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Joint Development Between Eavor and Turboden

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ABSTRACT

Eavor's proprietary geothermal power technology consists of two vertical wells connected by one or more passes designed to circulate a working fluid in a closed loop system, with no interaction with the underground formation water, to supply heat at the surface.

Turboden Organic Rankine Cycle (ORC) Technology converts the heat available at the surface into electricity by means of a closed thermodynamic process involving a suitable working fluid which is heated up in a heat exchanger and expanded in a turbine to generate electricity.

Eavor and Turboden performed a joint optimization of a surface heat-to-power facility for integration with an Eavor-Loop™. Because Eavor employs a closed-loop design, there are several optimization levers not applicable to traditional ORC applications that require an integrated system view to properly optimize.

The joint scope of work consisted of the creation of an integrated Eavor-Loop™ + Turboden ORC techno-economic optimization workflow for baseload power operation of the system. The optimization targeted minimizing the levelized cost of electricity of the Eavor-Loop™ + Turboden ORC system and analyzed each piece of surface equipment, choice of working fluid, and any other design considerations to determine if any modifications to traditional ORC design could be made to improve the economics.

The paper summarizes the joint optimization work, including key findings from the joint optimization effort, design considerations for an Eavor-Loop™ + Turboden ORC integrated system, and final recommendations of fluids and cycle configurations.

1. Introduction

Eavor-Loop™ is a disruptive geothermal system which eliminates or mitigates many of the issues with traditional geothermal. The key technical differentiator relative to conventional geothermal is that it is a subsurface closed-loop radiator, or heat exchanger, that relies only on conductive heat transfer, rather than convection or reservoir fluid flow. This design removes the need for a rare hydrothermal source, has no fracking or continuous water use, eliminates the complex resource characterization cost and time associated with geothermal reservoirs (natural or man-made), provides extremely predictable output, and is truly dispatchable without a reduced capacity factor. These features allow the system to be financed and scaled massively with a standardized, repetitive, manufacturing approach similar to wind or solar – without being held back by a scarce resource and high-risk exploration.

Turboden S.p.A. is an Italian company founded in 1980 by Prof. Mario Gaia of Politecnico di Milano. Today it is a world leader in designing, manufacturing and supplying Organic Rankine Cycle (ORC) systems, with more than 400 references worldwide. Since 2014, Turboden is part of the Japanese industrial giant Mitsubishi Heavy Industries, world leader for installed power from geothermal sources.

Due to the differences between an Eavor-Loop™ and traditional geothermal, an integrated system level approach is needed to optimize the operation of an Eavor-Loop™ with the design of the ORC. In an Eavor-Loop™ system, a feedback effect between the Eavor-Loop™ inlet temperature and the outlet temperature (a higher inlet temperature corresponds to a higher outlet temperature) impacts the selection of an Eavor-Loop™ operating point and the ORC design. Another unique feature of the Eavor-Loop™ is that the flowrate of working fluid (driven by thermosiphon) can be controlled to achieve a desired outlet temperature. The joint optimization effort between Eavor and Turboden aimed to identify the optimal operational conditions for the Eavor-Loop™, and the optimal ORC configuration for baseload operation with the objective of minimizing the levelized cost of electricity production over a 30-year project lifetime.

2.0 System Description

2.1 Eavor-Loop

In the Eavor-Loop™ 2.0 configuration considered for the analysis in this paper, two vertical wells are drilled from the same surface location and 12 passes (1 pass = 2 legs) propagate from the vertical wells at a slight off-vertical angle (10-30°), with the intersection occurring at the toes of the passes. Figure 1 illustrates the progression of the Eavor-Loop™ design. The circulation rate through the loop is maintained through the thermosiphon effect between the inlet and outlet well bores. This effect arises from the fluid density difference between the cold inlet and hot outlet wells and generates the required pressure driving force eliminating the need for a parasitic circulating pump.

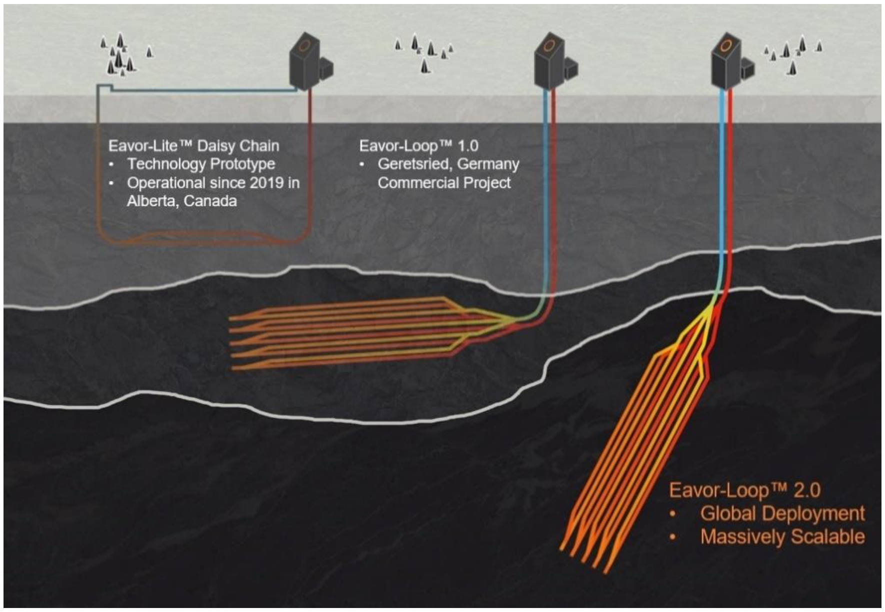


Figure 1: Eavor-Loop™ evolution

2.1.1 Baseload Operation of an Eavor-Loop™

An Eavor-Loop™ initially produces fluid at temperatures close to the reservoir temperature (with some cooling as the fluid is produced up the vertical production well). This temperature declines steeply during the initial days of production as the rock immediately surrounding the wellbore is cooled. Over time, the temperature decline is diminished, and temperatures stabilize with only a slight decline observed to year 30+. An Eavor-Loop™ has remarkably consistent and predictable output over long timeframes (productive lifetime of 100+ years) (Holmes et.al, 2021). As heat is extracted from the earth the radius of the temperature affected area around the wellbore expands; beyond this radius the reservoir is still at virgin temperature. This radius is a logarithmic function of time, and the lateral wellbores have minimal interference with each other if spaced properly.

2.2 ORC Technology

The ORC turbogenerator (Macchi, Astolfi, 2017) uses the geothermal fluid to preheat and vaporize a suitable organic working fluid, which is expanded in the turbine, generating electrical power. Organic fluids have unique thermodynamic characteristics, if optimally selected, to allow for the cost-effective exploitation of low to high enthalpy geothermal resources.

2.2.1 ORC Binary Geothermal Power Plant

Figure 2 shows the temperature-entropy diagram of a general thermodynamic cycle of the ORC, and Figure 3 shows schematically the ORC binary loop. The organic working fluid is pumped (1→2) into the recuperator (2→3), where it is heated before entering the evaporator (3→4→5); here the geothermal source, is cooled through the heat exchangers, providing heat to the working fluid which flows inside an independent loop. The cooled geothermal source can be reinjected. The hot working fluid passes through the turbine (5→6), which is directly coupled to the electric generator, resulting in reliable electric power. The exhaust organic vapour flows through the regenerator (6→7), where it heats the organic liquid (2→3) and then enters the condenser (with water or air) where it is condensed by the cooling circuit (7→8→1), thus completing the closed-cycle operation.

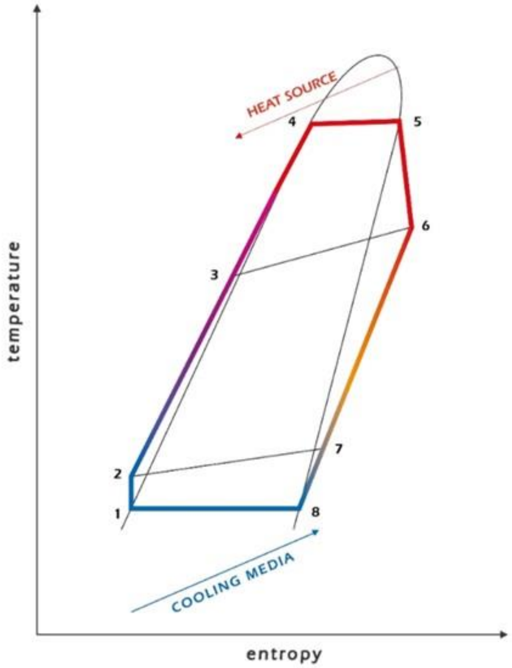


Figure 2: Temperature vs Entropy diagram of a general ORC thermodynamic cycle.

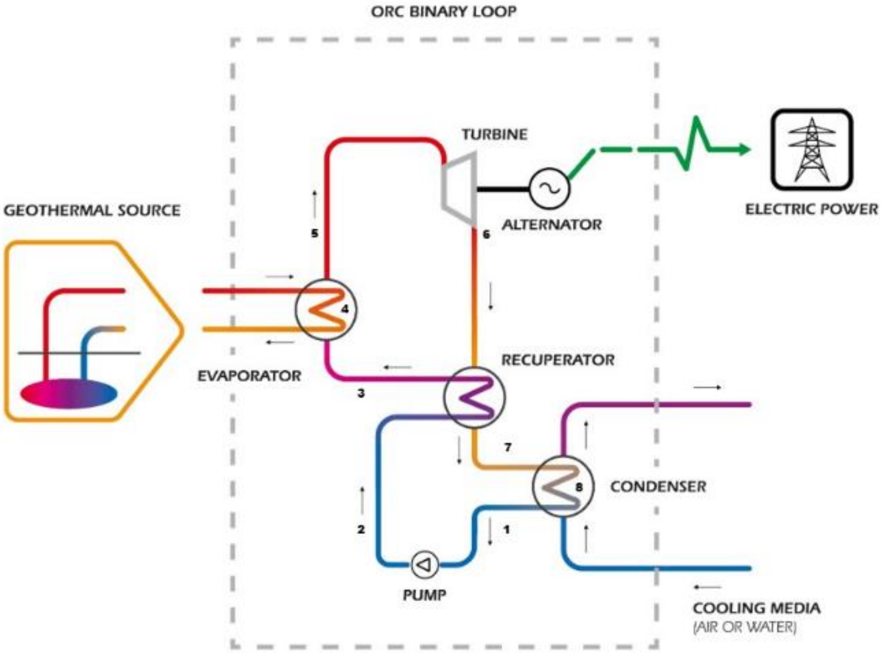
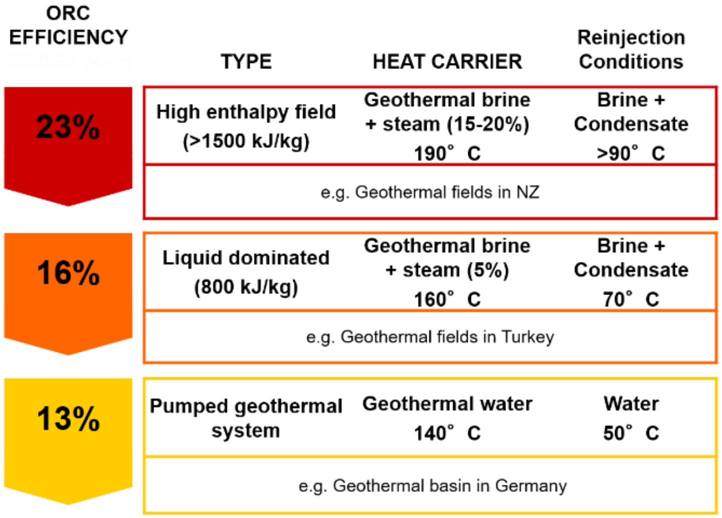


Figure 3: Schematic representation of the ORC binary loop.

The ORC conversion efficiency is dependent on the temperature of geothermal resource, as illustrated in Figure 4. The ORC efficiency is computed as the net power output divided by the total thermal input. In the case of high enthalpy field, the ORC efficiency can reach significantly beyond 20%. ORC technology is the ideal heat-to-power solution for an Eavor-Loop™ across a wide range of geological conditions.



ORC EFFICIENCY	TYPE	HEAT CARRIER	Reinjection Conditions
23%	High enthalpy field (>1500 kJ/kg)	Geothermal brine + steam (15-20%) 190° C	Brine + Condensate >90° C
	e.g. Geothermal fields in NZ		
16%	Liquid dominated (800 kJ/kg)	Geothermal brine + steam (5%) 160° C	Brine + Condensate 70° C
	e.g. Geothermal fields in Turkey		
13%	Pumped geothermal system	Geothermal water 140° C	Water 50° C
	e.g. Geothermal basin in Germany		

Figure 4: ORC efficiency depending on the geothermal source (traditional hydrothermal reservoir, Macchi, Astolfi, 2017).

3.0 Baseload Eavor-Loop™ + ORC Optimization Workflow

A techno-economic workflow was established to integrate the results of Eavor's subsurface model and Turboden's ORC models to reach an optimized Eavor-Loop™ + ORC configuration. The workflow consisted of four main steps:

1) The generation of Eavor-Loop™ thermodynamic performances across a range of operating points;

2) Initial scoping to determine the optimal Eavor-Loop™ + ORC operating window;

3) Detailed analysis using commercial software and proprietary cost databases to identify the optimal ORC specifications;

4) Sensitivities on alternative ORC designs and the expected energy production throughout the lifetime of an Eavor-Loop™ + ORC system.

The focus of this paper is on the ORC design and system integration with the Eavor-Loop™, while holding the well design and geometry constant.

3.1 Eavor-Loop™ Thermodynamic Performance

Eavor's propriety subsurface 2-D model calculates the heat conduction from the rock into the wellbore based on radial and axial coordinates and has been validated based on the thermodynamic and wellbore data from the Eavor-Lite™ demonstration project in Alberta (Toews, Holmes, 2021). Additionally, Eavor's subsurface model has been validated by numerous independent third parties including NREL (Beckers, Johnston, 2022), TNO (van Wees, 2021) and UT Austin (Fallah et. al. 2021). The key input parameters are the inlet well pressure, temperature, flow rate, rock temperature and rock thermal conductivity. Combining these parameters and specifying the wellbore geometry, the outlet temperature and pressure of the system are calculated numerically by closing the energy and momentum equations for each discretized segment of the Eavor-Loop™ vertical and lateral wellbores. In this paper, a high gradient Eavor-Loop™ 2.0 system, indicative of the geological conditions in western United States, with the following specifications were simulated and analyzed in conjunction with an ORC system:

Table 1: Eavor-Loop™ and Geology Specifications

Parameter	**Value**	**Units**
Eavor-Loop™ Specifications		
Vertical Well Length	4000m	m
Leg Length	3000m	m
Total Vertical Depth	6819m	m
Leg Angle (0=Vertical)	20	°
Number of Passes	12	#
Lateral Section Roughness	1.5E-4	m
Vertical Section Roughness	5.0E-5	m
Wellbore Diameter	0.216	m
Working Fluid	Water	-
Geology Specifications		
Geothermal Gradient	60	°C/km
Bulk Formation Thermal Conductivity	2.5	W/m-K
Bulk Formation Density	2750	kg/m^3
Bulk Formation Specific Heat Capacity	800	J/kg -K

Different operating points were simulated with the above Eavor-Loop™ and geology specifications using Eavor's proprietary subsurface 2-D model, for inlet Eavor-Loop™ temperatures varying from 40°C - 180°C and Eavor-Loop™ flowrates from 20kg/s – 180kg/s. Figure 5, on the left, illustrates the relationship between Eavor-Loop™ outlet temperature, thermal duty and mass flowrate of the circulating working fluid for a fixed Eavor-Loop™ inlet temperature of 110°C at year 5 of the project with the well and geology specifications of Table 1. As flowrate is decreased, the Eavor-Loop™ circulating fluid approaches rock temperature, and thermal duty decreases. The figure on the right outlines the feedback effect of Eavor-Loop™ inlet temperature on outlet temperature, and the corresponding impact on thermal duty for flowrates utilizing all the available thermosiphon pressure. The subsurface model outputs were used in the subsequent steps of analysis to determine the optimal Eavor-Loop™ operating point in combination with Turboden's ORC models.

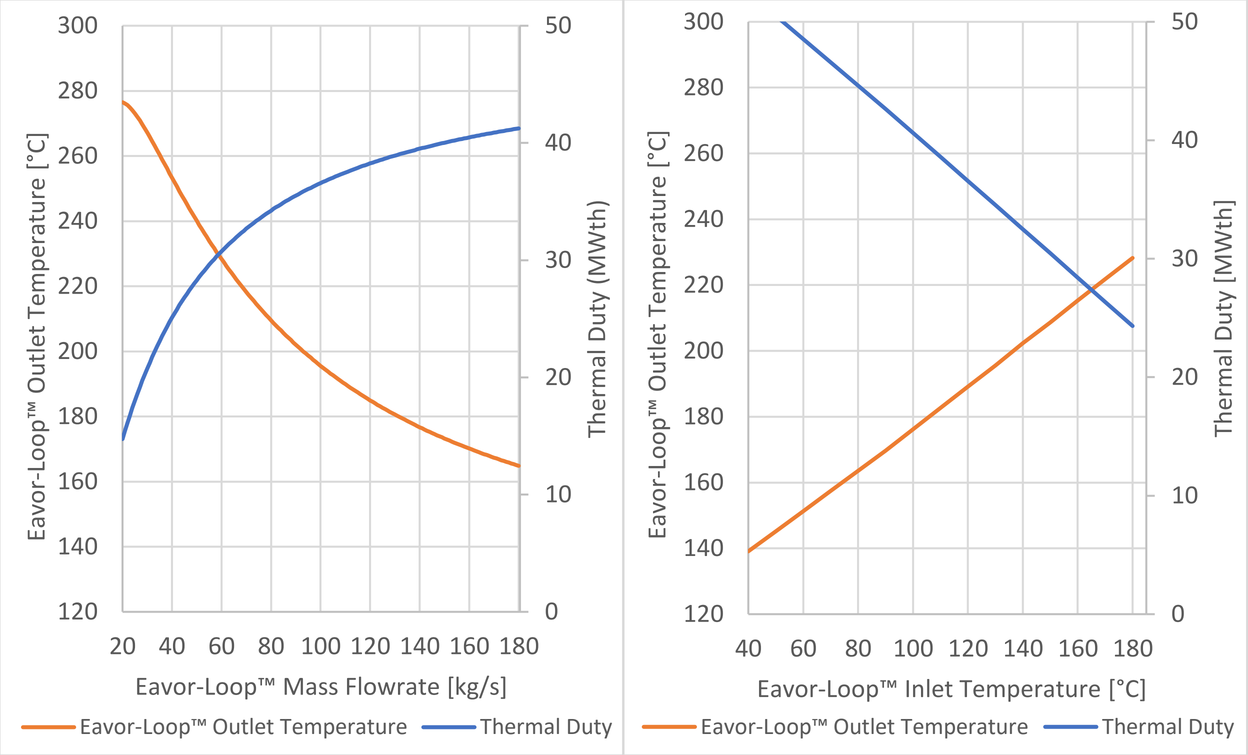


Figure 5: Thermal duty and Eavor-Loop™ outlet temperature as a function of Eavor-Loop™ flowrate and inlet temperature based on the specifications of Table 1

3.2 Scoping of the Optimal Eavor-Loop™ + ORC Operating Window

The initial assessment of the ORC power output as a function of the Eavor-Loop™ operating conditions was computed using the Lorenz cycle efficiency (Bertani et al., 2017), rather than the Carnot efficiency, since the sources of the cycle present temperature glides. Assuming a 55% conversion factor between the net real thermodynamic cycle efficiency from the ideal Lorenz efficiency, the net power output of each Eavor-Loop™ operating point was determined for the purposes of identifying the optimal operating window.

3.3 Detailed ORC Analysis

The detailed analysis and modelling of the ORC loop were performed using Aspen Plus software. The selection of the ORC design capacity was based on the Eavor-Loop™ fluid properties at year 5, representing the relatively flat thermal output of the Eavor-Loop™ over the project lifetime.

A single-pressure level cycle with four organic fluids (normal-butane, isopentane, normal-pentane, and cyclopentane) was investigated. The applicability of dual-pressure cycles was also evaluated. The pinch points of both the hot and cold heat exchangers were fixed for all the analyzed operating points. An air-cooled condenser (ACC) was considered for the cold heat exchangers with an ambient air dry-bulb temperature of 15°C. The turbine efficiency has been described by a simplified proprietary model to account for the differences of the fluids and of the ORC thermodynamic conditions at turbine inlet and outlet with a range in turbine efficiency between 85% - 91%. The ORC power output was calculated net of the internal ORC power consumption (working fluid pumps and ACC fans consumption).

3.4 Energy Production

Following the detailed ORC analysis, the electrical energy production of the Eavor-Loop™ + ORC system over the course of a 30-year project lifetime was calculated. The impact of fluctuating seasonal ambient temperatures and alternative ORC design capacities were also considered.

4.0 Results

4.1 Optimal Eavor-Loop™ + ORC Operating Window

The maximum power production for three representative points (years 1, 5, and 20) in the lifetime of an Eavor-Loop™ + ORC system across differing Eavor-Loop™ inlet temperatures is illustrated in Figure 6. In addition to the ORC's internal power consumption, the pump work required for the flowrates exceeding the Eavor-Loop™ thermosiphon rate is included in the net power figures below. Figure 6, on the left, illustrates the maximum power computed using Lorentz efficiency for varying Eavor-Loop™ inlet temperatures. The figure on the right, outlines the system performance of differing Eavor-Loop™ flowrates, with a fixed Eavor-Loop™ inlet temperature of 110°C.

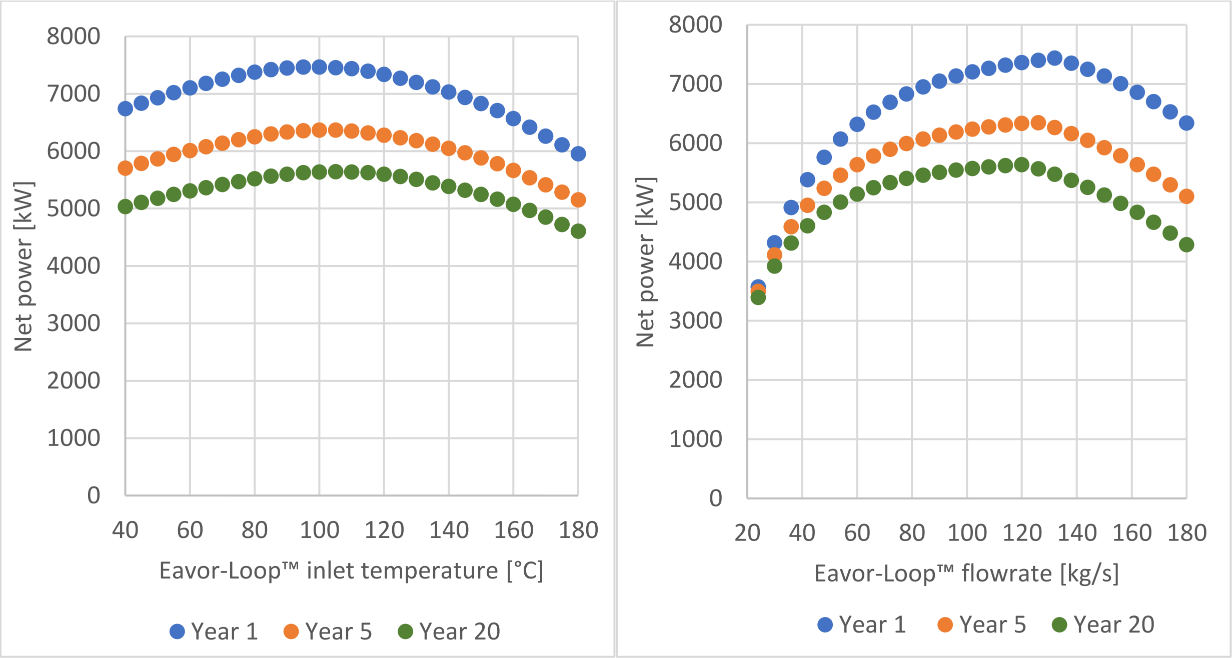


Figure 6: Maximum ORC net power output as function of Eavor-Loop^{TM} inlet temperature and flowrate

The result of this preliminary scoping indicated that the maximum power output of the ORC plant occurs when the Eavor-Loop™ inlet temperature is relatively high, between 95°C - 115°C, and at or near the maximum flowrate the available thermosiphon pressure can support (120-130kg/s). Thus, these operating points were the focus of the detailed ORC simulations and subsequent optimization steps.

4.2 Results of the Detailed ORC Analysis

The results for two of the five Eavor-Loop™ inlet temperatures analyzed are reported in Figure 7 and the main parameters of the five optimum points of the curves are reported in Table 2.

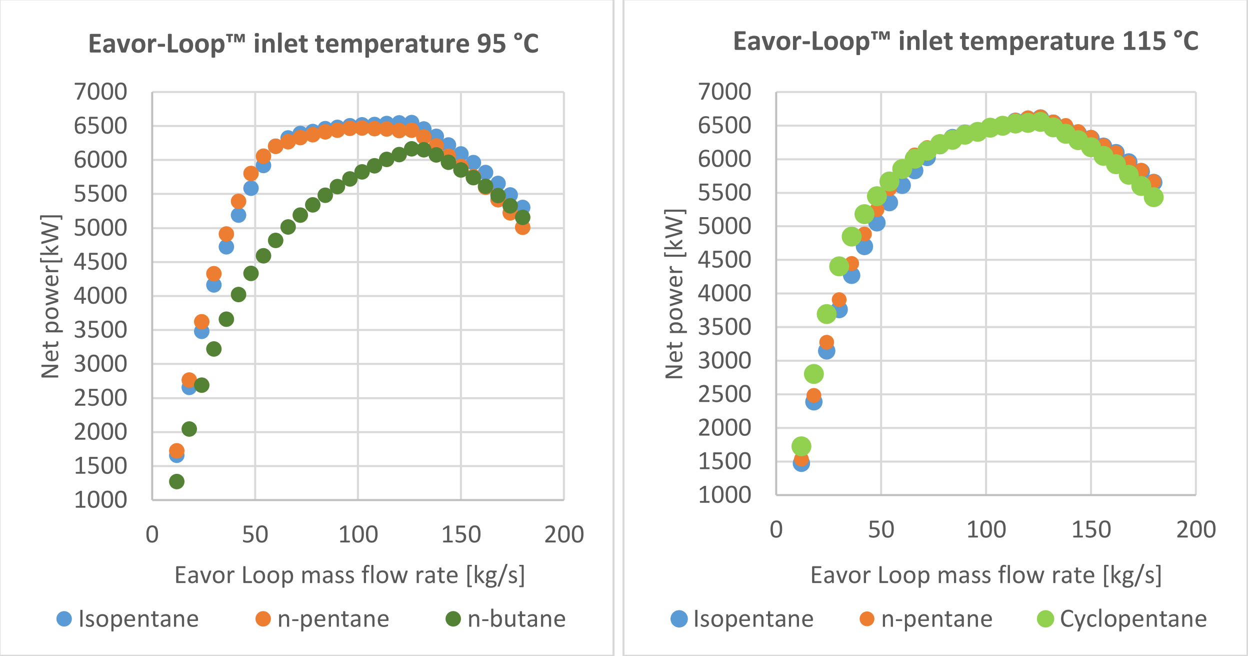


Figure 7: ORC net power output as function of the Eavor-Loop™ mass flow rate.

Table 2: Optimum ORC designs as function of the Eavor-Loop™ inlet temperature

Eavor-Loop™ Inlet Temperature [°C]	Eavor-Loop™ Outlet Temperature [°C]	Optimal ORC Working Fluid	ORC's Net Power [kW]	Indicative ORC's n° of ACC Bays	UA Hot heat exchangers [kW/K]	Cycle net efficiency
95	172.8	Isopentane	6550	12	2593	15.6%
100	175.8	Isopentane	6625	12	2509	16.2%
105	178,8	Isopentane	6656	12	2518	16.7%
110	181.8	n-pentane	6643	11	2317	17.1%
115	184.9	n-pentane	6630	11	2334	17.5%

The maximum net power values of Figure 7 and the values in Table 2 coincide with a mass flowrate that utilizes all the available thermosiphon pressure of the Eavor-Loop™ (approximately 126 kg/s at year 5).

The net power output corresponding to the Eavor-Loop™ inlet temperature 105°C and 110°C is comparable, however there are equipment and cost differences between the two thermodynamic cycles. Both the hot heat exchanger surface area (UA hot heat exchangers in Table 2) and the surface area of the ACC are larger for the isopentane ORC designs without a proportional increase in performance. A larger heat exchanger surface area implies a higher equipment cost. Thus, the normal-pentane thermodynamic cycle with an Eavor-Loop™ inlet temperature of 110°C has been selected as the optimum cycle.

4.2.1 Evaluation of Dual Pressure Cycles

The optimization analysis was extended to include dual-pressure binary cycles (DiPippo, 2012), with identical assumptions and operating conditions of the single-pressure cycle analysis.

Figure 8 illustrates the results of the dual pressure ORC optimization for three different working fluids at varying Eavor-Loop™ inlet temperatures. The optimal dual pressure ORC design corresponds to an Eavor-Loop™ inlet temperature of 105°C with cyclopentane as working fluid and an Eavor-Loop™ flowrate of 126 kg/s. However, the net power output gain with respect to the single-pressure level cycle is 3.2% (6854 kW vs 6643 kW). The ORC capex increase for the dual-pressure cycle was assessed, and the minor increase in net power did not justify the additional cost. For this example, the dual pressure ORC costs are approximately 30% higher. Note that the additional capex of a dual-pressure ORC, and its relative impact on the economics of an Eavor-Loop + ORC system, must be evaluated case by case. A dual-pressure cycle is typically employed with the objective of dropping the reinjection temperature of the geothermal fluid further, which is not beneficial with an Eavor-Loop™ 2.0 in high geothermal gradient geologies due to the relatively high optimal inlet temperature.

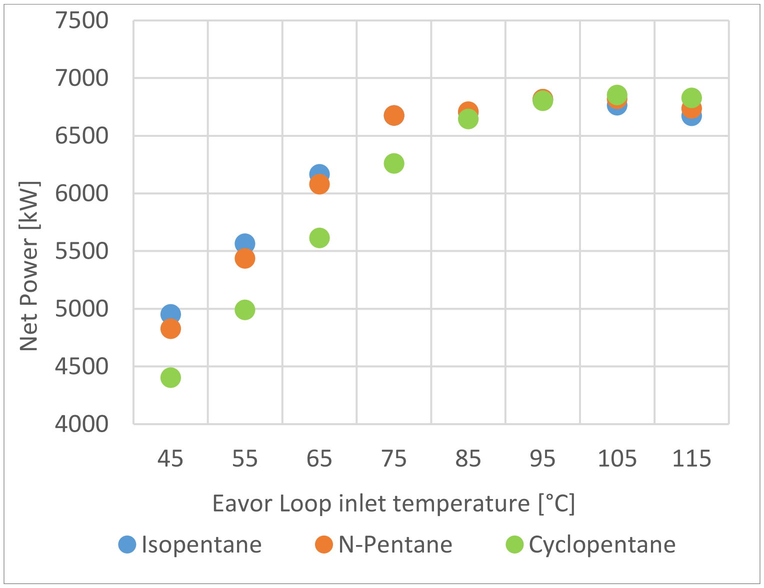


Figure 8: Optimum Dual Pressure Level ORC net power as a function of Eavor-Loop^{TM} inlet temperature.

4.3 Baseload Operation Energy Production

With the optimum operating condition of the Eavor-Loop™ and the ORC thermodynamic cycle defined, the energy production of the Eavor-Loop™ over a 30-year project lifespan was evaluated, incorporating ambient temperature fluctuations and the expected yearly decline in Eavor-Loop™ thermal output. A generic continental monthly temperature distribution was assumed, with a minimum monthly average of 6°C in January and 25°C as a maximum monthly average in August. The corresponding annual average temperature is 15°C.

In the case of traditional liquid dominated geothermal power plants, limitations on the geothermal brine reinjection temperature may be required to avoid scaling and solid deposition. Typically, an active control procedure on the ORC plant is used to limit the geothermal resource reinjection temperature. Since the circulation water of the Eavor-Loop™ does not contain dissolved solids, there is no need for a constraint on the Eavor-Loop™ inlet temperature. Eliminating this constraint allows for the maximum utilization of ORC heat exchanger area across a broad range of operating conditions, increasing system performance in off-design conditions.

4.3.1 Ambient Temperature Off-Design Performance

The performance of the ORC in varying ambient temperature conditions was computed in Aspen Plus with constraints on the dimensions of the heat exchangers and turbine from the optimized ORC design in section 4.2. The feedback impact of the adjustable Eavor-Loop™ inlet temperature was accounted for in the off-design performance calculations of the ORC.

For air cooled ORC systems, as ambient temperatures increase, condensation pressures increase, leading to reduced electrical output. The Eavor-Loop™ + ORC system displays unique behavior in different ambient conditions as a consequence of the feedback impact within the closed loop system. In warmer ambient conditions, the optimal Eavor-Loop™ inlet temperature increases from design point, contributing to a slightly higher Eavor-Loop™ outlet temperature, thus, improving ORC efficiency. The converse effect is prevalent in cooler ambient conditions (reduced Eavor-Loop™ inlet and outlet temperatures). As shown in Table 3, this interdependence between inlet and outlet temperatures flattens the net electrical output of an Eavor-Loop™ + ORC system across seasonal ambient temperature variations when compared to an equivalent traditional geothermal system (identical temperatures/flowrates and no limitation on the geothermal reinjection temperature). However, the balance of these contributions counteracts, with a negligible impact to the annual energy production. While the effect is relatively minor, it is an advantageous characteristic of the Eavor-Loop + ORC system, as electricity demand in many regions peaks during the warmer months of the year.

Table 3: Comparison of the monthly energy production of a traditional geothermal ORC plant and of an Eavor-Loop™ + ORC system

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Eavor Loop (GWh)	5.29	4.70	5.17	4.80	4.77	4.48	4.42	4.37	4.43	4.91	5.00	5.25
Traditional Geothermal (GWh)	5.39	4.78	5.24	4.81	4.74	4.41	4.30	4.23	4.35	4.91	5.07	5.34
% Change	-1.99	-1.58	-1.37	-0.24	0.75	1.56	2.73	3.05	1.84	0.00	-1.37	-1.79

4.3.2 Net Energy Production

Figure 9 outlines the electrical production impact of thermal performance decline for the optimized Eavor-Loop™ + ORC system. The energy production has been calculated with a constant Eavor-

Loop™ mass flow rate and an assumed overall plant availability of 98%. The total energy production of the 30 years lifetime of the plant is 1613 GWh.

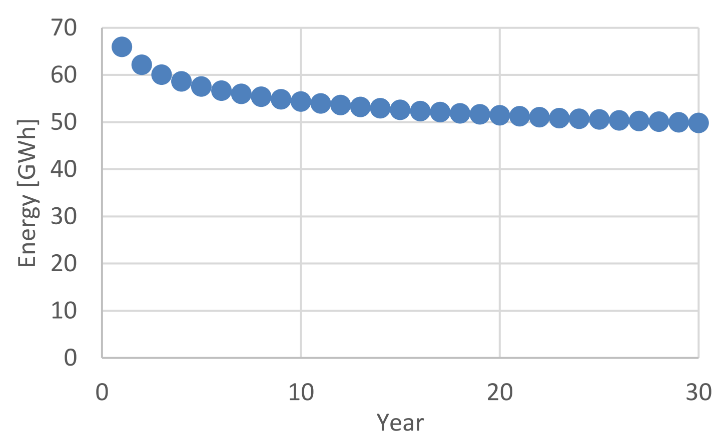


Figure 9: Annual electrical energy production of the optimized Eavor-Loop™ + ORC system.

5.0 Conclusion

The joint development effort between Eavor and Turboden explored the distinct features of an Eavor-Loop™ + ORC system as a baseload power plant. A performance and cost optimized single pressure ORC with n-pentane as a working fluid was designed and simulated in Aspen Plus for heat-to-power conversion of an Eavor-Loop™ thermal output. The transient impact of the Eavor-Loop™ yearly thermal output decline, changes in ambient temperature, alternative ORC configurations and capacities were considered to reach an optimized system design that minimized the levelized cost of electricity over a 30-year period. The optimized system produces 6643 kW of net electrical power at the nominal design condition (year 5) and 1613 GWh of electrical energy over a 30-year period. Continued collaboration between Eavor and Turboden will aim at identifying additional system level opportunities and further reducing the levelized cost of electricity. Further improvement of the present work consists in the study of the dispatchability mode operation of the Eavor-Loop™ + ORC system: this kind of operation can be coupled with other kind of energy production, such as solar and wind power, to cover different grid power requirements.

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