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The Gemini Turbine: A Boost For Power Generation In Large-Scale ORC Geothermal Plants

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ABSTRACT

Geothermal plants using Organic Rankine Cycle (ORC) technology face high volumetric flow rates combined with medium enthalpy drops. While increasing the size of heat exchangers and piping can easily accommodate higher resources, the expansion phase presents more challenges, especially for radial outflow turbines (ROT). For ROTs, there is a critical volumetric flow rate threshold, typically around 50 m^3/s. Beyond this, the blade height plays a crucial role in maintaining mechanical integrity, as it is directly related to the amount of input. The traditional approach of Exergy has been to split the flow into two turbines, each handling a portion of the flow.
This study outlines a significant innovation in the realm of large-scale geothermal power generation: the Gemini Turbine, a ROT design developed by Exergy to address the challenges posed by high volumetric flow rates in ORC. The core of the innovation lies in the ability of the Gemini Turbine to handle large geothermal resources—up to 50–60 MW—without the need to split the flow into two turbines, as is traditionally done in these systems.
The paper includes a case study demonstrating how the Gemini Turbine could be applied in real-world geothermal power plants. This case study would help illustrate the potential benefits, such as more efficient operations, greater reliability, and more compact plant layouts.

1 INTRODUCTION

Geothermal energy represents a key contributor to the decarbonization of the energy sector due to its continuous availability and low greenhouse gas emissions. In contrast to intermittent renewable sources such as wind and solar, geothermal power provides a stable and dispatchable baseload supply. Geothermal power plants can operate continuously, independent of weather conditions or time of day, thereby enhancing grid stability and reducing reliance on auxiliary generation systems.
In ORC geothermal power plants, mechanical power is typically generated by turbines designed for medium enthalpy drops, generally in the range of 40 to 100–110 kJ/kg. These turbines operate under high volumetric flow conditions, with inlet flow rates reaching up to 10 m^3/s and outlet flow rates increasing to as much as 50 m^3/s. ROT are particularly well-suited to accommodate these operating conditions. Their geometry, especially the increasing flow passage area at larger radii, facilitates effective fluid expansion. As the working fluid expands through the turbine, its pressure decreases while the volumetric flow rate increases, necessitating a proportional enlargement of the flow passage—defined by the stage radius and blade height—to maintain efficient operation. However, when volumetric flow rates exceed 50 m^3/s, design and operational challenges become more pronounced. This issue is increasingly relevant with the growing deployment of geothermal power plants exceeding capacities of 30–40 MW.
The maximum radius of a turbine is primarily constrained by the permissible peripheral speed, which is dictated by mechanical limitations such as blade structural integrity and rotor dynamic stability. In radial outflow turbine design, blade height is a key parameter, as it directly correlates with the volumetric flow rate and influences mechanical stress distribution. When the required blade height for a given stage radius approaches critical mechanical thresholds, alternative design strategies must be employed. A practical and effective solution, as previously discussed, involves dividing the flow between two parallel turbine units. This approach reduces the individual volumetric load on each turbine, thereby lowering the required blade height and simplifying the mechanical design, while also contributing to more manageable overall system complexity.
The Gemini Turbine represents the outcome of a comprehensive design analysis aimed at delivering a competitive, efficient, and cost-effective solution for Exergy's geothermal applications. The name "Gemini" denotes the turbine's distinctive architecture: a multistage radial outflow configuration featuring a single central rotor disk with blades mounted on both sides. This symmetrical arrangement creates two parallel flow paths within a single turbine casing, effectively doubling the volumetric flow capacity relative to conventional Exergy turbine designs. The subsequent sections present a detailed case study of the Gemini Turbine, including the

results of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) analyses conducted to evaluate the aerodynamic performance and structural integrity of the proposed configuration.

2 THE GEOTHERMAL TRANSITION: ENABLING NEXT-GENERATION ENERGY SYSTEMS

Recent advancements in technologies such as directional drilling and hydraulic stimulation are enabling geothermal energy to expand beyond conventional hydrothermal resources. Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) facilitate heat extraction from subsurface formations lacking naturally occurring permeability or fluid content, thereby significantly broadening the geographic and geological applicability of geothermal power. As technological innovations continue and development costs decline, geothermal energy has the potential to meet up to 15% of the projected global growth in electricity demand by 2050.

2.1 Binary Cycle Systems as Fundamental Technologies for EGS and AGS

EGS improve subsurface permeability through advanced drilling and stimulation techniques. The most widely employed method is hydraulic stimulation, which involves the injection of high-pressure fluids to induce fractures in low-permeability rock formations. Complementary thermal and chemical stimulation methods can further enhance fracture networks and heat extraction efficiency. These engineered fractures facilitate fluid circulation through the reservoir, enabling effective heat transfer from previously inaccessible "hot dry rock" zones for electricity generation or direct thermal applications. Another emerging frontier in next-generation geothermal technologies is represented by AGS. These systems utilize closed-loop configurations in which a working fluid circulates through sealed subsurface conduits, extracting heat conductively from the surrounding rock. Unlike conventional and EGS approaches, AGS systems operate without direct fluid interaction with the geological formation, thereby minimizing environmental impact and reservoir uncertainty.

Subsurface technologies such as EGS and AGS can be effectively integrated with binary cycle power plants for electricity generation. Binary systems are particularly well-suited to next-generation geothermal reservoirs due to their high efficiency in utilizing low-to medium-enthalpy resources, operational flexibility, and relatively low maintenance requirements. These attributes align well with the technical and environmental demands of EGS and AGS applications. Binary cycle power plants operate as closed-loop systems, with no atmospheric emissions, making them a highly sustainable option. Unlike flash steam plants, the geothermal fluid in binary systems does not come into direct contact with the turbine or generator. Instead, thermal energy is transferred to a secondary organic working fluid via a heat exchanger, after which the geothermal fluid is reinjected into the reservoir, preserving reservoir pressure and minimizing environmental impact.

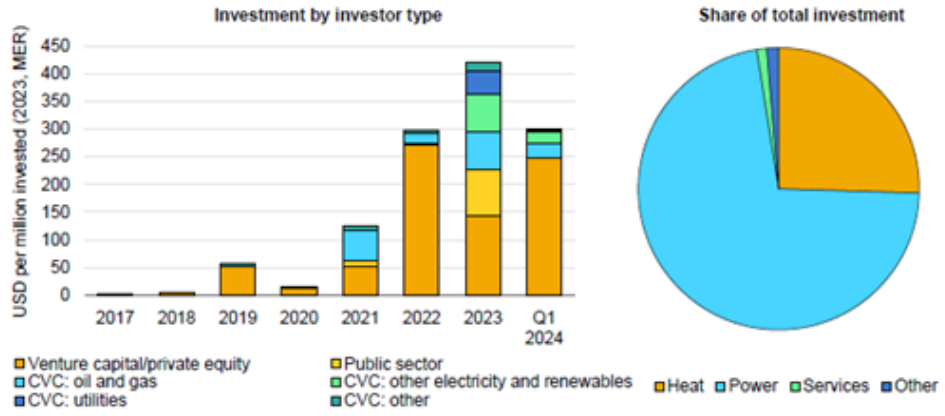


Figure 1. Annual geothermal investments, investor type and investment shares by sector, 2017-Q1 2024.

2.2 International Perspective on the Expansion of EGS Technologies

Enhanced Geothermal Systems are rapidly emerging as a pivotal technology for sustainable energy generation, supported by increasing global investments that foster technological innovation and scalability. These systems are progressively overcoming geographical and geological limitations, enabling geothermal energy production in regions previously deemed unsuitable. Continued support from both public and private sectors is driving advancements, positioning geothermal energy as a key contributor to the global energy transition (Figure 1). Projections indicate that by 2050, geothermal energy could substantially reduce greenhouse gas emissions

while supplying a significant share of global electricity and heat demand. This growth trajectory is reinforced by targeted funding initiatives, with countries such as the United States, Canada, and Germany playing leading roles in accelerating the development and deployment of EGS and AGS.

3 PLANT CASE STUDY: GEX 5000 GEOTHERMAL POWER PLANT

The thermodynamic cycle employed in this large-scale EGS binary cycle power plant is based on the Organic Rankine Cycle, optimized to deliver a net electrical output of approximately 50 MWe. Geothermal brine, extracted from the production well, is utilized to preheat, evaporate, and superheat the organic fluid, which is then expanded through the turbine in a vapor phase.

In this configuration, the working fluid expands through a single high-efficiency radial outflow turbine, specifically the Gemini Turbine, which represents a significant advancement in ORC technology. Unlike conventional approaches that require two parallel turbines to accommodate high volumetric flow rates, the Gemini Turbine achieves the entire expansion process within a single unit by employing a dual-flow path design. In this design, the working fluid symmetrically enters from both sides of the rotor and expands radially outward through mirrored stages. This innovation simplifies plant layout, reduces mechanical complexity, and decreases erection and civil construction requirements, while maintaining high efficiency and operational reliability as in standard parallel turbines configuration. Additionally, the turbine is directly coupled to the generator, eliminating the need for a gearbox, which reduces mechanical losses and improves overall system availability. Following expansion, the organic vapor is condensed in an induced air-cooled condenser. The resulting condensate is pressurized by vertical feed pumps and recirculated to complete the thermodynamic cycle.

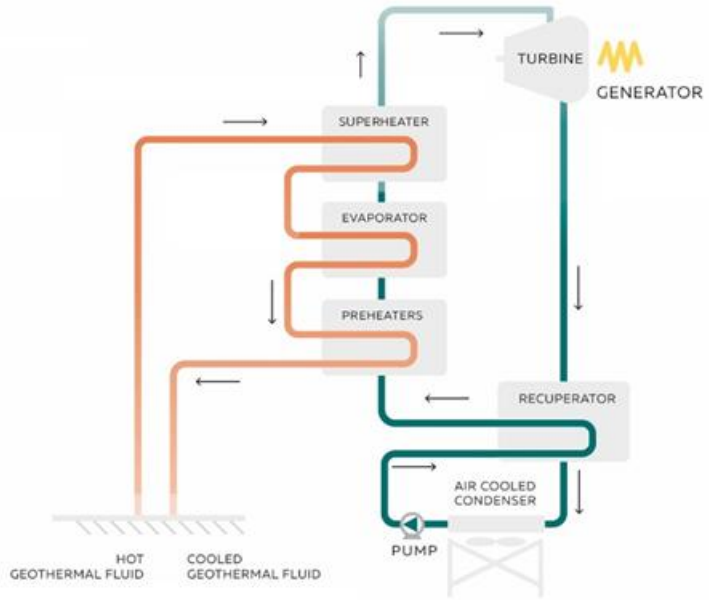


Figure 2. Simplified diagram of an air-cooled ORC with heat delivered from a geothermal system.

The implementation of air cooling in the condensation process eliminates the requirement for water, making the system particularly suitable for deployment in water-scarce regions. Furthermore, as the plant utilizes geothermal hot water rather than steam and reinjects the working fluid without atmospheric emissions, it qualifies as a zero-emission baseload power plant. This configuration enables continuous, sustainable energy generation with minimal environmental impact.

3.1 ORC Power Plant Performance

Exergy's GEX 5000 ORC power plant will be supplied by geothermal brine extracted from multiple production wells. In this configuration, the geothermal brine is assumed to enter the heat exchangers as a pressurized liquid at a temperature of 200 °C, where it transfers thermal energy to the organic working fluid in the duplex tubes of the shell and tube heat exchangers. The brine is subsequently cooled to ≈ 96.1 °C before reinjection into the geothermal reservoir. For a single 50 MWe ORC module, the estimated brine flow rate is approximately 2000 metric tons per hour, (14.6 million U.S. gallons per day), assuming a brine density close to that of water. This substantial flow rate ensures sufficient thermal input to sustain continuous power generation while maintaining reinjection temperatures that preserve reservoir sustainability.

This results in a gross power at generator terminals of 50'675 kWe and a net power ORC to grid (this value includes ORC internal consumption—feed pump, ACC, turbine auxiliaries, ORC electrical boards, PLC, and

electrical losses such as transformers, VFD, and cables) of 44'021 kWe with a net efficiency of 17.7% (gross efficiency of 20.4%).

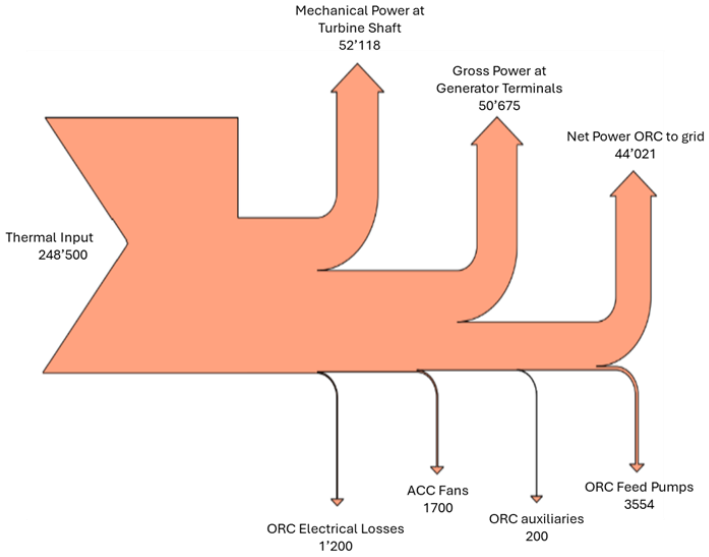


Figure 3. Sankey Diagram for power flow.

4 THREE-DIMENSIONAL MODELING OF THE GEMINI TURBINE

To comprehensively evaluate the Gemini configuration, it is necessary to examine the innovative architecture of this radial turbine. In contrast to conventional radial turbine designs, the Gemini system incorporates a dual-inlet configuration in which the working fluid is introduced symmetrically through two opposed inlet ducts located on either side of the turbine casing. The fluid then expands radially inward toward a central exhaust flange, where it is discharged. The central rotor disk supports rotor blades for both flow paths, while stator blades are mounted on lateral stator disks positioned on either side of the machine, as illustrated in Figure 4. This symmetric configuration ensures uniform pressure distribution within the inlet chambers, resulting in a self-balancing force on the rotor that effectively mitigates axial thrust. Additionally, the rotor is supported in a between-bearings arrangement, replacing the traditional overhung configuration. This design enhancement reduces rotor deflection and lowers vibrational amplitude, thereby improving overall dynamic stability and mechanical reliability.

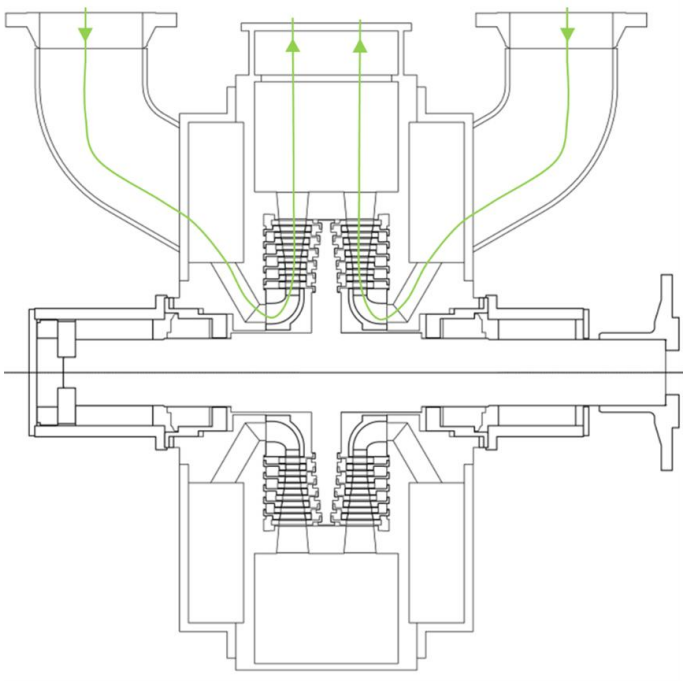


Figure 4. Cross-section layout of the Gemini Turbine

5 DESIGN OF THE RADIAL OUTFLOW TURBINE

Following the development of the preliminary plant layout, the turbine must be dimensioned according to the operating conditions identified in the process analysis. The turbine design procedure comprises two principal stages: an initial one-dimensional preliminary sizing, followed by validation of the geometry through three-dimensional CFD analysis. Upon achieving satisfactory aerodynamic performance from the CFD simulation, a FEM analysis is conducted to assess the mechanical integrity of the turbine blades. The following sections provide a detailed description of these steps as applied to the case study presented in this work.

5.1 Preliminary 1D Analysis

Thanks to an in-house developed one-dimensional design code, the ROT is designed to maximize isentropic efficiency while minimizing tangential velocity at the outlet of each stage. The properties of the working fluid are determined using *Refprop 9.0*, which supports a wide range of working fluids. The input thermodynamic parameters, listed in Table 1, of the one-dimensional tool include:

- The inlet total pressure and temperature (Pt_{in} and Tt_{in})
- The mass flow rate ($\dot{m}$)
- The outlet static pressure (P_{out})

Table 1. Design parameters.

Properties	Value	Unit of measure
Type of machine	ROT	-
# of stages	6	Radials
Rotational speed	1800	Rpm
Fluid	n-butane	Normal butane commercial grade
Pt_{in}	30	bara
Tt_{in}	168.4	°C
P_{out}	3.12	bara
$\dot{m}$	512.78	kg/s
Δh_{iso}	111.45	kJ/kg

The rotational speed and radius of each stage are determined based on the maximum allowable peripheral speed and the network frequency. In addition, the maximum machine radius is constrained by the permissible centrifugal acceleration of the blades. This assessment also accounts for the blade height, which is relatively large for this type of application and therefore significantly influences the mechanical stress limits.

The number of stages in a centrifugal turbine is meticulously selected to avoid supersonic flow conditions, thereby ensuring the turbine achieves the prescribed enthalpy drop while maintaining high efficiency across both design and off-design operating points. Typically, a subsonic centrifugal turbine stage attains a maximum enthalpy drop in the range of 25–30 kJ/kg. This performance metric improves with increasing reaction degree, beginning from impulse stages and reaching up to approximately 40–45% reaction in the final stages.

In the present one-dimensional analysis, the Gemini Turbine is modelled as a parallel turbine configuration, resulting in a halved mass flow rate per branch. Consequently, the blade passages are dimensioned to accommodate the corresponding volumetric flow rate. By optimizing the degree of reaction and blade loading for each stage, the turbine design converges on a configuration comprising six radial stages, operating at 1800 rpm, with a maximum blade height of roughly 125 mm on each side of the machine. The overall net power output is calculated to be 52.1 MW, accompanied by a total-to-static isentropic efficiency of 91.2%. The efficiency achieved with the Gemini turbine is comparable to that of a standard Exergy turbine. The main technical advantages of the proposed configuration include a more compact plant layout, the elimination of redundant components and a reduction in overall plant costs.

To elucidate the expansion process within the one-dimensional framework, the following notation is employed to designate stage sections: points 1–2 represent the stator inlet and outlet, respectively, while points 3–4

correspond to the rotor inlet and outlet. The stator (1–2) functions to convert pressure energy into kinetic energy. Subsequently, the working fluid expands through the rotor (3–4), where kinetic energy is transformed into mechanical work, producing shaft power at the turbine outlet.

5.2 Balde Design and Employed Hypothesis and Methodology

The initial step in blade profile definition involves using flow angles derived from one-dimensional (1D) analysis and iteratively refining them until the blade geometry ensures flow exit angles consistent with the 1D results. Blade geometry is designed in *Ansys BladeGen* (version *2024 R1*) using the "pressure and suction" methodology, which constructs blade profiles based on inlet and outlet flow angles, blade height, and the leading and trailing edge diameters. The mean camber line is shaped using six Bezier control points.

Key geometric parameters—such as flow angles and Bezier points—are manually adjusted to match gauging constraints, degree of reaction, and velocity triangles from the preliminary 1D design, with the objective of optimizing aerodynamic performance and maximizing overall turbomachine efficiency. Following blade profile generation, the computational mesh is created in *Ansys TurboGrid*. A global size factor of 1.3 is applied, along with a first element offset of 0.002 mm, to ensure sufficient resolution of the boundary layer. These meshing parameters are selected to yield a high-quality grid compatible with the selected turbulence model, while remaining within computational resource limitations. To streamline design and manufacturing, the blades are modeled as cylindrical. Stator blades incorporate a flaring height, whereas rotor blades maintain a constant span from inlet to outlet.

Assuming a steady and periodic flow field with respect to the blade passages, the CFD analysis is confined to a single blade passage per stage, representing a periodic sector of the machine. The inlet boundary conditions are defined by the total pressure and total temperature values provided in Table 1, while the outlet boundary is specified by the static pressure at the exhaust. Simulations are performed under steady-state conditions using the *k–ω* Shear Stress Transport (SST) turbulence model. A high-resolution advection scheme is applied, with the inlet turbulence intensity set to 5%.

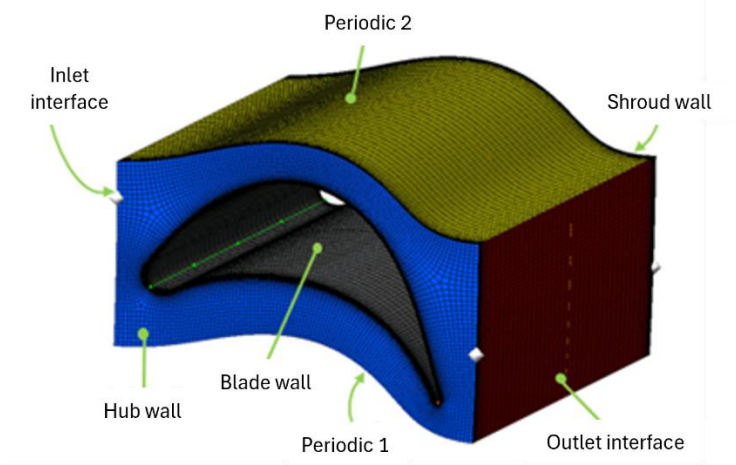


Figure 5. Interfaces and walls of each passage row.

Rotor–stator interfaces are modelled using the *Stage* (Mixing-Plane) approach, with the *Stage Average Velocity* option applied to mitigate shock wave reflections at the interfaces. Inter-domain communication is handled via the General Grid Interface (GGI) method in Ansys CFX. A no-slip boundary condition is imposed on all solid walls, and periodic boundary conditions are applied across all computational domains.

High-quality meshes for both rotor and stator components are generated using *Ansys TurboGrid*. The resulting dimensionless wall distance (y^+) values fall within the range of 0 to 50, which is acceptable for the selected turbulence model, given computational resource limitations. The working fluid is modelled using thermophysical properties from *Refprop 9.0*, with tabulated data spanning a pressure range of 0.4–34 bar and a temperature range of 0.85–276.85 °C. Convergence is considered achieved when the residuals drop below 10^{-6}.

5.3 CFD Results

Upon satisfying the convergence criteria, the CFD results are thoroughly analyzed. Key evaluation parameters include the distribution of total enthalpy and pressure drop across the stages, velocity triangles, and overall machine efficiency. The primary objective is to optimize the turbine design by validating and refining the preliminary one-dimensional analysis results, with the aim of enhancing predicted performance where possible.

Figure 6 illustrates that the pressure and temperature drops across the stages predicted by the CFD analysis closely correspond to those obtained from the one-dimensional analysis. The main discrepancy between the two approaches arises from the treatment of the diffuser: the one-dimensional model excludes the diffuser, whereas the CFD simulation enforces the exhaust pressure boundary condition at the diffuser outlet. Consequently, a slight shift in the pressure drop distribution along the stages is observed.

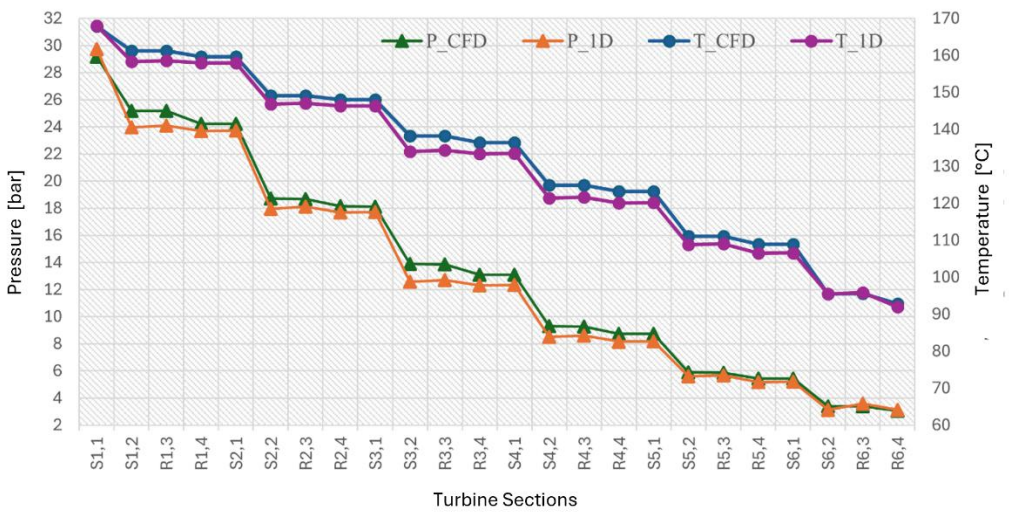


Figure 6. Pressure and Temperature of the six stages.

Despite certain modeling approximations, the deviations in pressure and temperature across the stages remain within 5%, thereby validating the blade profiles as sufficiently accurate for the intended application. Presented below are the Mach Number distributions and streamlines within the blade passages, alongside velocity triangles derived from the CFD simulations and their comparison with preliminary one-dimensional results. Furthermore, the overall performance of the machine is reported.

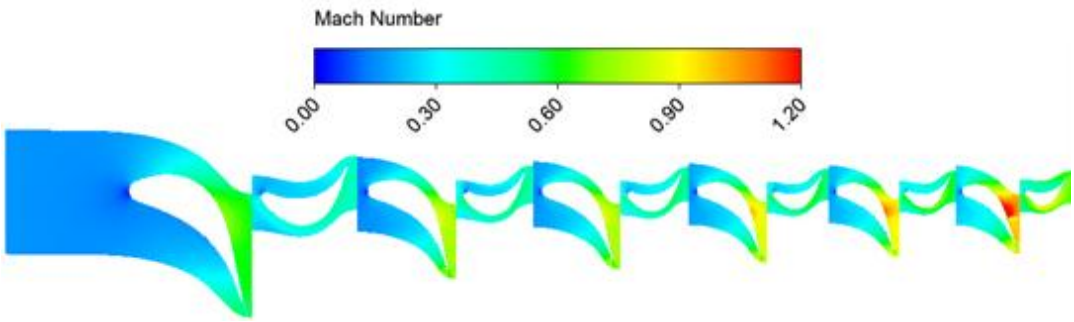


Figure 7. Blade-to-blade Mach Number.

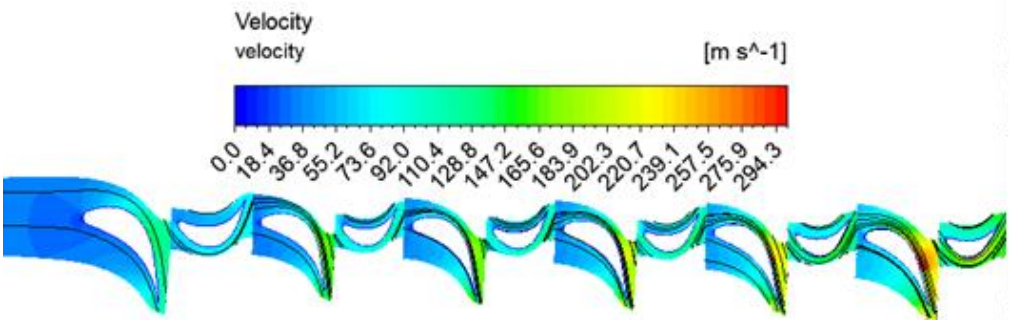


Figure 8. Streamlines and Velocity Field in the blade-to-blade plane.

Figure 9 compares the velocity triangles obtained from the CFD-optimized solution with those derived from the preliminary one-dimensional analysis. The results indicate that the designed blades accurately reproduce the intended flow behavior, showing close agreement with the target velocity profiles. It should be noted that this comparison is performed under design operating conditions. For off-design analyses, the blade geometry remains fixed, while only the inlet and outlet pressure and temperature conditions are varied.

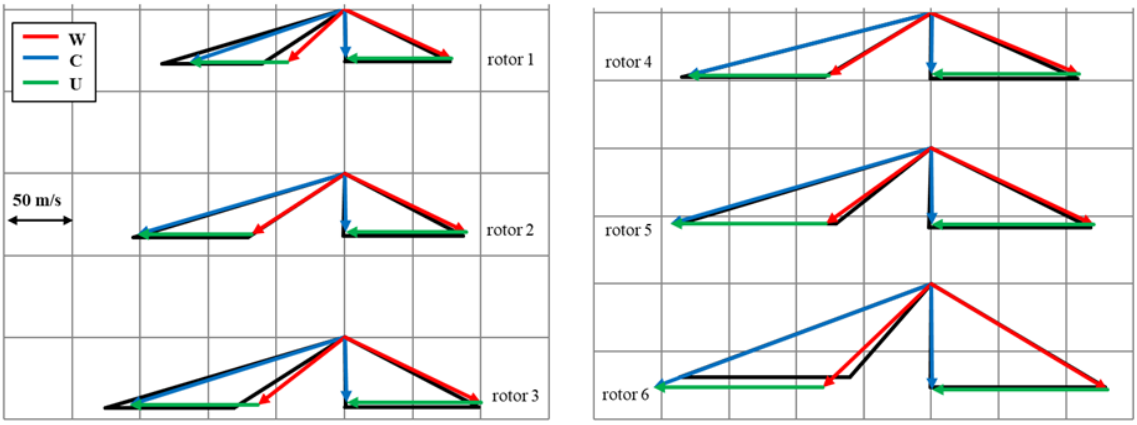


Figure 9. 1D velocity triangles (black) vs CFD results (colors).

Overall, the numerical simulation results across all stages exhibit strong agreement with the one-dimensional design predictions. The aerodynamic performance satisfies the specified requirements, and owing to the individual optimization of each blade, the CFD-predicted efficiency surpasses that of the preliminary one-dimensional analysis. A comprehensive summary of the performance data is provided in Table 2.

Table 2. 1D Results vs CFD Results.

Variable	Design value	CFD value	Δ
Isentropic Efficiency: $\eta_{iso,t-s}$	91.2%	91.4%	+0.2%
Thermodynamic Power: W_{net} (MW)	52.1	52.5	+0.7%
Mass Flow Rate: $\dot{m}$ (kg/s)	512.78	515.72	+0.6%

5.4 Off-design and Performance Curve

After achieving the target performance at the design point, the turbine is further evaluated under off-design operating conditions to validate its robustness. The enthalpy drop is a critical parameter in determining the optimal number of stages for ROT. An incorrect stage count—whether excessive or insufficient—can lead to reduced efficiency in both design and off-design conditions. Nonetheless, centrifugal configurations are inherently well-suited for varying operating regimes, typically exhibiting a relatively flat efficiency curve that sustains high performance even when operating away from the design point (Figure 10).

In this study, the expansion ratio varies between 0.07 and 0.16, corresponding to changes in ambient temperature from 30 °C to 0 °C. Under these off-design conditions, the guaranteed power output deviates from the nominal value by −19% to +13%, reflecting the impact of thermal conditions on turbine performance.

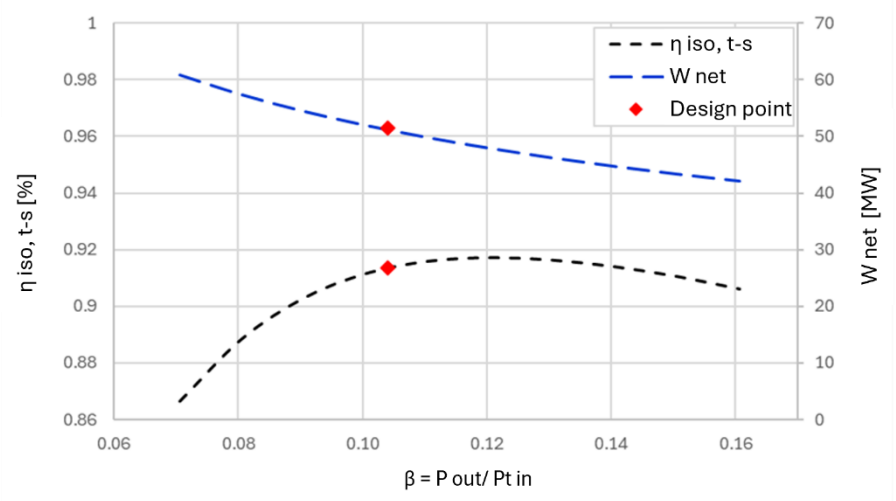


Figure 10. Trend of the efficiency and power with respect to the pressure ratio.

6 FEM STRUCTURAL AND MODAL ANALYSIS

Upon achieving satisfactory results from the CFD simulations, structural and dynamic assessments of key components are performed. A static stress analysis is conducted using *SolidWorks Simulation* to evaluate the mechanical integrity of the rotor disk and individual rotor stages. Subsequently, a dynamic analysis is carried out using a *MATLAB*-based model to determine the rotor's natural frequencies, vibration mode shapes, and to construct the Campbell diagram for rotor dynamic validation.

6.1 Stress Analysis

As previously outlined, the initial step in the structural assessment involves verifying that the stresses on the blades, under both nominal and overspeed conditions, remain below the material's yield strength. This analysis includes evaluating the von Mises stress distribution and accounting for thermal effects at critical locations on the blades. The final-stage blades are typically the most critical, due to their larger size and exposure to the highest centrifugal loads. Simulation input parameters include material properties and centrifugal forces, while boundary conditions—such as convective heat transfer coefficients, temperature fields, and pressure gradients—are derived from the CFD results. The blades are modeled with clamped boundary conditions at the root to simulate a rigid attachment, thereby ensuring accurate representation of the stress distribution.

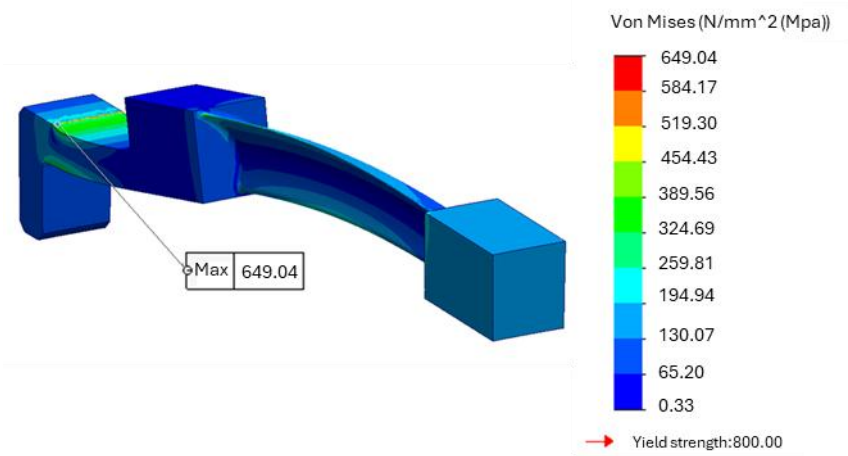


Figure 11. Sixth rotor nominal stress.

The objective of the structural analysis is to ensure that mechanical stress remains within the elastic range of the blade material, thereby preventing plastic deformation during operation. In the present case, the simulation yielded a safety factor of 1.2 with respect to a material yield strength of 800 MPa, confirming the structural adequacy of the blade design. Should this criterion not be satisfied, further geometric optimization—such as increasing the blade thickness—would be necessary to maintain structural integrity under operational loading conditions.

6.2 Rotordynamic Verification

The dynamic analysis is performed using a MATLAB-based model specifically developed for rotor dynamic assessment. This model simulates the behavior of the rotor assembly—including the shaft, wheel, and coupling—under operational conditions, characterizing the system's bending and vibrational response at its natural frequencies. The primary objective is to determine whether any of the system's natural frequencies coincide with excitation frequencies that occur during turbine operation.

Figure 12 presents the Campbell diagram, where the blue curves represent the natural frequencies of the rotor system as a function of rotational speed. The red and green lines correspond to the excitation frequencies at 1x (fundamental) and 2x (second harmonic) of the rotational speed, respectively. To avoid resonance, it is essential that the natural frequency curves do not intersect the excitation lines. A sufficient separation between these frequencies confirms that the operational speed range does not excite the rotor's natural modes, thereby mitigating the risk of harmful vibrational responses.

7 CONCLUSIONS

This study presents an innovative configuration of a centrifugal turbine, featuring a rotor design initially developed using a proprietary one-dimensional modeling tool and subsequently refined through CFD and FEM analyses. The numerical results from the optimized stages show strong agreement with the one-dimensional predictions, and the aerodynamic performance meets the established design criteria.

The proposed radial outflow turbine exhibits a wide operational range and robust off-design performance, positioning it as a viable solution for various geothermal energy applications. A distinguishing feature of this configuration is the novel rotor disk design, which enhances flow-handling capability relative to conventional Exergy turbine designs. Specifically, the new rotor accommodates a maximum volumetric flow rate of up to 82 m^3/s, compared to 50 m^3/s for the standard configuration.
Future work should focus on optimizing the inlet volume and casing geometries. This effort will benefit from the use of high-performance computing (HPC) resources, enabling large-scale parallel simulations to improve both the accuracy and efficiency of the design process.

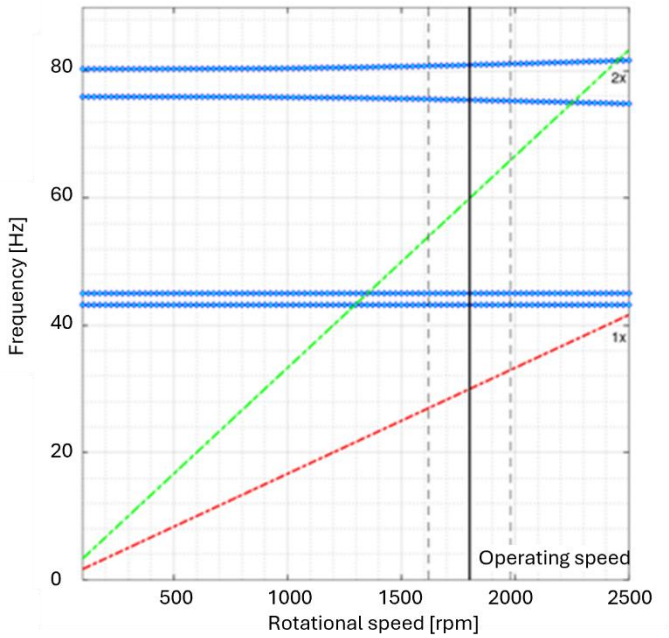


Figure 12. Campbell Diagram.

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