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Eavor-Lite Performance Update and Extrapolation to Commercial Projects

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Geothermal, closed-loop, multilateral, load-following, Eavor-Loop, Eavor-Lite, Rock-Pipe, district heating

ABSTRACT

Eavor-Lite™ is a full-scale demonstration project of a multilateral closed-loop geothermal system. An update is presented based on ~16 months of operations and testing. The project is located near Sylvan Lake, Alberta, Canada and consists of two 1.7 km long multilateral horizontal wellbores connecting two 2.4 km deep vertical wellbores to create a U-tube shaped closed-loop geothermal system. The horizontal wellbores are intersected using magnetic ranging technology, and sealed with a chemical completion technique, resulting in a large subsurface heat exchanger.

An update is provided on project construction, operations, and thermodynamic performance. A transient thermodynamic model is used to history match the outlet temperature and demonstrate the predictability of conduction-based systems. An analytical model is derived and closely tracks the transient model and field data. This analytical model is then extended to case studies of a district heating project and a high temperature electricity project, demonstrating that they can produce predictable, low decline output over long timeframes. The high temperature case study produces an average of 8 MWe over a 30-year operating period when controlled with a constant mass flow rate.

1. Introduction

Over the past decade wind and solar have been the renewable energy source of choice with increased manufacturing economies of scale and improvements in technology contributing to a precipitous decline in cost. Both wind and solar are variable power sources that produce electricity when their fuel, wind or sun, is available. Advanced zero-emitting firm or flexible technologies are needed for electricity grids to transition to a net-zero carbon future. Further, in northern Europe and North America almost 50% of total residential and commercial energy demand, and therefore carbon emissions, is for heating rather than electricity. These are two of the fundamental problems facing the energy transition. The current market consensus on potential solutions to address these problems appears to be focused on Battery Energy Storage and Hydrogen. However, both technologies have technical risks, require significant capital until they become viable, have many qualitative drawbacks, and are more expensive than geothermal even at their 2050 projected costs on an aggregate grid level (Holmes et al., 2021).

Geothermal is a natural fit for these two unsolved issues but still only accounts for < 0.3% of the world's energy output. In addition, while conventional geothermal has had a flat or slightly increasing cost per unit over the last decade, Wind, Solar, and Shale oil/gas wells have each shown a tremendous cost decline driven by a repetitive, fast, manufacturing approach (Toews et al., 2020). Geothermal has remained a niche solution partly due to its lack of scalability and speed.

Closed-loop systems can address these challenges and provide both heat and firm or load-following electricity. These systems differ from conventional geothermal and Enhanced Geothermal Systems (EGS) as they consist of a subsurface closed-loop heat exchanger, that relies only on conductive heat transfer into a network of pipes, rather than reservoir or fracture fluid flow. Several recent efforts describe the technical challenges and opportunities. The impact of well diameter in a deep closed-loop system has been shown to be relatively small while the most important design consideration is depth (Esmaeilpour et al., 2021). Thermal interference between wellbores in a multilateral closed loop system has been investigated with a natural coupling analytical method (Yuan et al., 2021). Specific capital cost of a multilateral closed-loop system has been investigated along with various sensitivities, showing that drilling cost of cased lateral sections is a challenge to achieving commercially viable economics (Malek et al., 2021). This paper specifically addresses the progress made with multilateral closed-loop geothermal systems, their technical and financial advantages (Table 1), and their commercial potential.

	Hydrothermal or EGS	Multilateral Closed-Loop Systems
System design	Open System: Brine produced from reservoir, fluid exchange between system and geological formation	Closed System: Working fluid circulates in isolation from reservoir, no fluid exchange
Permeability	Hydrothermal requires a hot and permeable reservoir; EGS creates a reservoir through fracking.	No need for permeable reservoir or hydrothermal source.
Parasitic power load	Requires an electric pump to circulate brine continuously	Driven by thermosiphon, no pumping required
Induced Seismicity	Fracking or high injection pressures can lead to induced seismicity. Seismicity has caused several failed EGS projects in Europe, Asia.	No fracking, pressure-balanced, no induced seismicity
Water treatment	Continuous water treatment issues that may include scale, erosion, corrosion, produced gases, NORMs	Minimal water treatment, simply circulating a benign working fluid
Dispatchable	Baseload	Baseload and Dispatchable, able to time-shift output while maintaining 100% capacity factor
Operating Costs	In projects with low enthalpy or high TDS brine, Opex can be greater than Capex over life of project	Significantly lower due to inherent removal of key Opex drivers
Thermal Output Uncertainty	Large initial output uncertainty prior to spending capex. Even after operating for 5 years or longer, there remains substantial risk of precipitous drop in revenue due to cold water breakthrough.	Thermal output predicted accurately prior to spending capital. No thermal output risk or uncertainty.
Project Cycle Time	Typically 5-10 years or longer	~18 months, depending on regulatory regime

Table 1 - Comparison of Hydrothermal and EGS to multilateral closed-loop geothermal systems

2. Eavor-Lite™ Project

To develop the base technologies required for a multilateral closed-loop system, the Eavor-Lite™ demonstration project was constructed in Alberta in 2019. The project is described in a previous paper by the author and preliminary results were presented (Toews, Riddell, Vany, & Schwarz, 2020). This paper provides an update to those results up to May 2021.

Eavor-Lite™ (Figure 1) is a full-scale prototype of the Eavor-Loop™ technology intended to de-risk the key technical components. The project was partially financed through grants from several Federal and Provincial agencies in Canada and Alberta: Sustainable Development Technology Canada, Natural Resources Canada, Emissions Reductions Alberta, and Alberta Innovates. It consists of a large U-tube shaped well with 2 multilateral legs at 2.4km depth, a test facility, and a pipeline connecting the two sites at surface. It was constructed with two drilling rigs 2.5km apart that drill and intersect these horizontal multilateral wells midway between the sites. The circulating water picks up heat in the subsurface loop, exits at surface, and the thermal energy is discharged in an aerial cooler. The test facility is designed to allow the circulating water to be treated with additives to enhance performance. The multilateral heat exchange section was sealed with Rock-Pipe™ technology, a chemical sealing system that removes the need for steel casing. The well completion design, multilateral junctions, multilateral wellbore intersections, and thermodynamic performance is consistent with a commercial design.

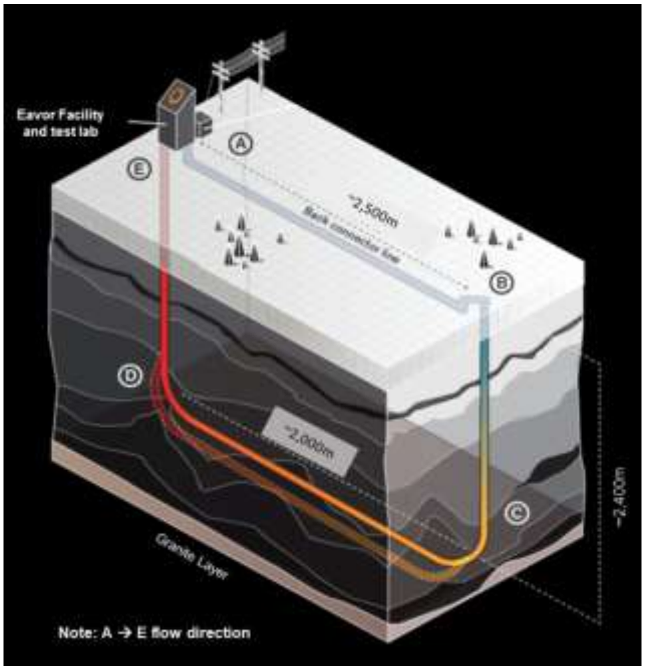

Figure 1 - Eavor-Lite™ Schematic

The project was executed successfully, on-time and on-budget, demonstrating that an Eavor-Loop™ can be drilled, sealed, and operated purely driven by a thermosiphon effect with thermodynamic results in agreement with the predicted output from simulations. A summary of the key technical objectives and outcomes is outlined in the Table 2.

Technical Objective	STATUS	Summary of Results
1. Drill and intersect a multilateral Eavor-Loop with two laterals	✓	LEG-2 was successfully intersected on September 1, 2019
	✓	LEG-1 was successfully intersected on September 11, 2019
	✓	Drilling program was completed and rigs were demobilized on September 14, 2019.
2. Create a closed system by chemically sealing the Eavor-Loop (Rock-Pipe™ completion)	✓	9 x formation integrity tests to 5 MPa performed throughout drilling and upon completion of drilling program with > 97.5% of pressure maintained.
	✓	Current operation leak off rate is < 0.5 m3/d.
	✓	Visual samples and filter differential pressure monitoring indicating negligible solids production, facility has been running at ~95% uptime since Dec 4, 2019 start-up.
3. Validate thermodynamic performance and demonstrate thermosiphon	✓	Thermosiphon has been fully operational, ongoing circulation without use of pump since Dec 4, 2019 start-up.
	✓	Thermodynamic model validation has been completed with measured performance within 2% of predicted.
	✓	Ongoing data collection and validation to prove out simulation capability over longer time frame. Third party validation of results received from multiple organizations.

Table 2 - Summary of Eavor-Lite™ technical objectives and results

Construction of the pipeline and surface facilities was executed during October and November of 2019, and the entire facility was commissioned in December 2019. The facility has continued to perform without issue, operating consistently on thermosiphon mode (i.e. no pumping required) since December 4, 2019. Figure 2 illustrates some of the project components; there is also a virtual tour of the facility and description of the process online at https://www.eavor.com/eavor-lite-virtual-tour.

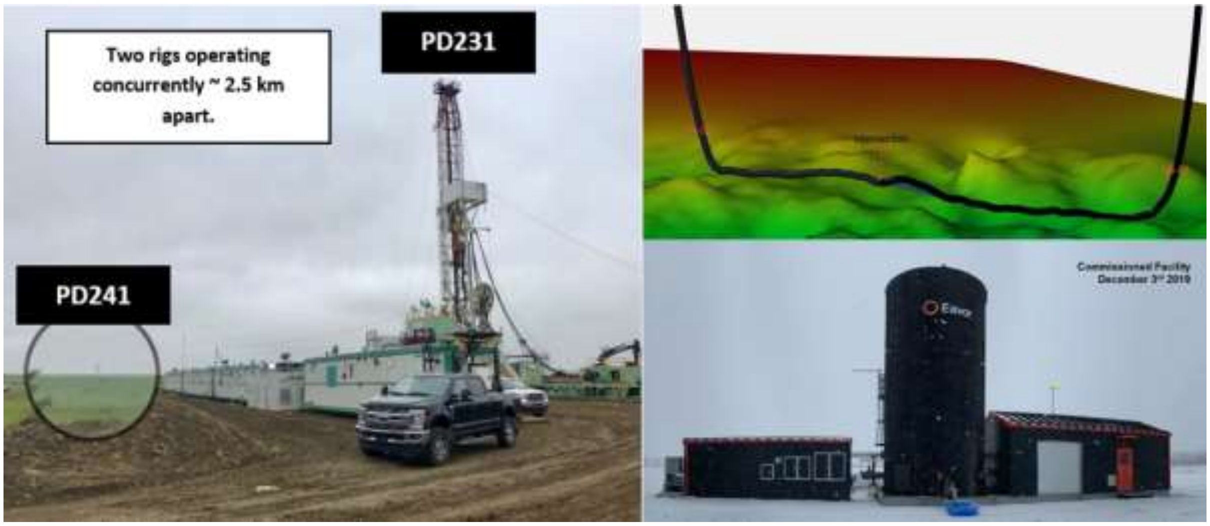

Figure 2 - Eavor-Lite™ Drilling Operations, initial Leg #1 intersection, and commissioning of the facility.

2.1 Drilling and Intersection

Both Leg #1 and Leg #2 wellbore intersections were successfully achieved by PD Rig #241 on Sept 1 and Sept 11, 2019, respectively. Wellbore ranging operations were executed flawlessly on the LEG #1 segment – nearly a direct hit. After intersecting, we reamed into the target wellbore 50+ meters taking measurements while drilling surveys throughout to further verify mechanical intersection. See Figure 3 below where the target well (14-12) is shown in 'green' and the intersecting wellbore (06-01) is shown in 'blue'. For Leg #2 a more typical intersection was achieved, intersecting at a low convergence angle roughly 83m laterally back from the toe of the target well.

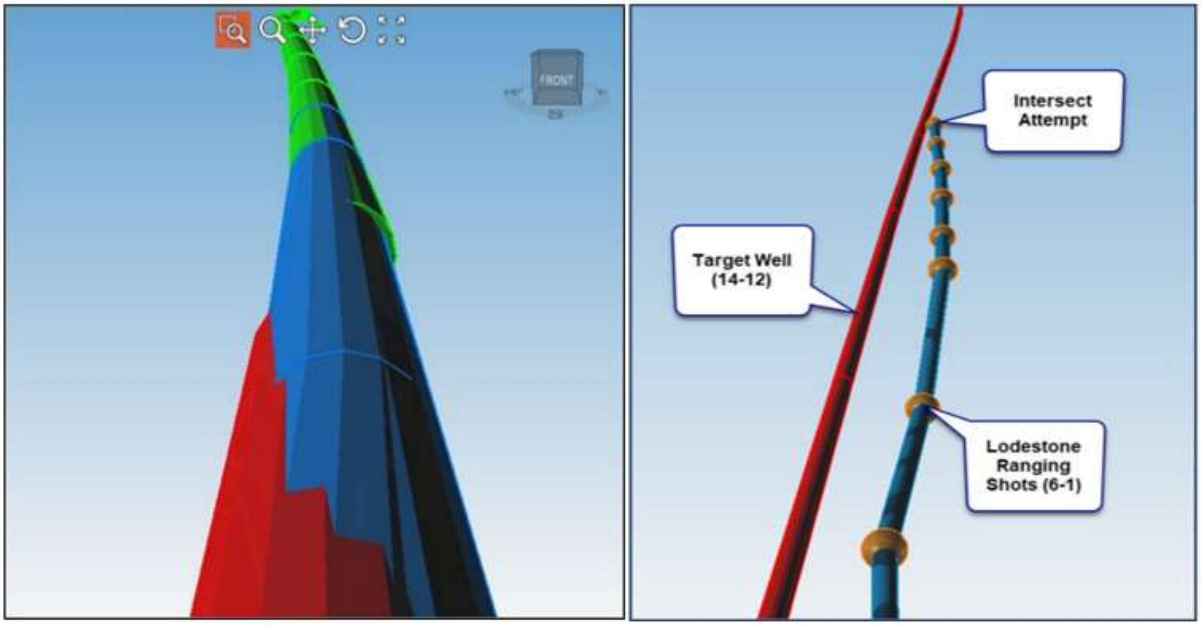

Figure 3 - Intersection diagrams, Leg #1 (L) and Leg #2 (R)

2.2 Rock-Pipe™ wellbore sealing

The vertical wells are cased with steel casing and cemented in place, following best practices from the geothermal and oil and gas industries. However, the multilateral heat exchange section is sealed with Rock-Pipe™, an Alkali-Silicate based sealant system. It is designed to:

- Permanently seal the near wellbore porosity / permeability while drilling the open hole laterals of an Eavor-Loop™
- Maintain the seal during the operational life using working fluid additives and treatments
- Maintain Wellbore Integrity throughout the operational life

Rock-Pipe™ has two primary components: the initial sealing phase function which is achieved during the drilling phase, and the additives/ treatments deployed with the long-term circulating fluid ("working fluid") within the Eavor-Loop™. These additives maintain and improve the seal, by naturally leaking-off and plugging any remaining permeability. Further, the working fluid is designed to provide important well integrity functions such as chemical stability to shales/muds and maintain appropriate compressive strength to the formation.

In laboratory core flooding tests at in-situ pressure and temperature, the sealant penetrates several centimeters into the core before setting into a solid. Results indicate the core does not completely plug off with the initial treatment, however >99.9% of permeability is lost.

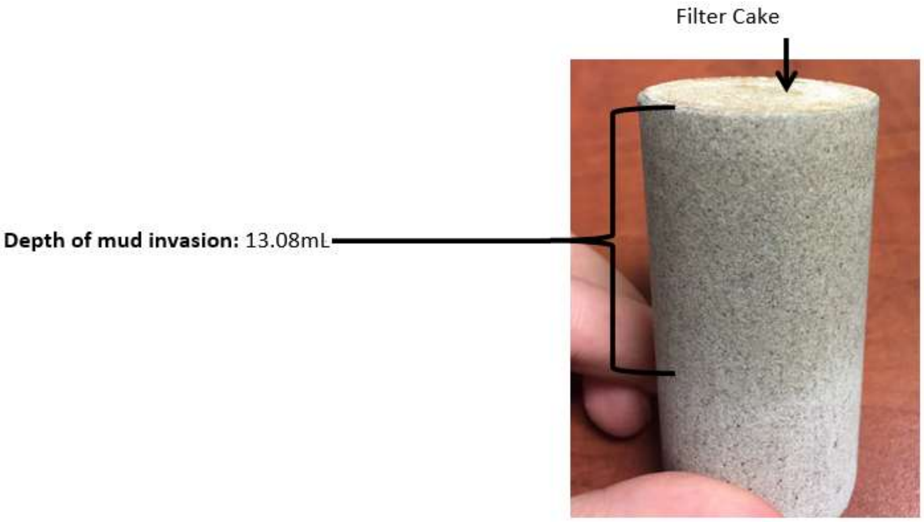

Figure 4 – Rock-Pipe core, after sealing

The key performance indicator for success of the Rock-Pipe™ system is the operational sub-surface leak-off rate. The measured daily leak off over time is shown in Figure 5. The steady state leak off rate is only ~0.5 m3/d, despite the circulating fluid being over-pressured by ~2800 kPa relative to the in-situ pressure of the formation. The leak-off rate varies slightly with working fluid chemistry yet remains below the 1 m3/d target for the project and continues to trend down over time. This rate of leak-off is immaterial to thermodynamic performance or project economics.

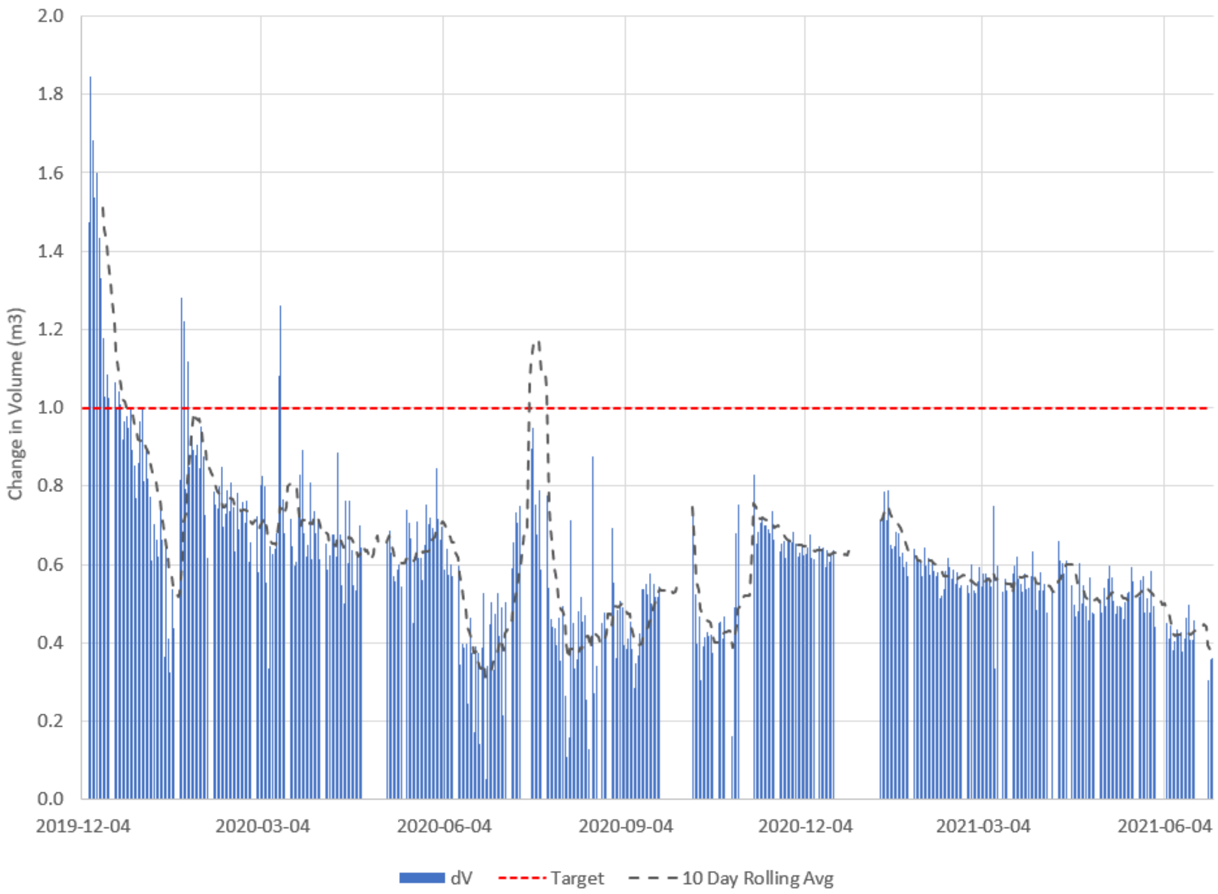

Figure 5 - Eavor-Lite™ Leak-off rate

2.3 Thermodynamic Performance

Thermodynamic performance of the Eavor-Lite™ project is measured and compared to the simulated performance calculated using thermodynamic modelling software. Data has been collected since start-up on December 3, 2019 which is then imported into Eavor's transient 2D thermodynamic model, described in (Toews et al., 2020) and (Holmes et al., 2021). The key input parameters are inlet well pressure, temperature, flow rate, rock temperature and rock thermal conductivity. Using these parameters along with the wellbore geometry, the outlet temperature and pressure of the system are calculated numerically by closing the energy, mass, and momentum equations for each discretized segment of the Eavor-Loop™ vertical and lateral wellbores. The prediction of the outlet temperature is directly tied to the amount of thermal or electrical energy that the Eavor-Loop™ can produce.

Validating the model involves generating a history match of the empirical field results using the model, then forecasting that model forward to predict future performance. A good history match is obtained if the model accurately predicts measured values.

The transient 2D model was used to predict the measured performance data from Eavor-Lite™. The model was history matched using 60 days of time series production data comprising outlet wellhead temperature, outlet wellhead pressure, and outlet well temperature at varying depth measured by a 6-point thermocouple in the outlet well. Time series of measured circulation rate, inlet wellhead temperature, and inlet wellhead pressure were provided as inputs. Properties of the working fluid must also be accounted for as working fluid chemistry changes. History match parameters were the rock thermal conductivities adjacent to the vertical and lateral wellbores. The history match was performed using a genetic algorithm to minimize an objective function specified as a weighted sum of squared error terms between the model's prediction and the measured data. Rock thermal conductivities, and accordingly thermal performance of the system, were calculated to be within 5% of the values estimated prior to drilling the loop, highlighting the predictability of closed-loop geothermal systems.

Figure 6 below shows the measured and predicted outlet temperature. The vertical solid black line separates the data used for the history match (left) from the extrapolation and forecast (right). Circulation rate is shown for reference. Note that periods where there is no measured wellhead temperature correspond to periods where the loop was shut down (circulation rate of 0) for thermal recharge testing. To date, the model has been used to successfully predict over 16 months of operating data with a mean absolute error of only 0.19°C (0.37%).

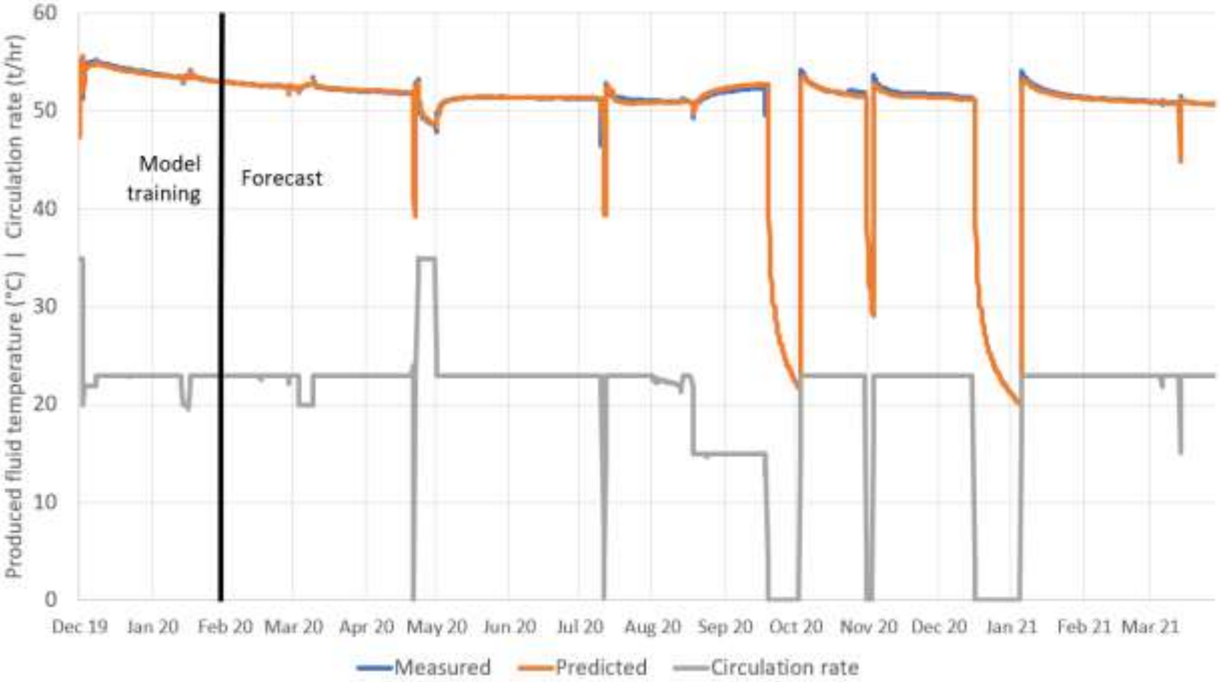

Figure 6 Comparison of Measured and Simulated outlet temperature results from Eavor-Lite™

A thermocouple string with 6 temperature measurement points was installed in the outlet well. The model properly captures the potential energy and Joules-Thomson effects in the outlet well, matching all 6 thermocouple points closely.

Figure 7 - Comparison of Measured and Simulated thermocouple data from Eavor-Lite™

2.4 Analytical method

A simple analytical equation can be derived to estimate the outlet temperature from a horizontal lateral well. This equation is analogous with the approach developed by Ramey (Ramey, 1962) for vertical wellbores under the key assumption that the heat transfer can be treated as quasi-steady state radial heat conduction from the rock into the fluid flowing through the well bore.

The steady-state radial heat conduction equation is given by:

$$dq_r = \frac{2\pi k_r dL(T_r - T_w)}{ln\left(\frac{r_{eff}}{r_w}\right)} \tag{1}$$

where dq_r is the incremental heat flow from the rock to the fluid in the lateral at a given axial position

k_r is the thermal conductivity of the rock
dL is the incremental length in the axial direction
r_{eff} is the effective thermal radius
r_w is the radius of the horizontal lateral wall
T_r is the temperature of the undisturbed surrounding rock
T_w is the temperature of the horizontal lateral wall

The steady-state heat conduction is based on an effective thermal radius for the rock beyond which the temperature of the rock is unchanged. The effective radius varies with time and is governed by the non-dimensional Fourier number, Fo, for this transient radial conduction problem:

$$\mathrm{Fo} = \frac{\alpha_r t}{r_{eff}^2} \tag{2}$$

where α_r is the thermal diffusivity of the rock; $\alpha_r = k_r/\rho_r C_{p_r}$

C_{p_r} is the specific heat capacity of the rock
ρ_r is the density of the rock

The Fourier number is assumed to be a constant for this transient heat transfer problem with the prescribed geometry. Based on a linear, least-square regression against our numerical transient radial heat transfer model, Fo $= 2.4675$. Equation (2) can be re-arranged in terms of the effective radius:

$$r_{eff} = \sqrt{C_t \alpha_r t} = \sqrt{2.4675 \alpha_r t} \sim \frac{\pi}{2}\sqrt{\alpha_r t} \tag{3}$$

This equation (3) for the effective radius can be directly substituted into the "quasi" steady-state heat conduction equation (1.1):

$$dq_r = \frac{2\pi k_r dL (T_r - T_w)}{ln\left(\frac{\pi\sqrt{\alpha_r t}}{2r_w}\right)} \tag{4}$$

Here we assume that the thermal resistance due to convective heat transfer in wellbore is negligible compared to the thermal resistance of the rock. Therefore, the temperature of the lateral wall, T_w is essentially the same as the bulk fluid temperature, T_f at a given axial location, i.e. $T_w \sim T_f$

The energy equation for the fluid flowing in a horizontal lateral be written as:

$$dq_r = \dot{m} C_{p_f} dT_f \tag{5}$$

Where C_{p_f} is the specific heat capacity of the fluid flowing through the horizontal lateral and $\dot{m}$ is the mass flow rate.

Equating the incremental heat flow from the rock, equation (4) with the incremental heat flow into the fluid flowing in the lateral, equation (5), yields:

$$\dot{m}C_{p_f}dT_f = \frac{2\pi k_r dL(T_r - T_f)}{ln\left(\frac{\pi\sqrt{\alpha_r t}}{2r_w}\right)} \tag{6}$$

Re-arranging equation (6) and integrating it from the start to the end of the lateral:

$$\int_{T_{f_{in}}}^{T_{f_{out}}} \frac{dT_f}{T_r - T_f} = \int_0^L \frac{2\pi k_r dL}{\dot{m}C_{p_f}\, ln\left(\frac{\pi\sqrt{\alpha_r t}}{2r_w}\right)} \tag{7}$$

Assuming the fluid properties remain constant over the length of the horizontal lateral, equation (8):

$$T_{f_{out}} = T_r - \frac{T_r - T_{f_{in}}}{\exp\left[\frac{2\pi k_r L}{\dot{m}C_{p_f} \ln\left(\frac{\pi\sqrt{\alpha_r t}}{2r_w}\right)}\right]} \tag{8}$$

k_r is the thermal conductivity of the rock (W/m K)
L is the length of a single lateral in the axial direction (m)
m is mass flow rate through a single lateral (kg/s)
r_w is the radius of the horizontal lateral wall (m)
T_r is the temperature of the undisturbed surrounding rock (deg C)
T_{fin} is the inlet fluid temperature (deg C)
T_{fout} is the inlet fluid temperature (deg C)
C_{p_f} is the specific heat capacity of the fluid (J/kg K)
α_r is the thermal diffusivity of the rock; $\alpha_r = k_r/\rho_r C_{p_r}$
C_{p_r} is the specific heat capacity of the rock (J/kg K)
ρ_r is the density of the rock (kg/m3)

This analytical equation has several limitations. It assumed constant fluid properties and it is only valid for horizontal wellbores. Despite these limitations it still provides a close match to the Eavor-

Lite™ field data and the more complex numerical models. Figure 8 displays the measured data from the deepest thermocouple in the outlet well compared to the 2D transient model and the analytical equation. Inputs into the analytical equation are in Table 3. Lateral length has been adjusted slightly, from 1700m to 1900m, to account for the heat transfer that occurs within the vertical inlet well and build/turn section that is otherwise ignored in this analytical method.

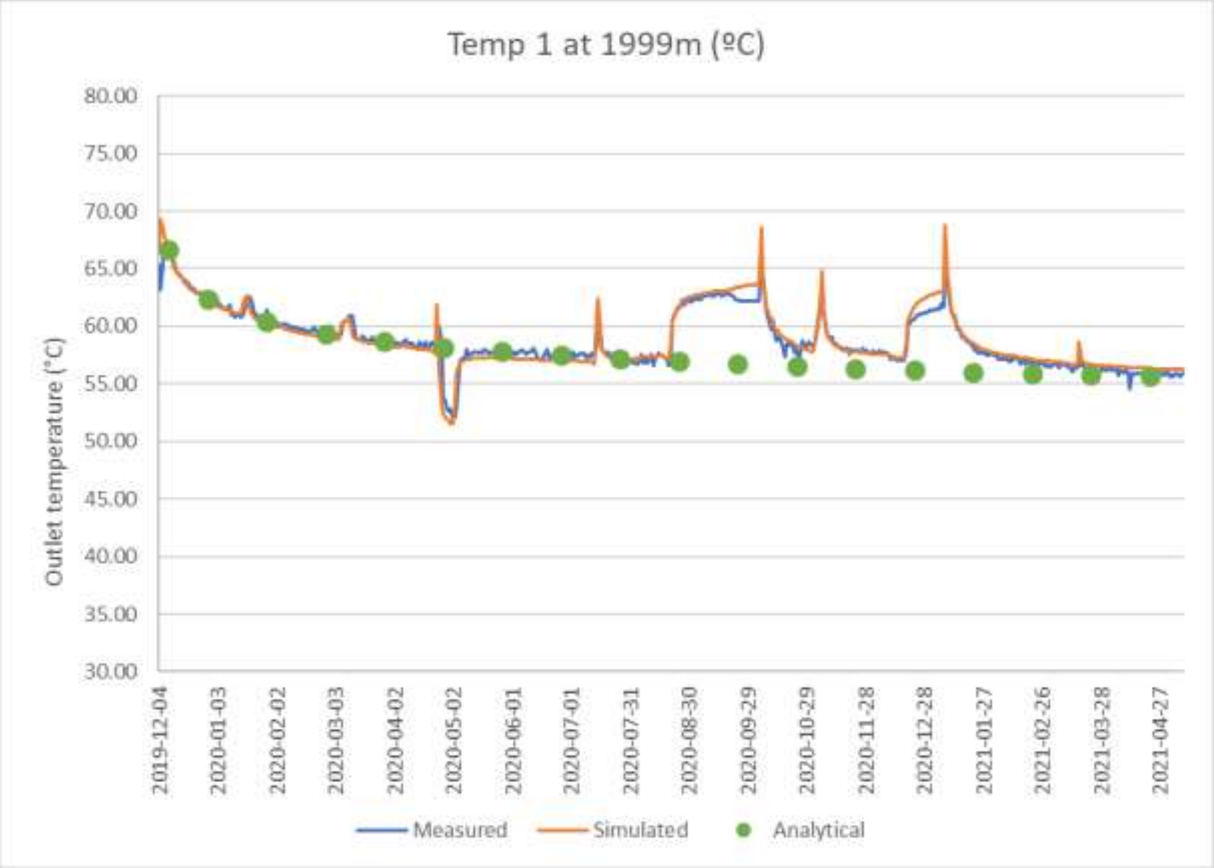

Figure 8 - Analytical equation comparison

Average rock temperature	77.8	°C
Inlet fluid temperature	24	°C
Rock conductivity	4.64	W/m.K
Effective Lateral length	1,900	m
Mass flow	2.88	kg/s/lateral
Wellbore radius	0.079	m
Fluid specific heat capacity	4.18	kJ/kg.K
Thermal diffusivity	1.57E-06	m2/s

Table 3 - Analytical model inputs for Eavor-Lite™

3. Commercial projects

Multilateral Closed-Loop systems can be applied to many market segments, such as

- District heating or cooling in cities (i.e. as commonly found in Northern Europe)
- Large scale (100's of MW to GW capacity) baseload or flexible clean electricity generation projects
- Distributed electricity (i.e. behind-the-fence for data centers or industrial end-users)
- Remote or Island Communities (currently generating energy with shipped or trucked diesel)
- Resiliency markets (ex: Defense)

In each of these segments there are limited or no commercially available solutions to decarbonize energy at a competitive price. The geometry and design of an optimum multilateral closed-loop system depends on the project specifics, the application, and the technological maturity of the underlying components. Figure 9 shows the technical evolution of Eavor-Loop™, from the Eavor-Lite™ project to the first projects being commercialized in Europe, and a deeper, hotter version informally called "Eavor-Loop™ 2.0" which is currently under development.

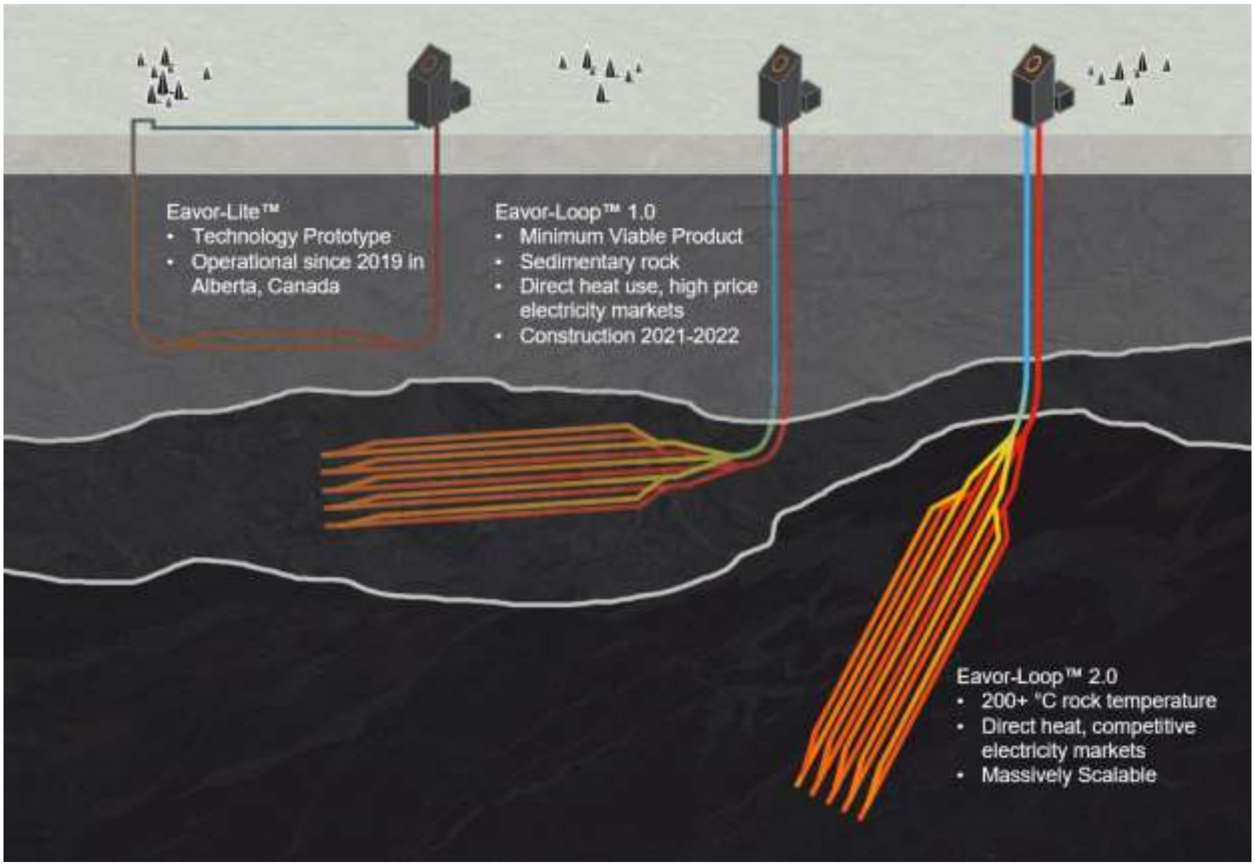

Figure 9 – Eavor-Loop™ design evolution

Case studies are described below for a district heating project and a high temperature scalable electricity project. The analytical method provides a simple, quick method with sufficient accuracy to evaluate commercial projects, and has been shown to closely match Eavor-Lite field data and more rigorous numerical models.

3.1 District Heating commercial project case study

District heating grids are common throughout Europe and in some locations in North America. The required supply/return temperatures vary depending on the age of the network; for geothermal in general it is more attractive to supply later generation networks with lower temperatures. However, the biggest existing grids generally have high inlet temperatures. Table 4 shows parameters for a typical district heating system in Europe to replace coal-fired hot water.

Minimum network supply temperature	100	°C
Network return temperature	55	°C
# of laterals	12	
Depth	4500	m
Average rock temperature	150	°C
Inlet fluid temperature	55	°C
Rock conductivity	3.50	W/m.K
Effective lateral loop length	6,000	m
Mass flow	5.00	kg/s/lateral
Wellbore radius	0.108	m
Fluid specific heat capacity	4.18	kJ/kg.K
Thermal diffusivity	1.18E-06	m2/s

Table 4 – District Heating case study inputs

Figure 10 shows the performance of this system, using the analytical model and a 2D transient model with a fixed flow rate of 60 kg/s (5 kg/s/per lateral). Since the analytical model ignores heat transfer in the vertical wellbore segments, it is not expected to match exactly – however it still shows a close approximation to the more rigorous numerical method.

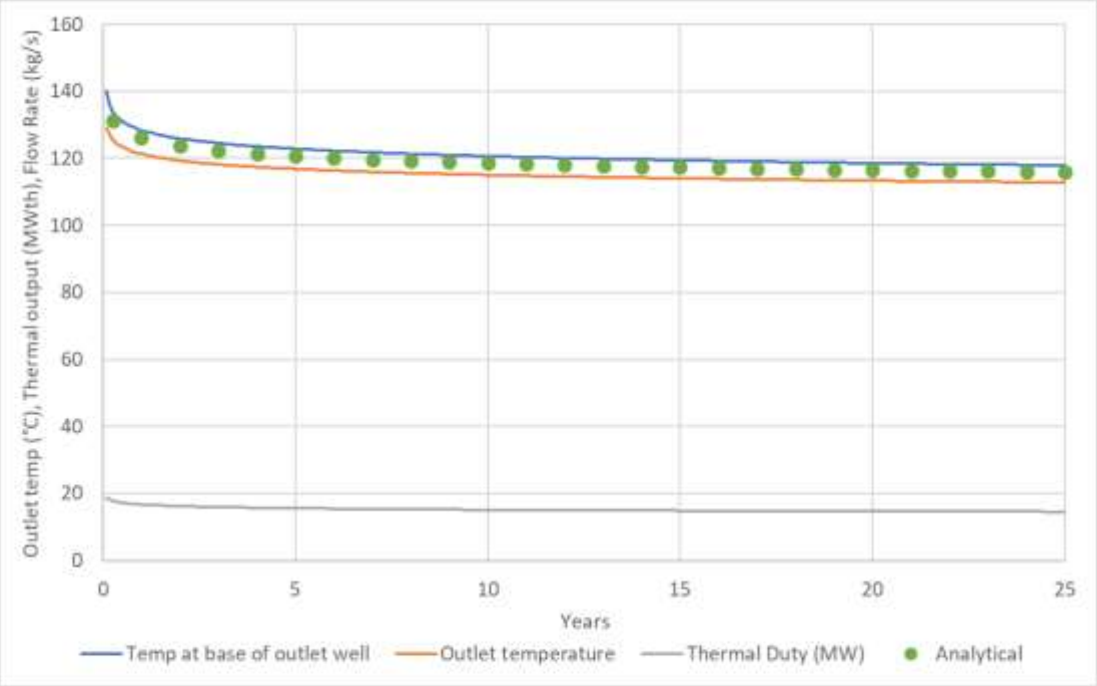

Figure 10 - District Heating case study output - constant flow rate

Figure 11 is the same well design, but rather than operating with a fixed flow rate, the flow rate is varied automatically in the transient model to output the fixed temperature of 100 °C required for the district heating system.

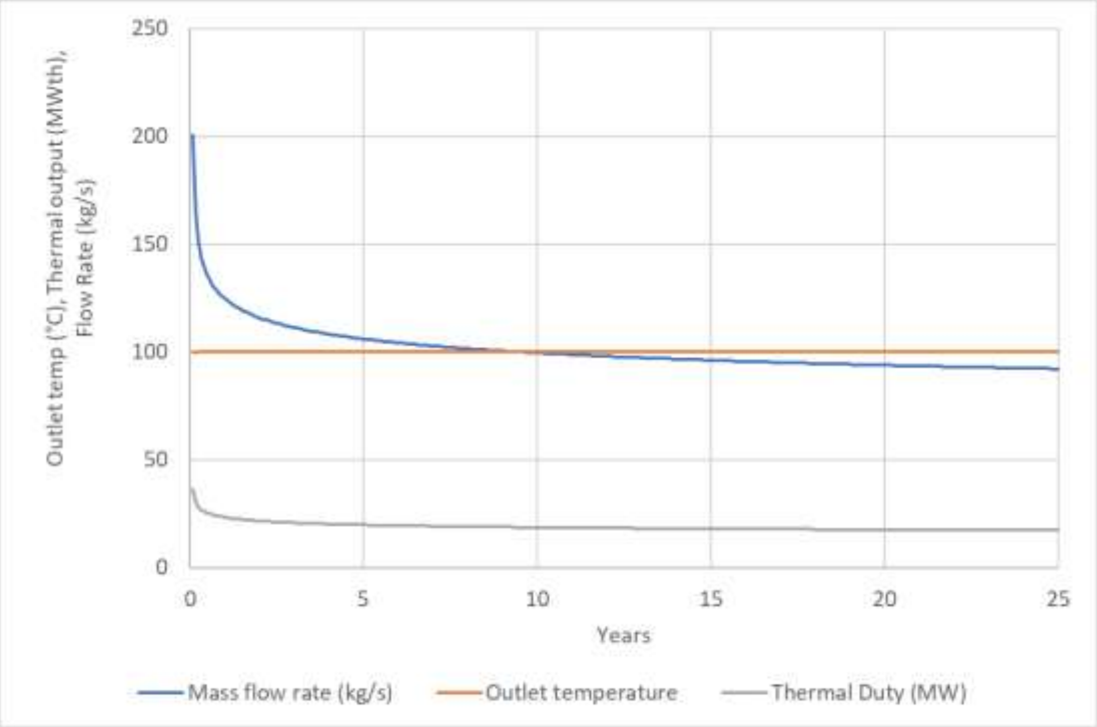

Figure 11 - District Heating case study output - constant outlet temperature

Another method of controlling the system is to operate with a fixed thermal output, as depicted in Figure 12.

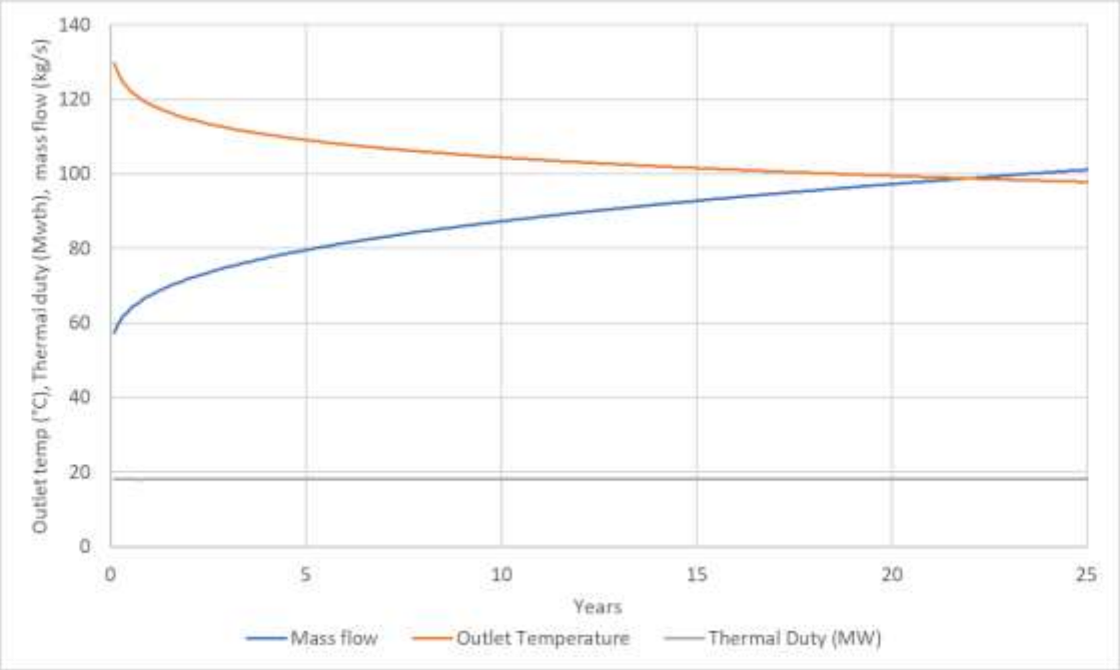

Figure 12 - District Heating case study output - constant thermal duty

3.2 High temperature electricity case study

Electricity generation is inherently more scalable than heating yet requires higher temperatures to be cost competitive in the near term. Many areas of the western United States, Asia, Islands, and some parts of Europe have regions with sufficiently high conductive gradients to reach an average temperature in the multilateral section well over 200°C, particularly if the multilateral section is not horizontal but extends deeper. This "Eavor-Loop™ 2.0" configuration is depicted in Figure 9. Many Eavor-Loops™ can be directionally drilled from centralized surface pads to scale-up electricity generation to hundreds of MWs or potentially GWs. A generic example for such a project is described below in Table 5.

Net heat to power efficiency was calculated based on the outlet wellhead temperature, an assumed utilization efficiency of 50% relative to Carnot efficiency, and an assumed cold sink temperature of 15°C.

# of laterals	12	
Average rock temperature	350	°C
Inlet fluid temperature	80	°C
Rock conductivity	2.50	W/m.K
Effective lateral loop length	6,000	m
Mass flow	8.00	kg/s/lateral
Wellbore radius	0.108	m
Fluid specific heat capacity	4.18	kJ/kg.K
Thermal diffusivity	8.44E-07	m2/s

Table 5 – High temperature electricity case study inputs

As in the previous district heating example, the loop can be operated with a constant circulation rate, constant thermal duty, constant outlet temperature, or with a variable flow rate designed to provide shaped or flexible output (Reference sister paper). Figure 13 plots the thermal output over time, if operated with a fixed circulation rate. The red line shows the peak output within the first several days, and the green line is the average output over 30 years. The peak output is somewhat irrelevant as this is constrained by surface facility design, but more importantly the economics of a given project are dependent on the discounted average output, which is approximated by the simple average shown in green.

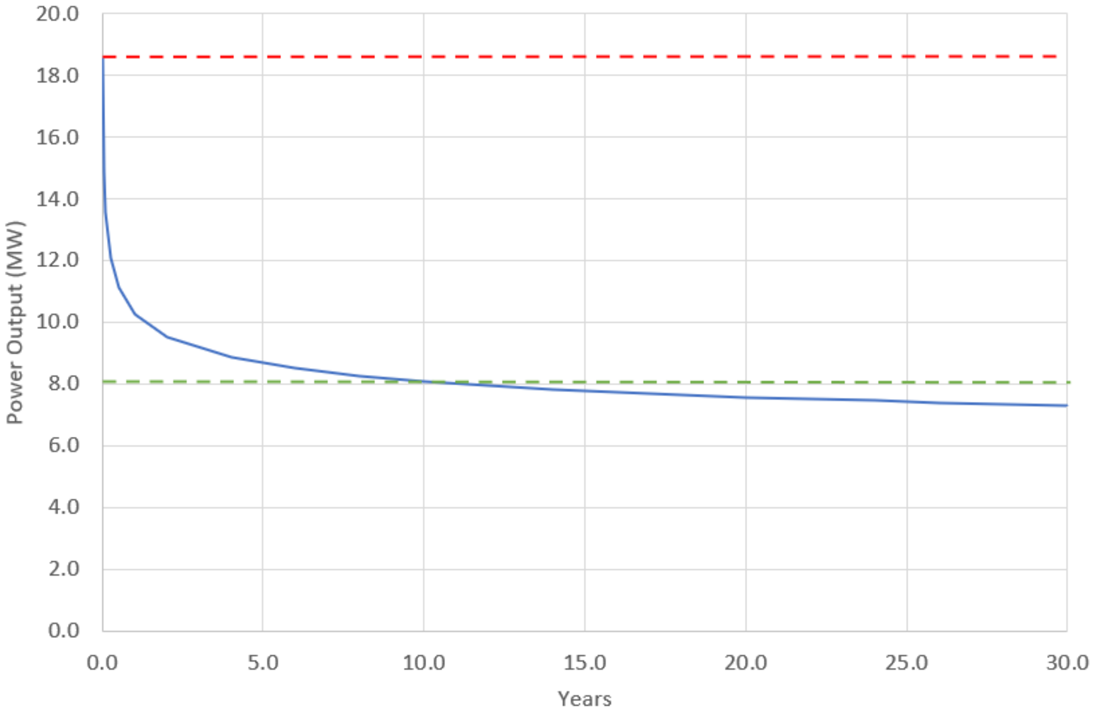

Figure 13 - High temperature electricity case study output - constant flow rate

4. Conclusion

The Eavor-Lite™ project has been successful in demonstrating the key technical components required for a multilateral closed-loop geothermal system. A 2D transient model has been used to history match the project using 60 days of data. After 490 days the model is matching extremely closely, illustrating the predictable nature of closed-loop systems. An analytical model has been derived that also closely matches performance.

Case studies have been presented for a district heating grid in Europe and a scalable high temperature electricity project. Both the analytical and transient models confirm that a significant thermal and electrical output can be produced, respectively. The high temperature electricity case study produces an average of 8 MWe over 30 years. Depending on operational and economic considerations, the loop can be controlled with a fixed flow rate which results in a minimal decline over a 25-year operating life; or it can be controlled to have a constant outlet temperature or constant thermal output.

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