifer (reservoir name)	Slochteren Sst	Delft Sst	Tubbergen Fm	Bentheim Sst
Thickness of aquifer (m)	60-70	63	30-40	30-40
Porosity	22%	20%	20%	22%
Permeability (mD)	490	2330	200	140
Flowrate (m^3/hr)	325	165	100	35
ΔT heat extraction (°C)	40	35	30	35
Corrosion prevention	sacrificial pipe	chemical + logs	CRA[3]	CRA[3]
Fluid velocity (% of ϑ_c)[4]	325%	400%	85%	50%
kinetic Energy – E_{kin} (kJ)	260	100	35	9
IRR - earning power (%)	unknown	5%[5]	14%	14%
NPV @4%[6] (€ x10^6)		<< 22	12.7 (20 yr)	6 (30 yr)
Profitability[7] (%)		<< 100%[8]	210%[9]	166%[9]
Economic success POS (%)	50[1]	< 10	> 90	> 90

Notes

[1] calculated estimate based on data from www.nlog.nl, ministry of EZK, Staatscourant (government paper) and other public sources

[2] power-ratio: delivered thermal-power over total electric pump-power needed (to operate the system)

[3] CRA is Corrosion Resistant Alloy (e.g., 13Cr material, also CRA-cladding of wellhead equipment)

[4] ϑ_c critical (erosional) fluid velocity generally assumed to be 1,5 m/s for a clear fluid

[5] calculated from publicly available data: https://www.nlog.nl/haagse-aardwarmte-leyweg

[6] the rate (%) at which future money is discounted to calculate NPV of the investment

[7] the increase of the investment sum (over total project duration) against a given bank-rate (interest)

[8] this project is unlikely to generate a positive economic return on total invested capital

[9] profitability does not take the recently announced CO2 pricing of € 125/ton (by 2030) into account

Enschede and has been eroded to the South of Enschede below the Hercynian unconformity. The complete Tubbergen sequence has never been penetrated for the purpose of geothermal development and if successful could become a geothermal play-enabler, unlocking a range of projects that are currently considered “prospective”. A full and successful penetration will de-risk existing seismic and logically cross into Germany for geothermal investment opportunities.

Developing this prospective reservoir by conventional installations consisting of two (or perhaps three) slanted wells that are spaced some 1,500 m apart (at the reservoir horizon), is a very costly, and hence risky adventure as uncertainties of the project economics are large. Commercial success requires undisturbed production of large volumes over many decades. This also means that wells (producer and injector) must be drilled with large borehole diameters and volumes must be injected under high pressure. Typically, conventional installations in The Netherlands operate under the maximum pressure allowed by the National regulator. High pressures may induce seismicity, the main socio-political obstacle for geothermal projects in The Netherlands. Moreover, static calculations on which the maximum allowed pressures are based, do not take the effects of kinetic energy into account. High kinetic energy means that the total mass of the fluid column (in the injection well) at a certain velocity, is very hard to stop if it would encounter (temporary) restrictions. Therefore, operating under high pressures (with high volumes and at high speed) makes reservoir management and fine-tuning of heat harvesting a considerable challenge. The uncertain production potential of the Tubbergen sands is a high risk for a conventional geothermal project, due to the fixed design of the conventional installation. Using conventional methods investors discover if the desired rates can be produced only after most of the capital has been spent. In other words, the financial exposure equals the CAPEX of both (all) wells. That CAPEX of a typical conventional geothermal system in The Netherlands is some € 20 million (Table 1).

With an LUC development, a pilot hole is first drilled through the entire Tubbergen Formation. This is done using MWD-LWD, as it is not possible to predict from seismic data at what depth the most suitable aquifer will be encountered in the

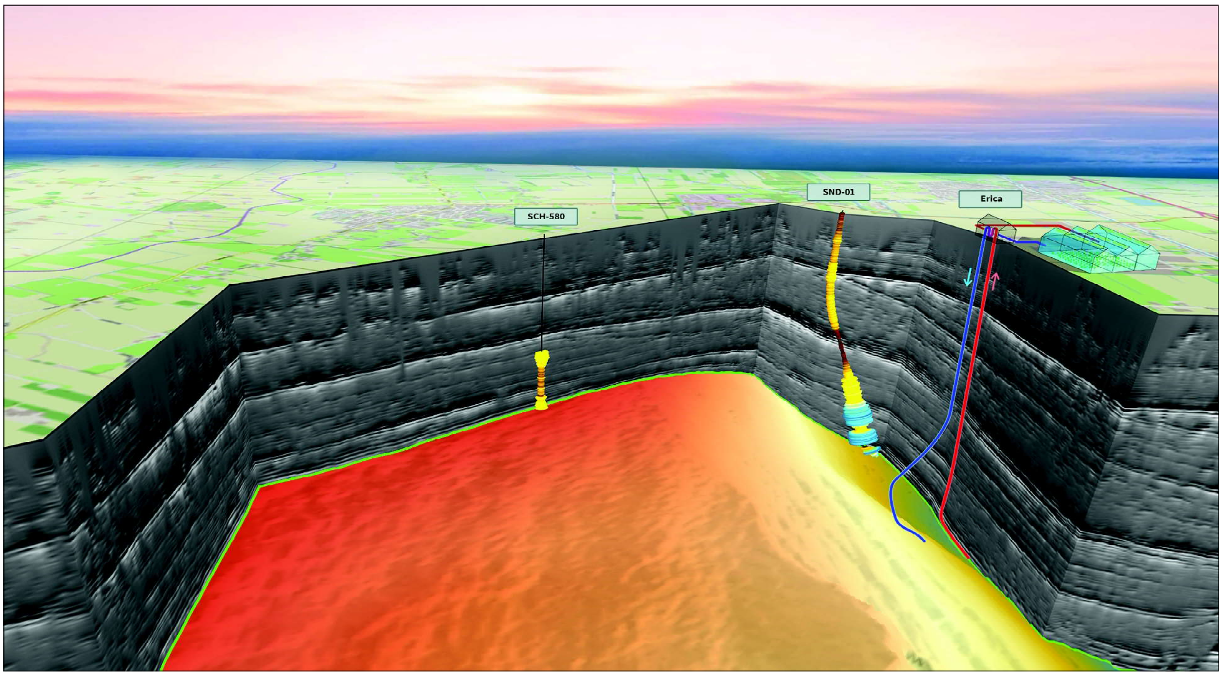

Fig.4 3D perspective view of the LUC installation at the proposed location in Erica. Most of the production facilities of a LUC installation are hidden below ground level in the multi-purpose cellar that is part of the design concept.

Tubbergen sequence. The diameter of the pilot hole is smaller than a conventional bore, meaning small waste streams and lighter drilling equipment. This translates into low costs. Following this stage, static and dynamic tests are performed in the best aquifer identified from LWD-logs. These tests determine the final geometry (spacing and horizontal extent) of the producer and injector wells which are drilled next. If the tests show that the required energy cannot be produced at the location, the project can be stopped. The total financial exposure in a LUC project equals the costs for drilling and testing the pilot hole, which is approximately € 500,000.

If the LUC project is continued, then we estimate the CAPEX investment for a 3,6 MW_{th} system, to be € 6,5 million. We assume that the project will be subsidized for the first 15 years. Aquifer temperature is estimated at 63^{o}C and the return temperature is set at 33^{o}C. This is a conservative estimate as it corresponds to the best reservoir sand being encountered near the top of the Tubbergen sequence. The resulting Net Present Value (NPV) of this project is € 12,7 million, the Internal Rate of Return (IRR) is 14% and the Total Return is 210% after 20 years. As the Tubbergen formation has not before been tested for geothermal development, it can also be argued that a dedicated exploration well should be drilled to de-risk a prospect-portfolio. That exploration well would not be constrained by economic POS but on exploration POS instead.

The second example has few exploration aspects, but is actually a portfolio development, whilst still appraising and de-risking each project and subsequent investments. The authors describe a 1,5 MW_{th} geothermal installation for heating a greenhouse business in Erica, also in the Eastern part of The Netherlands (Fig. 2, de Groot et al., 2020). The target aquifer is the early Cretaceous coastal-marine Bentheim Sandstone at a depth of ca 1,500 mTVD (Fig. 4). The aquifer characteristics are such that this aquifer is not considered a viable target for conventional geothermal solutions. However, our calculations show that LUC development here is economically viable. Here the pilot hole will be located near an optimal technical position.

In Erica, we estimate the investment for LUC to be € 3.6 million. This investment is peer-reviewed. It is considerably lower than in Enschede, due to the fact that the Enschede site requires drilling through salt. Heat delivered by the Erica LUC installation will benefit from government subsidy for the first 15 years. We estimate reservoir temperature to be 61°C and the return temperature is set at 26 °C. The NPV of this project is € 6 million, the IRR is 14% and the Total Return is 166% after 30 years.

Conclusions

In this article we present a concept for geothermal developments in low-enthalpy basins. We believe this concept to be globally applicable and economic and commercial viability is demonstrated by examples. The peer-reviewed estimates in our examples are representative for LUC development in The Netherlands. To apply the concept elsewhere, the financial estimates must be tailored to local circumstances (availability of equipment, knowledge, regulations, subsidy, etc.). When successfully implemented, the LUC concept can be considered a game-changer. The concept has potential for large-scale implementation for heating and cooling, and could provide a significant contribution to meeting reduction targets for CO2 emission under the global Paris Accord.

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about the authors

Andre Mol graduated (1989) in mechanical engineering and started his career as international staff with Shell in Thailand. In 2002 he started his own business and has since worked as management consultant for a wide range of reputable clients in the energy industry. In addition, Andre Mol has been involved in not-for-profit business, notably as director of a program called “the business of performance” is cooperation with the Olympic winter-sports facilities in Calgary. Between 2005 - 2009 he was a member of the Clinton Global Initiative (CGI) with an emphasis on poverty alleviation. Since 2017 he has dedicated almost all his time, experience and expertise to help with the implementation of geothermal energy, this resulted in the creation of a non-profit foundation Stichting Geothermie Groep Nederland (2018) of which he is Chairman.

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