CEMAC Clean Energy Manufacturing Analysis Center

Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines

Sertaç Akar, Chad Augustine, Parthiv Kurup, and Margaret Mann
National Renewable Energy Laboratory

CEMAC is operated by the Joint Institute for Strategic Energy Analysis for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy.

Technical Report
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NOTICE

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Foreword

The U.S. Department of Energy (DOE) established the Clean Energy Manufacturing Analysis Center (CEMAC) at the National Renewable Energy Laboratory (NREL) to conduct credible, objective, industry-relevant, recurring and consistent analyses of clean energy technologies based on established methodologies and prior successful analyses. These analyses provide insights on supply chain dynamics that can aid decision-makers in creating strategies for innovation in manufacturing. CEMAC analyses include several components that enable development of technology-specific and cross-technology insights affecting manufacturing cost and location decisions (Sandor et al., 2017). The main types of CEMAC analysis include;

- Current and prospective global supply chains and trade flows of materials and components necessary for the manufacture of clean energy technologies,
- Detailed manufacturing costs analysis, including the total costs of products manufactured in the U.S. relative to regions around the world,
- Determination of the main drivers of costs and the sensitivity of those drivers to technical and market inputs,
- Qualitative factors and their role in determining the location of new manufacturing facilities such as; intellectual property ownership and protection, opportunities for automation and advanced manufacturing, supporting infrastructure impacts, and trade restrictions.

In this study, we have undertaken a robust analysis of the global supply chain and manufacturing costs for components of Organic Rankine Cycle (ORC) turboexpanders and steam turbines used in geothermal power plants. We collected a range of market data influencing manufacturing from various data sources and determined the main international manufacturers in the industry. We developed a bottom-up manufacturing cost model which includes the raw materials, intermediate products, and final manufactured parts. In addition, we established industry contacts to discuss challenges currently faced by the industry, focusing on both economic factors (e.g. labor availability, energy cost, and capital availability) and non-economic factors (such as innovation culture, proximity to universities/innovation hubs, government policies, trade security and ease of doing business), that influence manufacturing cost.

Acknowledgments

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Nomenclature or List of Acronyms

DCF	Discounted Cash Flow
IRR	Internal Rate of Return
NPV	Net Present Value
PPA	Power Purchase Agreement
NCC	Net Capital Cost
IDC	Interest During Construction
MSP	Minimum Sustainable Price
MAWH	Maximum Allowable Working Hours
DOE	U.S. Department of Energy
NREL	National Renewable Energy Laboratory
CEMAC	Clean Energy Manufacturing Analysis Center
SAM	System Adviser Model
GETEM	Geothermal Electricity Technology Evaluation Model
GEA	Geothermal Energy Agency
IEA	International Energy Agency
BNEF	Bloomberg New Energy Finance
ORC	Organic Rankine Cycle
WHR	Waste Heat Recovery
CSP	Concentrated Solar Power
CNC	Computer Numerical Model
OSTB	Over-Speed Testing and Balance
CMM	Coordinate Measuring Machine
DFMA®	Design for Manufacturing and Assembly
IPSEpro®	Software for Thermal Process Simulation
WACC	Weighted Average Cost Capital
COGS	Inflation on Cost of Goods Sold
SG&A	Selling, General and Admission
D&E	Design and Engineering
FTE	Full Time Employee
NCG	Non-Condensable Gas
ACC	Air Cooled Condenser
HX	Heat Exchanger

Executive Summary

The global geothermal electricity market has significantly grown over the last decade and is expected to reach a total installed capacity of 18.4 GWe in 2021 (GEA, 2016). When planning geothermal power projects, geothermal project developers currently customize the size of the power plant to fit the resource being developed. The turbine is designed and sized to optimize efficiency and resource utilization for electricity production; most often, other power plant components are then chosen to complement the turbine design. These custom turbine designs demand one-off manufacturing processes, which result in higher manufacturing setup costs, longer lead-times, and higher capital costs overall in comparison to larger-volume line manufacturing processes. In contrast, turbines produced in standard increments and manufactured in larger volumes could result in lower costs per turbine. This study focuses on analysis of the global supply chain and manufacturing costs for Organic Rankine Cycle (ORC) turboexpanders and geothermal steam turbines.

In this study, we developed a manufacturing cost model to identify requirements for equipment, facilities, raw materials, and labor. We analyzed three different cases 1) 1 MWe geothermal ORC turboexpander 2) 5 MWe ORC turboexpander and 3) 20 MWe geothermal steam turbine, and calculated the cost of manufacturing the major components, such as the impellers/blades, shaft/rotor, nozzles, inlet guide lanes, disks, and casings. Then we used discounted cash flow (DCF) analysis to calculate the minimum sustainable price (MSP). The results showed that MSP could highly vary between 893 $/kW and 30 $/kW based on turbine size, standardization and volume of manufacturing. The analysis also showed that the economy of scale applies both to the size of the turbine and the number manufactured in a single run. As an example, the unit price of a 5 MW standard design turbine could be 150 $/W cheaper than the custom design. Sensitivity analysis indicated that these savings come largely from reduced labor costs for design and engineering and manufacturing setup. In addition to manufacturing cost savings, there is a delivery time saving up to 10 months, which could have a positive effect on construction financing operation time. Another advantage of these standard turbines is their adaptability to different geothermal systems by operating at off-design conditions.

Standard turbine designs only make economic sense if the manufacturing cost savings offset potential losses in electricity generation and revenue over a wide range of operating conditions. Off-design turbine efficiencies determine the commercially-favorable operating range of a standard ORC compared to custom-designed ORC equipment. To compare the economics of standard and custom turbine designs, we developed a model of a 5 MW Geothermal Power Plant using a given design point optimized to maximize power generation for a 175 °C, 80 kg/s geothermal resource by using IPSEpro® software. Then, we varied the geothermal resource over a range of temperatures and flow rates and compared power generation of the standard turbine operating at off-design conditions to a custom turbine operating a constant isentropic efficiency. We used these performance calculations and power output results in a DCF analysis, using NREL's System Advisor model (SAM), of plant operations, costs and financing, thereby creating representative techno-economic models of a total geothermal power plant using Geothermal Electricity Technology Evaluation Model (GETEM) and).performed DCF analysis of standard and custom design turbines using results from IPSEpro over a range of temperatures of interest; 63 different off-design cases were analyzed. These data helped us to explore the question; “Can today’s capital cost savings compensate the future revenue losses due to lower electricity generation?” The results showed that the net capital cost savings from a standard design vs. a custom design turbine at the standard turbine design point for the modeled 5 MW case study may reach up to $2.3M, while the difference in the NPV a could reach up to $1.4M. Our conclusion is that the study does not consider factors such as the demand for ORC turbines, the cost of carrying standard turbines as inventory, the optimum size for a standard turbine, etc., the results show that the standard turbines could be competitive over a wide range of temperatures and flow rates cases near their design point.

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1 Global Geothermal Energy Market

The global geothermal market has significantly grown over the last decade with approximately 4.75 GW of new capacity, contributing to overall geothermal power capacity of 13.65 GW (GEA, 2016; TGE Research, 2017; Enerji Atlasi, 2018). In the 10 years ending in December 2015, 118 binary cycle, 58 flash cycle, and 14 dry steam geothermal power plants were installed around the world, including (in order of installed capacity) the United States, New Zealand, Turkey, Indonesia, Kenya, Iceland, Italy, Mexico, Nicaragua, Philippines, Germany, El Salvador, Papua New Guinea, Costa Rica, Guatemala, Japan, Portugal, China, Russia, France, Australia, and Romania (Bertani, 2016). Flash cycle plants accounted for the greatest share of the new capacity (49.5%), and the greatest quantity of installations was binary cycle. The capacity share of binary cycle and dry steam turbines was 38.7% and 11.8% respectively (Bertani, 2016).

1.1 Historical, current and projected global installations

Based on pipeline projects (BNEF, 2016), and forecasts (GEA, 2016), the number of geothermal electricity projects are expected to grow and reach about 18.4 GW by 2021 (Figure 1), which could then create demand for a diverse mix of geothermal turbine types. It is unclear currently whether the additional expected capacity increases and the demand are sufficient to allow for standard turbines and turboexpanders to be created, rather than the customized turbines today that can be optimized for the resource conditions. However, Given the information about proposed projects and resource assessments, there is potential value in creating standard turbine sizes that could be adapted to the diversity of projects to offer an economic advantage. This study evaluates the economics of possible standard geothermal turbine sizes and the associated manufacturing costs in the United States.

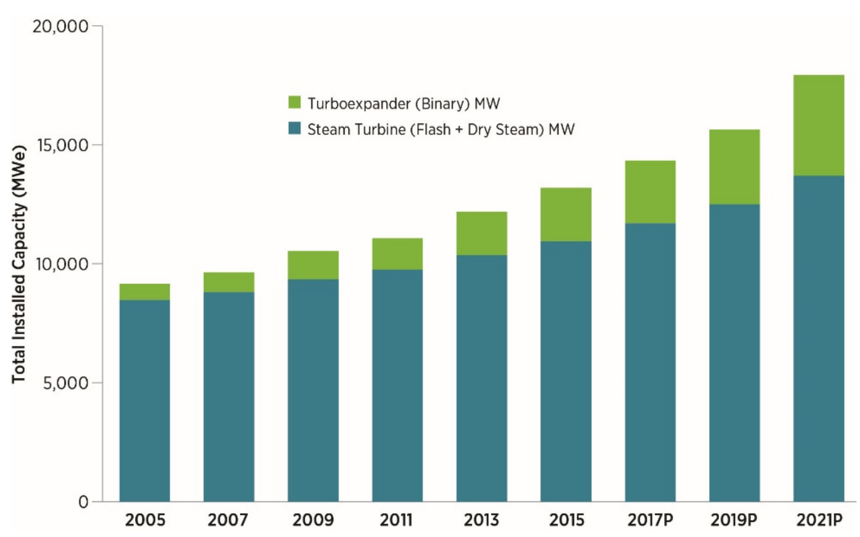


Figure 1 Historical, current, and projected global installations of geothermal power plant turbines. Data displayed represent the median figures which have been compiled from GEA (2016), BNEF (2016), and Bertani (2016). (P = projection)

1.1.1 Organic Rankine Cycle Turbines

Binary cycle geothermal plants mostly utilize ORC turboexpanders. Apart from geothermal energy applications, the ORC technology has also been used for other commercial applications—such as waste heat recovery (WHR), bioenergy production (from biogas and landfill gas), and concentrating solar power (CSP)—over the last decade. While bioenergy has the greatest number of ORCs installed (for waste heat recovery with smaller installed sizes), geothermal power plants contributed to 71% of all ORC installed capacity in the world between 2005 and 2016 (Figure 2), bioenergy and WHR follow with 15% and 13.7%, respectively (Tartiere, 2016).

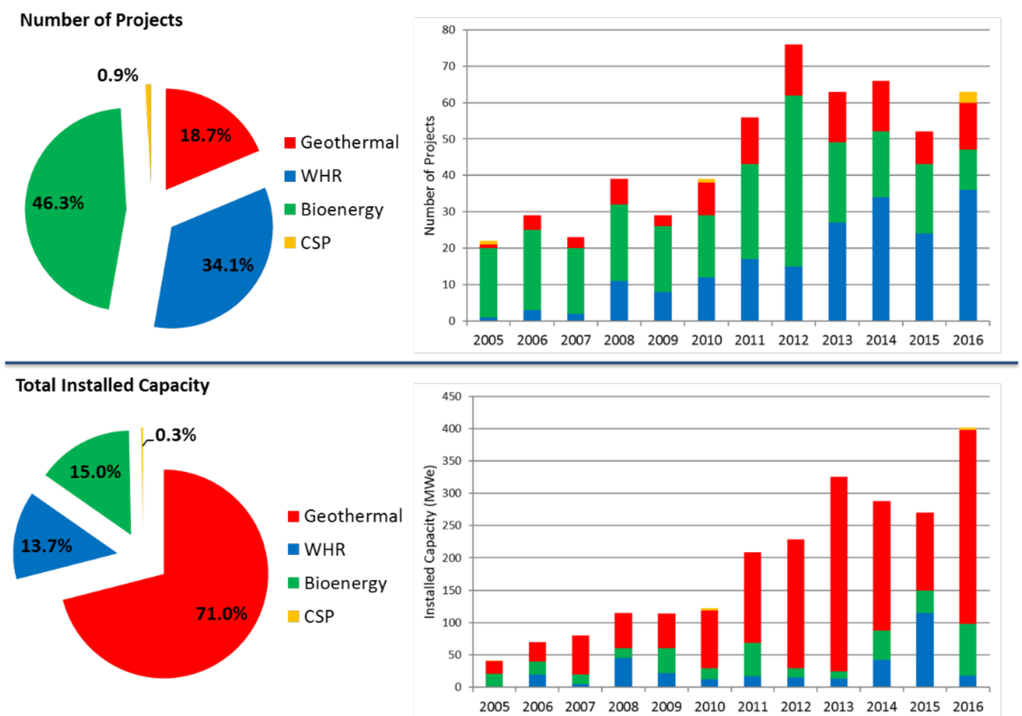


Figure 2 Overview of global ORC turboexpander market between 2005 and 2016 (Data modified from Tartiere (Tartiere 2016); lab-scale prototypes and installed capacity lower than 50 kWe have not been included)

1.2 Global Value Chain and Trade Flow

Geothermal project developers customize the size of the power plant to fit the resource being developed. The steam turbine in particular is designed and sized to optimize efficiency and resource utilization for electricity production; most often, other power plant components are then chosen to complement the turbine design. For example, in the Imperial Valley, Southern California, the Salton Sea Unit 5 geothermal steam turbine is designed and optimized for 58.32 MWe (Fuji Electric, 2012). These custom turbine designs demand one-off manufacturing processes, which result in higher manufacturing setup costs, longer lead times, and higher capital costs overall than larger-volume line manufacturing processes. In contrast, turbines produced in standard capacity increments are manufactured in larger volumes for the fossil-based power industry, which results in lower costs per turbine.

Based on interviews with industry experts, the current manufacturing process for geothermal turbines is made-to-order; the challenges of geothermal reservoir chemistry force designs to use specialty metals that cost more than those used in fossil fuel-powered turbines; additionally, the large fixed costs of resource development and low geothermal energy sales prices lead developers to customize their turbine sizes to maximize resource utilization. In the case of turboexpanders, these factors result in greater manufacturing set-up costs, more extensive engineering and design, and up to 18 months lead time from initial design to installation. In turn, these factors may impact developers' returns and decrease the attractiveness of deploying geothermal energy.

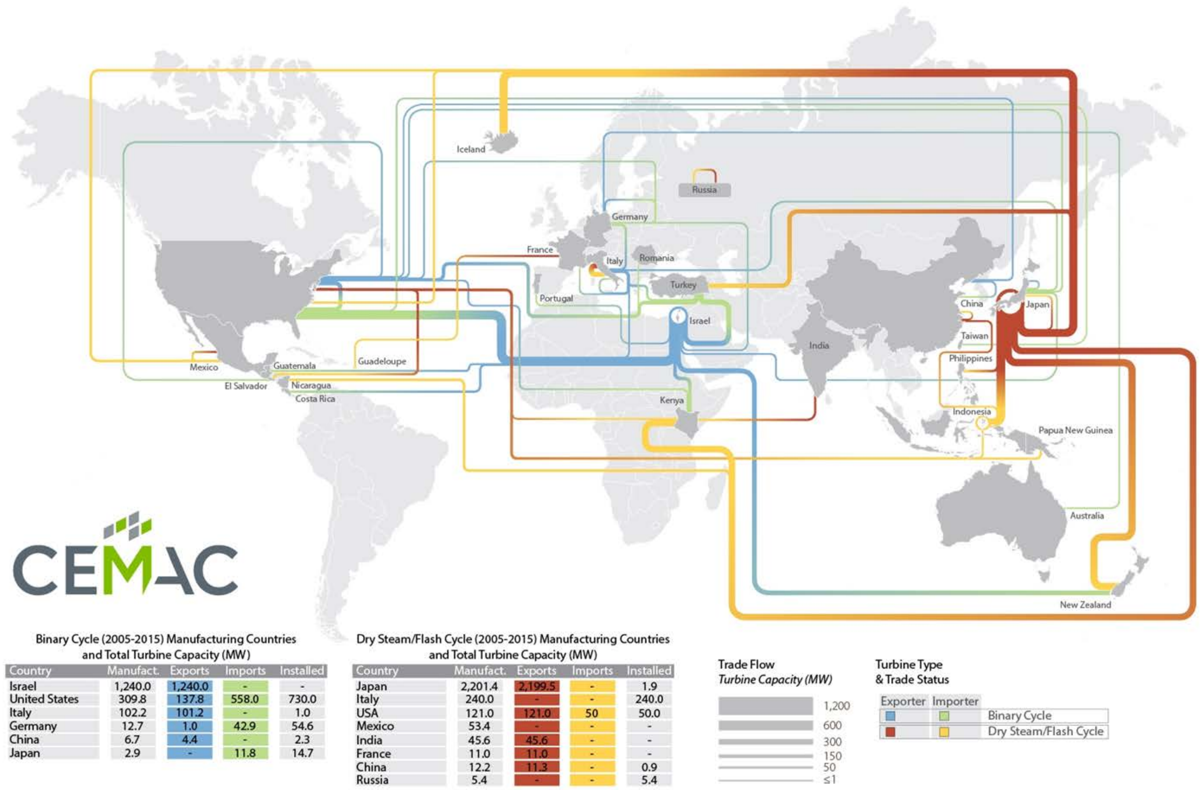
The steam turbine market is driven by large coal-fired, natural gas-fired, and nuclear power plants. The global steam turbine market is expected to increase from $14.5 billion in 2013 to $17.4 billion by 2020, with an annual growth rate of 2.6% over this period (Frost and Sullivan, 2014). Annual global orders for steam turbines are broadly stable at around 100 GW, and geothermal steam turbines constitute only 1%–2% of the total annual demand (Frost and Sullivan, 2014).

In this study, we evaluated two major geothermal turbine technologies: binary cycle turboexpanders and flash cycle steam turbines. The analysis included manufacturing location decisions, manufacturing processes, and global regional costs, with a focus on potential economies of scale of both turbine technologies using different annual production rates and standardized unit design.

A handful of international manufacturers dominate the global geothermal turbine market. The main manufacturing locations for binary cycle turboexpanders are Israel, the United States, Italy, and Germany. The flash cycle geothermal steam turbine manufacturing countries are Japan, Italy, the United States, France, Mexico, Russia, India, and China. Japan accounts for 82% of the geothermal steam turbine manufacturing market while Israel accounts for 74% of the geothermal binary cycle turboexpander manufacturing market. Italian turboexpander manufacturers have started to increase their share in the geothermal market with significant growth in the last couple of years. The United States also plays an important role both as exporter and importer in the global trade flow of geothermal turbines (Figure 3). A full list of installed geothermal power plants between 1958 and 2015 can be found in Appendix.

A comprehensive study of the U.S. geothermal market by NREL suggests that approximately 784 MWe is expected to come online by 2020, and an additional 856 MWe could come online in the next 5 years if existing barriers could be removed to expedite project development (Wall and Young, 2016).

Indonesia is not only second worldwide in installed geothermal capacity; it also far exceeds all other countries in estimated geothermal potential and has a rapidly growing demand for electricity. Indonesia's current installed geothermal power capacity is 1,868 MWe, and the government has ambitious plans for geothermal development of 6,500 MWe by 2025 (Poernomo et al, 2015). Indonesia has a high feed-in-tariff (FIT) policy which ranges from 12.6 to 26.2 ¢/kWh (Poernomo et al, 2015).



Binary Cycle (2005-2015) Manufacturing Countries and Total Turbine Capacity (MW)

Country	Manufact.	Exports	Imports	Installed
Israel	1,240.0	1,240.0	-	-
United States	309.8	137.8	558.0	730.0
Italy	102.2	101.2	-	1.0
Germany	12.7	1.0	42.9	54.6
China	6.7	4.4	-	2.3
Japan	2.9	-	11.8	14.7

Dry Steam/Flash Cycle (2005-2015) Manufacturing Countries and Total Turbine Capacity (MW)

Country	Manufact.	Exports	Imports	Installed
Japan	2,201.4	2,199.5	-	1.9
Italy	240.0	-	-	240.0
USA	121.0	121.0	50	50.0
Mexico	53.4	-	-	-
India	45.6	45.6	-	-
France	11.0	11.0	-	-
China	12.2	11.3	-	0.9
Russia	5.4	-	-	5.4

Figure 3 Global trade flow map of geothermal turbines, 2005–2015. Data are from a CEMAC analysis of industry outreach, GEA (2015 and 2016), BNEF (2013, 2014, 2015 and 2016), and Bertani (2016).

Turkey has 1,129 MW of installed capacity as of March 2018 and a capacity target of 1,900 MWe including the projects in the pipeline (Enerji Atlasi, 2018). Turkey implemented a renewable energy law in 2010 to reach its target for increasing the share of renewables up to 30% of the energy mix by 2023 (IEA, 2011). The Turkish FIT for geothermal power plants is 10.5 ¢/kWh. The FIT applies for 10 years of power generation and producers also benefit from an 85% discount on transmission costs for the 10 years. The 2010 Renewable Energy Law also includes bonus payments for hardware components made in Turkey to support and boost the national manufacturing sector. Companies who rely on locally produced equipment/components receive a bonus FIT, fixed at 1.3 ¢/kWh for turbines, 0.7 ¢/kWh for generators, 0.7 ¢/kWh for pumps and compressors (IEA, 2011). This has increased developers' and manufacturers' interest in domestic manufacturing. The total FIT for geothermal could reach up to 13.2 ¢/kWh with 10 years of purchasing guarantee.

Kenya reached 681 MWe of installed capacity in 2016 by adding 45 MWe of extra capacity from refurbishment of the existing Olkaria power plant units (GEA, 2016). Kenya is currently under a very aggressive phase of development with an aggressive construction pipeline of new projects in several geothermal resource areas. An additional 680 MWe of capacity is expected to come online by 2018. Total estimated resource potential of the country is around 10 GW (GEA, 2016).

2 Manufacturing Analysis

For this study, we developed a bottom up manufacturing cost model that considers the materials, manufacturing steps and equipment, and assembly of turbine subcomponents. First, we collected data from literature and informative interviews with industry regarding actual manufacturing operations. Existing published cost analyses and previous models of current manufacturing practices developed by CEMAC were also used. Next, we developed a process flow diagram to identify the raw materials, required manufacturing processes and equipment, and utility requirements that are inputs to the cost model (Figure 4). Raw materials required for pre-processing are iron ore, carbon, chromium, molybdenum, nickel, titanium, and aluminum. The most common processed materials used are stainless steel, Inconel (nickel) alloys, and titanium alloys (Ellis and Conover, 1981; Kaya and Hoshan, 2005). Additionally, epoxy-based refined plastics are used for insulation and sealing purposes.

2.1 Methodology for Manufacturing Analysis

2.1.1 Manufacturing process flow

The manufacturing cost model includes three main steps 1) Materials (raw and processed), 2) Manufacturing (in-house machining and outsourced parts) and 3) final assembly. The final product could be either an ORC Turboexpander or a geothermal steam turbine.

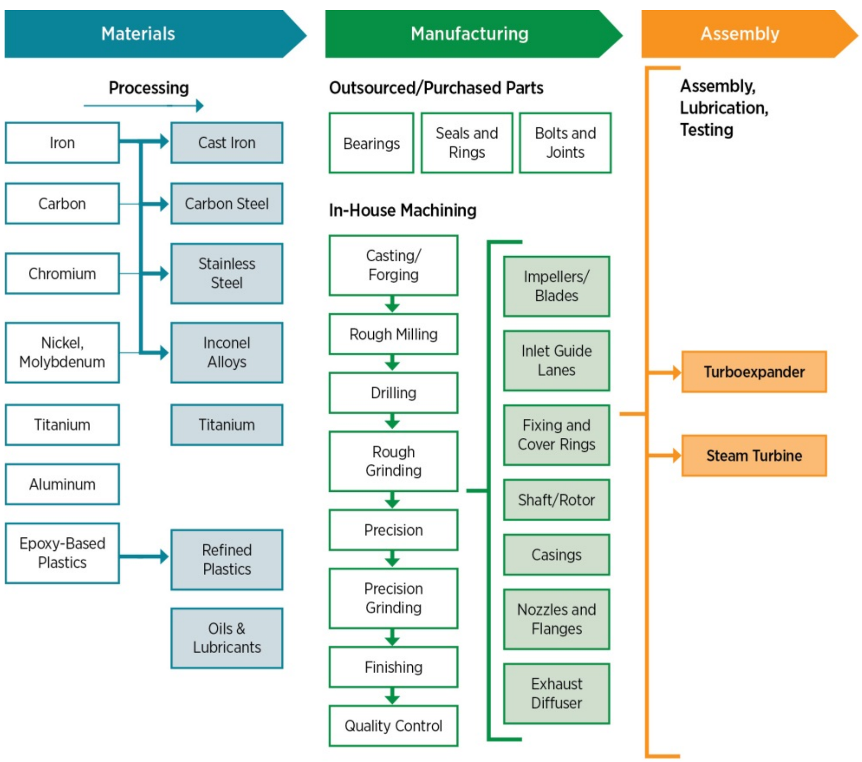


Figure 4 Manufacturing process flow diagram for geothermal power plant turbines

2.1.2 Materials

The most common corrosion resistant materials used for machining the impellers are titanium or stainless steel; the shaft is produced from stronger material such as forged nickel alloy or Inconel. Geothermal fluids contain dissolved CO_2, H_2S, NH_3 and chloride ions that can cause corrosion of metallic materials. The main corrosion problems are pit corrosion, cracking corrosion, breaking with stressed corrosion, breaking with sulphur stressed corrosion, corrosion between the particles and wearing corrosion (Kaya and Hoshan, 2005).

Stainless steel material decreases the probability of uniform corrosion formation in geothermal fluid environment. AISI 400 series stainless steels contain 12-18% chrome, which is more suitable for turbine blades. AISI 430 (Ferrite) and AISI 431 (Martensitic) stainless steels are often used for valve and pump components in geothermal systems. Stainless steel production is wide spread throughout the world (Figure 5). Based on world steel dynamics 2015 data, China, Japan, and the United States are the top three countries in stainless steel production.

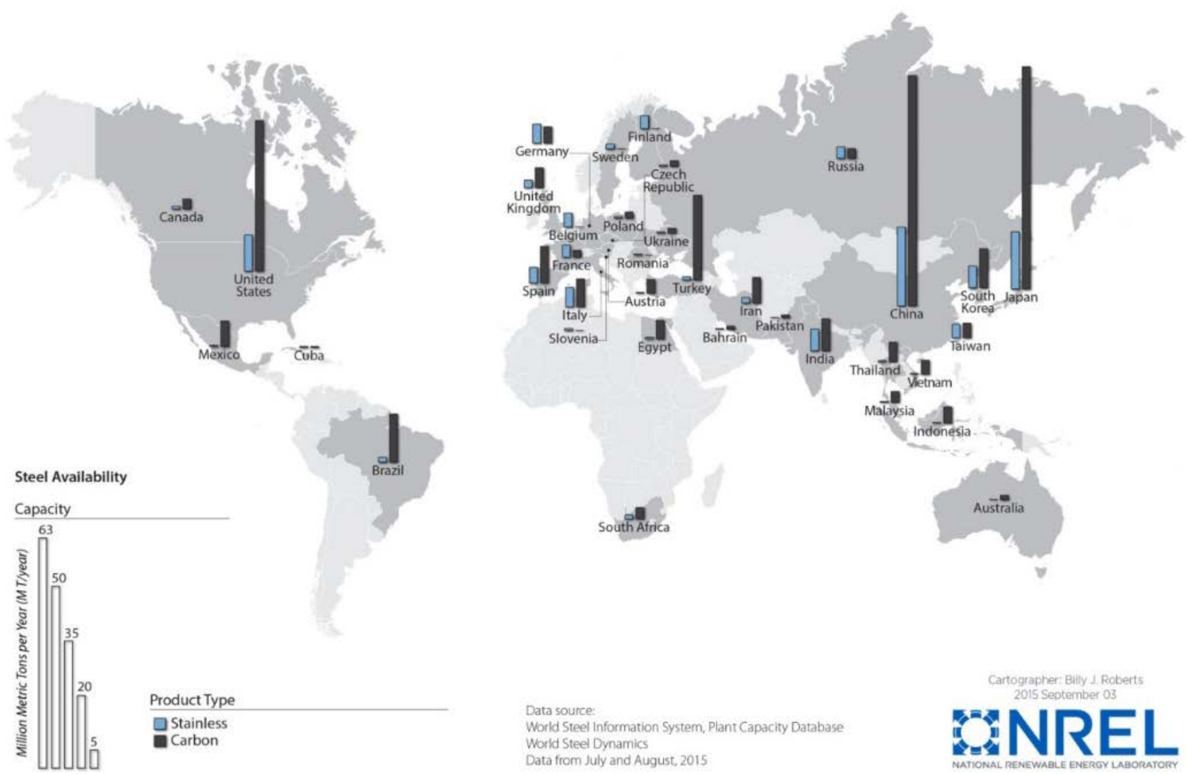


Figure 5 World Steel Production, *Units are in million metric tons per year. (Data Source: World Steel information system, World Steel Dynamics, 2015)

Titanium and titanium alloys are more resistant to corrosion. In addition, titanium is resistant to cavitation and impact damages. Titanium alloys are much more resistant to local corrosion than pure titanium. Ti-code-7 (Ti-0.15 Pd), Ti code-12 (Ti-0.3 Mo-0.8 Ni), and Ti-code-29 (Ti-6 Al-4 V-0.1 Ru) show well resistance. When they are compared on the basis of cost and performance, titanium alloys can be used properly as other stainless steel alloys. The critical places for the use of titanium alloys as the material can be; impellers, wellhead valves, pressure gauges, pipes and blow-out preventers.

The world`s titanium production is limited to certain regions (Figure 6). Based on USGS Minerals Year Book 2015 data, Canada, Australia, China, South Africa, Vietnam, the United States, Brazil, India, Mozambique, Madagascar, Norway, Ukraine, Kenya, Kazakhstan, Indonesia, Malaysia and Siri Lanka are the main countries for titanium production.

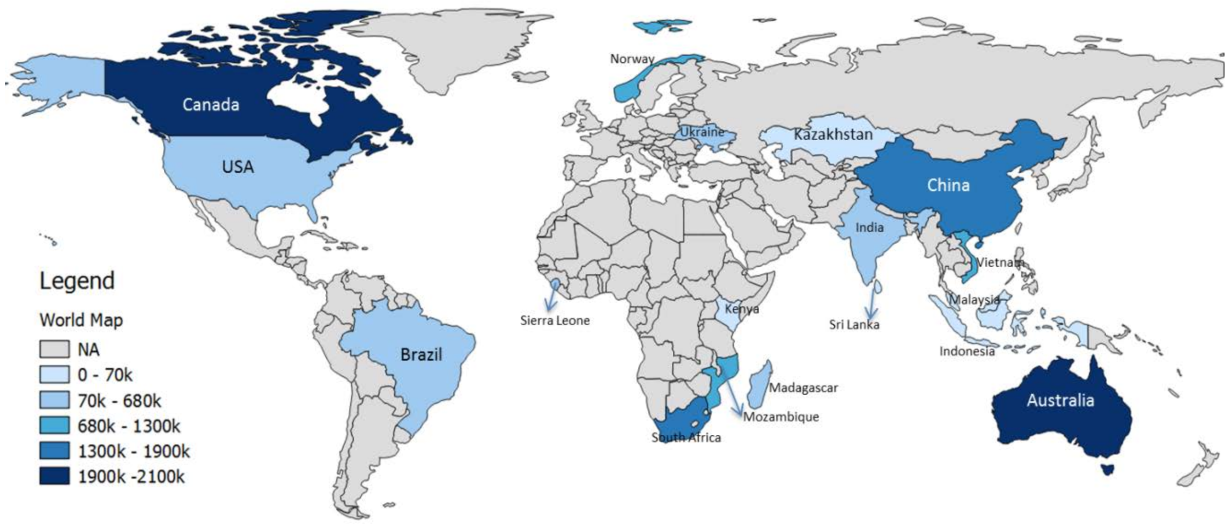


Figure 6 World Titanium Ore Production, *Units are in thousand metric tons per year. (Data Source: USGS Minerals Year Book, 2015)

Other important material for turbine manufacturing is the Inconel (nickel alloys). There are various types of Inconel available in the market, and the mineral content defines the strength and the corrosion resistance (Table 1). For the high temperature geothermal fluids, it is suitable to use nickel, chromium, and molybdenum (Ni-Cr-Mo) alloys as a material (Kaya and Hoshan, 2005). Inconel-625 and Hastelloy C-256 are especially strong in combatting corrosion. Other nickel alloys, which have iron elements, can also be used in some applications. These alloys are much stronger than the stainless steel. Forged Inconel is mostly used for turbine shafts because of its strength against rotational force.

Table 1 Inconel Alloy Element Compositions by Weight

Inconel Alloys	Elements % by Mass										
	Ni	Cr	Fe	Mo	Nb	Co	Mn	Cu	Al	Ti	Others
600	72	16	10	0	0	0	1	0.5	0	0	0.5
617	44	24	3	10	0	15	0.5	0.5	1	0.5	0.5
625	58	20	5	10	4	1	0.5	0	0.4	0.4	0.7
690	60	30	9	0	0	0	0.35	0.01	0.02	0	0.62
718	55	21	12	3	5	1	0.3	1	1	0.2	0.5
X-750	70	14	9	0	1	1	1	0.5	0.5	2.5	0.5

2.1.3 Machine inventory and factory model

Manufacturing processes for subcomponents include casting, forging, and machining. For casting and forging, an electric arc furnace and forging press are required. The manufacturing cost model that we developed includes the minimum factory space required for the machines in addition to machine-related labor requirements. We created an inventory of machinery for heavy machining and precise computer numeric control (CNC) machining processes (Klocke et al., 2014) in addition to quality control and assembly stages (Figure 7). Heavy machining includes electric arc furnace casting and forging operations. CNC machining includes a 5-axis CNC machine, a 3-axis CNC machine, a CNC horizontal lathe, and a CNC grinding machine. Quality control equipment includes a coordinate measuring machine (CMM) in addition to over-speed testing and dynamic balancing (OSTB).

We estimated a minimum machining rate for each machine based on annual maximum allowable working hours (MAWH) and operation hours with and without setup time for the factory model. MAWH is set at 3,400 hours based on 250 annual labor days, 8 working hours with 2 shifts per day, and 85% production-up-times.

Based on industry standard practices, these machines are as fully utilized as possible across several different projects. For this cost analysis, the capital cost share associated with facilities, space, and machine depreciation for the time when the machine is used on manufacturing the turbine parts is proportional to the use time. This splits capital costs for the equipment between turbine components and other projects that the manufacturer is involved in. In other words, we are only taking the capital cost share associated with facilities, space, and machine depreciation for the time when the machine is used on manufacturing the turbine parts, not the full 3,400 hours per year.

The amount of required machinery was selected based on total operational hours for different volumes of manufacturing and MAWH. If one of each machine type (e.g. one 5-axis CNC, one 3-axis CNC machine and so on) were chosen for all types, there would be enough manufacturing capacity to produce up to a volume of 100 units per year. For greater than 100 units per year, additional machines would be required (Table 2). We selected a manufacturing volume of 50 units/year as a threshold for our analysis, based on manufacturers' annual manufacturing capacities and project portfolio. Annual straight-line depreciation was selected for capital costs associated with machinery, as handled in accounting procedures. Facility cost is defined based on minimum required working area for each machine. Energy cost is calculated based on average power consumption of each machine, operating for a given number of operational hours. Storage and shipping costs of the turbine parts/components are not included in the factory model.

Precise CNC Machining		Heavy Machining	
5 Axis CNC Machine Price: \$150,000 - \$300,000 Footprint: 10-15 m^2 Energy Consumption: 20-30 kW		**Casting** Price: \$500,000 - \$1,000,000 Footprint: 1000 m^2 Energy Consumption: 500 kW	
3 Axis CNC Machine Price: \$100,000 - \$200,000 Footprint: 10-15 m2 Energy Consumption: 20-30 kW		**Forging** Price: \$400,000 - \$500,000 Footprint: 1000 m^2 Energy Consumption: 500 kW	
Horizontal CNC Lathe Price: \$60,000 - \$150,000 Footprint: 12-18 m^2 Energy Consumption: 30-40 kW		**Quality Control & Assembly**	
		Assembly Line Price: \$ 50,000 -\$300,000 Footprint: 50 - 60 m^2 Energy Consumption: 5-10 kW	
CNC Grinding Machine Price: \$80,000 - \$150,000 Footprint: 35-40 m^2 Energy Consumption: 10-20kW		**Over-speed Testing & Balancing Machine** Price: \$10,000 - \$20,000 Footprint: 10 m^2 Energy Consumption: 5-7 kW	
		CMM Dimension Measuring Machine Price: \$8,000 - \$10,000 Footprint: 10 m^2 Energy Consumption: 1-3 kW	

Figure 7 Machine inventory for the custom factory model

Table 2 Number of required machines for different volumes of manufacturing at MAWH

#Units	5 Axis CNC Machine	3Axis CNC Machine	CNC Horizontal Lathe	CNC Grinding Machine	CMM	OSTB	Assembly Line
10	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1
150	1	2	1	1	1	1	1
200	1	2	1	2	1	1	1
500	2	5	3	4	1	1	2
1000	3	9	5	7	1	2	3

2.2 Machining Cost Analysis

Design for Manufacture and Assembly (DFMA®) was used for some of the key, high value components such as impellers and shafts for the manufacturing cost analysis of turboexpanders. DFMA allows the user to produce a detailed projected cost of the component, based on the volume of material needed, the machines and process steps, machine setup time, and tooling if needed. Tooling investment is calculated for processes such as stamping, sand casting, and forging; it also considers tool wear and lifetime. Figure 8 shows the representative material and machining cost estimates of a typical impeller for both custom design and standard design (at a volume of 10 units) 5 MWe Turboexpander.

As can be seen in Figure 8, a custom design impeller could be ~$4,000/unit, compared to ~$1,000/unit with the standard design. If we assume same yield rate, the standard design impellers can lead a cost savings of between 25-30% compared to custom design (single unit) due to the setup times for machining the impeller. A similar approach is applied to other subcomponents of a turboexpander: shaft, nozzles, inlet guide lanes, disks and casings to calculate machining costs.

Part	Material	Procurement	Raw Material Unit Price ($/kg)	Purchased Material Unit Price ($/kg)	Estimated Volume (m^3)	Material Density (kg/m^3)	Estimated Weight (kg)	Material Cost ($)
Impeller	Titanium	Plate	22.82	39.04	0.037	4,500	167	6,500

Part	Machining Process	Setup Time/Unit (hours)	Process Time /Unit (hours)	Machine Rate/Unit ($/hour)	Machining Cost/Unit ($)	Manufacturing Subtotal Cost/Unit ($)
1 Unit (Custom Design)						
Impeller	Drilling	0.8	0.2	35	35	4,000
	5-Axis CNC Roughing	25.0	5.0	35	1,055	
	5 Axis CNC Rest Milling	42.0	8.0	35	1,760	
	5-Axis CNC Finishing	10.0	2.0	35	422	
	QC	2.5	0.5	27	80	
	Balancing	20.0	4.0	25	648	
10 Units (Standard Design)						
Impeller	Drilling	0.3	0.2	35	9	1,000
	5-Axis CNC Roughing	2.5	5.0	35	264	
	5 Axis CNC Rest Milling	4.2	8.0	35	440	
	5-Axis CNC Finishing	1.0	2.0	35	105	
	QC	0.3	0.5	27	20	
	Balancing	2.0	4.0	25	162	

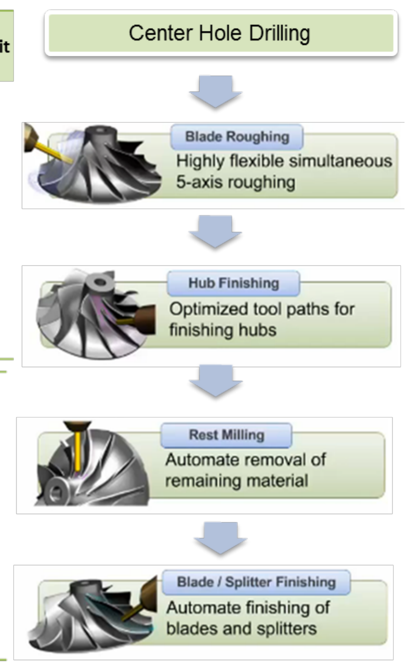


Figure 8 Representative material and machining cost estimates of a typical impeller for both custom design and standard design (at a volume of 10 units per year) 5 MWe Turboexpander

3 Minimum Sustainable Price (MSP) and Discounted Cash Flow (DCF) Analysis

MSP is the minimum price that a company would have to charge for a good or service to cover all variable and fixed costs and make sufficient profit to pay back investors at their minimum required rates of return (Goodrich et al., 2013). The MSP is computed by setting the net present value (NPV) of an investment equal to zero with the internal rate of return equal to the weighted average cost of capital (WACC). We used the U.S. capital assets pricing model to derive these debt and equity ratios, and weight them by their relative contribution to the overall capital structure of the firm to estimate WACC values (Ross et al., 2009).

We also developed a detailed financial model for the DCF of a manufacturing facility. The purpose of the DCF is to provide the necessary framework for deriving the MSP for each product. Within the DCF, we can account for several considerations for manufacturing, such as capital cost, fixed operating costs (labor, depreciation, inflation and taxes, insurance and rent), typical sales, general and administrative (SG&A) expenses; typical design and engineering (D&E) cost; and warranty coverage (Goodrich et al., 2013). Table 3 summarizes the input parameters for the DCF analysis.

We calculate the initial equipment and facilities expenditures over straight-line depreciation. The length of the calculation is set by the analysis period, and the discount rate is calculated from the required rates of return; the MSP is then derived by an iterative algorithm that runs until the NPV of the cash flows equals the total initial capital expenditure.

Table 3 Summary of input parameters for DCF analysis

Inputs for DCF Calculations	Values	Units
Inflation on cost of goods sold (COGS)	**3**	%
Corporate interest rate	**3.3**	%
Initial Loan (or bond) maturity	**10**	years
Corporate tax rate	**30**	%
Dividend payout rate	**0**	%
Cost of equity	**10.6**	%
Cash flow analysis period	**20**	years
Working capital collection period	**10**	years
Calculated WACC	**5.3**	%
Working capital inventory turnover	**4**	years
Working capital payable period	**10**	years
CAPEX Initial target capital structure, (% of debt)	**64**	%
Replacement equip. target capital structure	**50**	%
Depreciable life for plant	**25**	years
Capital replacement loan maturity	**10**	years
Equipment depreciation type	**7 Year Straight-line**	N/A
Tooling depreciation type	**3 Year Straight-line**	N/A
Building depreciation type	**15 Year Straight-line**	N/A

4 Manufacturing Analysis Case Studies

We analyzed the manufacturing cost and MSP for three different scenarios, where each scenario had 5 volumes of manufacturing: 1) a 1 MWe ORC turboexpander; 2) a 5 MWe ORC turboexpander; and 3) a 20 MWe steam turbine, at manufacturing volumes of 1, 5, 10, 25 and 50. All 3 scenarios assume U.S. production facilities and costs. The generator is considered as a separate piece and is not included in the manufacturing cost analysis. Increasing volumes of manufacturing effectively decreased the manufactured cost per unit, since we spread the capex over more units. Machine setup times and D&E costs are the cost components that are most impacted by volume manufacturing, as these are essentially one-time charges that are not volume dependent.

4.1 Case-1: 1 MWe geothermal ORC turboexpander

In case 1, the results showed that MSP decreases significantly when we increase the volume of manufacturing from 1 unit (custom design) to 5 units (standard design). The MSP of a single custom design 1 MWe turboexpander was found to be 893 $/kW whereas a standard-design 1 MWe turboexpander has an MSP of 226 $/kW at a manufacturing volume of 5 (Figure 9).

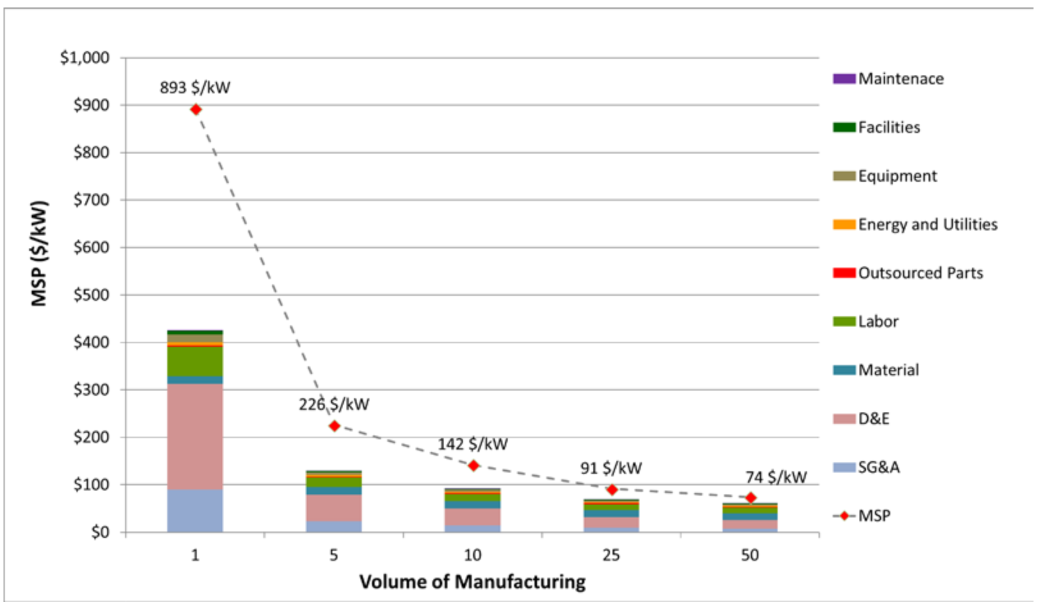


Figure 9 Calculated MSP and manufacturing cost breakdown for a 1 MWe ORC turboexpander in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC cost analysis.

4.2 Case-2: 5 MWe geothermal ORC turboexpander

In case 2, the results showed that MSP decreases significantly when we increase the volume of manufacturing from 1 unit (custom design) to 5 units (standard design). The MSP of a single custom design 5 MWe turboexpander was found to be 216 $/kW whereas a standard-design 1 MWe turboexpander has an MSP of 66 $/kW at a manufacturing volume of 5 (Figure 10).

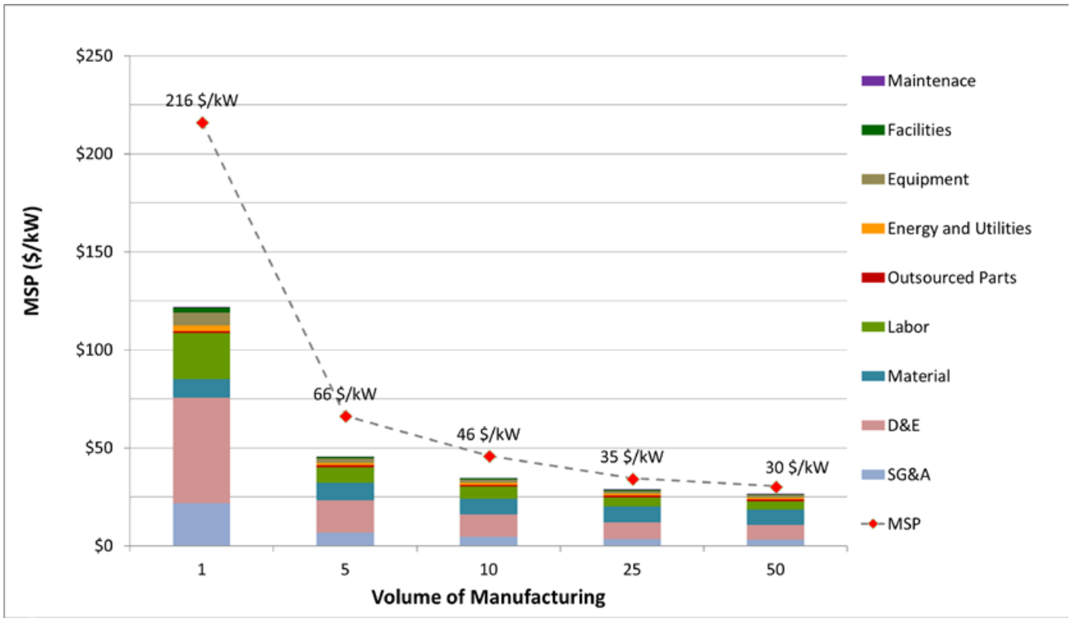


Figure 10 Calculated MSP and manufacturing cost breakdown for a 5 MWe ORC turboexpander in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC cost analysis

4.3 Case-3: 20 MWe geothermal steam turbine

For scenario 3, we selected a manufacturing volume of up to 5 units per year based on annual demand for geothermal steam turbines and the manufacturing capacities. The MSP of a single custom design 20 MWe geothermal steam turbine is found to be 361 $/kW, whereas the MSP of a standard-design 20 MWe steam turbine is calculated as 135 $/kW at an annual production rate of 5 unit/year (Figure 11).

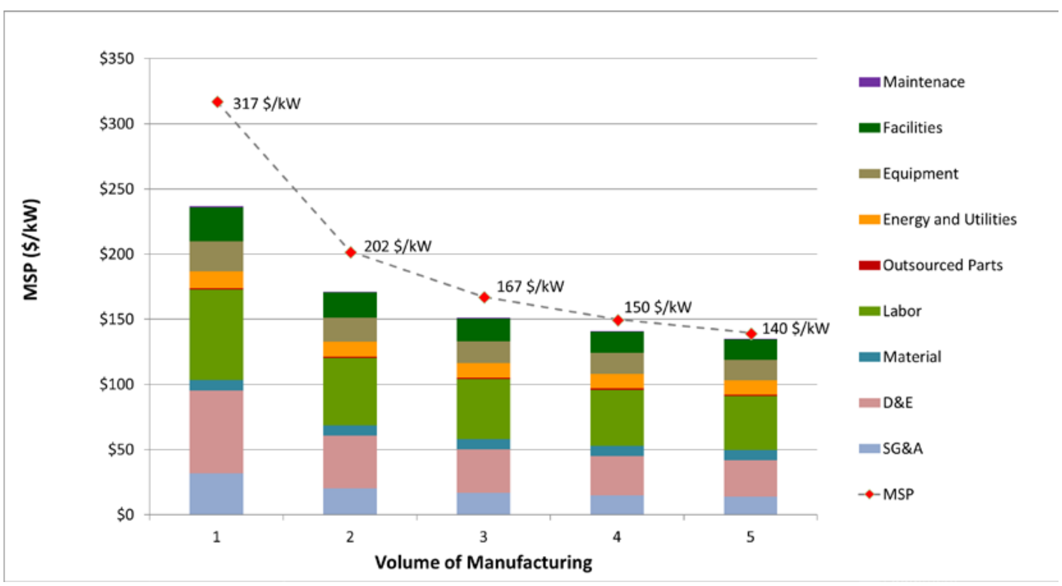


Figure 11 Calculated MSP and manufacturing cost breakdown for a 20 MWe geothermal steam turbine in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC

4.4 Sensitivity Analysis

We conducted a sensitivity analysis to determine which cost factors have the greatest impact on the results of the manufacturing cost model. We iteratively varied one input parameter of the cost model while keeping the others constant to determine the impact of each input on the calculated MSP. Each cost factor in the overall cost model has a different weight based on the relative importance, and as such a change in one input variable would have proportional effects relative to the weight on the manufactured cost. For the sensitivity analyses, we evaluated two cases: 1) custom design (1 unit) versus a standard design (10 units per year) for a 5 MWe ORC turboexpander; and 2) custom design (1 unit) versus a standard design (at 5 units per year) for a 20 MWe steam turbine.

The results of the MSP sensitivity analysis for a 5 MWe turboexpander showed that D&E is the most important cost factor for a custom design unit due to time spent on tailor made design for each custom unit (Figure 12). D&E is assumed to take 9 months and 2 full time employees (FTE). Manufacturing labor is the second most important factor at a custom design unit due to setup times. Labor includes set up time, which is 51% of total machining cost for a custom design unit. SG&A, capital (equipment and facilities), and materials are the other important factors which have a moderate effect on manufacturing cost for a custom design unit. When we assume standard design turboexpanders at volume of 10 units, materials and labor become dominant with shares of 46% and 31% respectively, while D&E and SG&A costs become less important. The cost drops by cost factor are also presented on cost waterfall charts (Figure 13).

The results of the MSP sensitivity analysis for a 20 MWe steam turbine showed that labor is the most important factor at a custom design unit due to setup times and high labor requirements during assembly (Figure 14). Labor includes set up time, which is 49% of total machining cost for a custom design single unit. Capital is the second most important cost factor at a custom design. D&E is assumed to take 12 months and 4 FTEs due to time spent on tailor made parts for each unit. Steam turbines need more detailed design than turboexpanders since they are in direct contact with saturated steam, non-condensable gases (NCG) like H_2S, and CO_2 and have multiple pressure stages. SG&A, capital (equipment and facilities), and materials are the other important factors that have a moderate effect on manufacturing cost for a custom design unit. When we have one-off-design turbines at a volume of 5 units, while impact factor of labor and material stays almost the same, D&E and SG&A cost become less important. The cost drops by cost factor are also presented on cost waterfall charts (Figure 15).

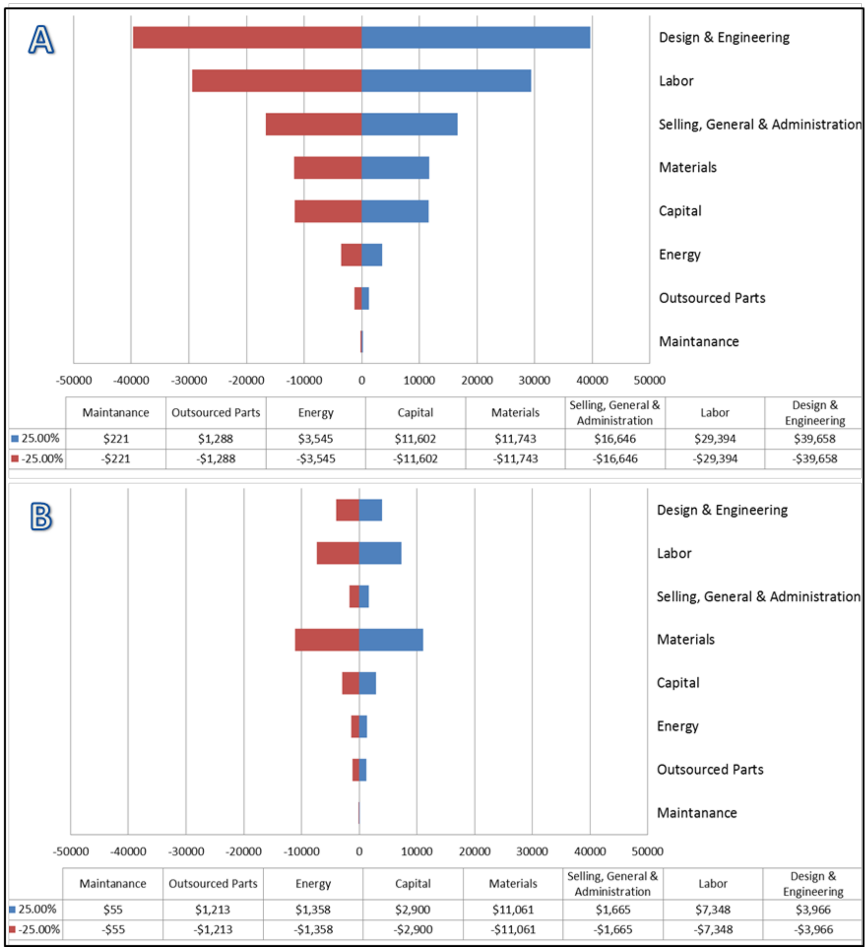


Figure 12 Sensitivity analysis for 5 MWe turboexpander based on A) Manufacturing volume of 1 unit/year (Custom Design) and B) Manufacturing volume of 10 units per year (Standard Design) in the United States (Data is from an ongoing CEMAC cost analysis).

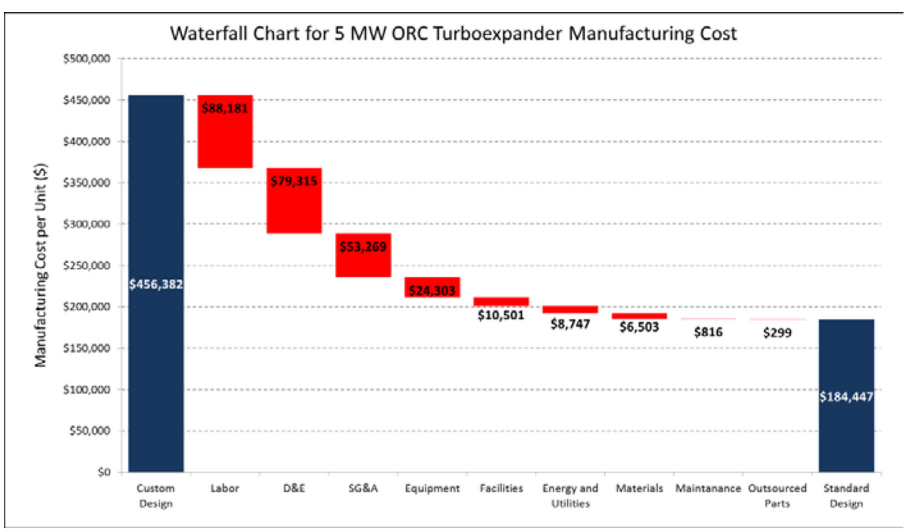


Figure 13 Manufacturing cost drop by cost factor for a standard design (10 units) 5 MWe ORC turboexpander (Data: ongoing CEMAC cost analysis)

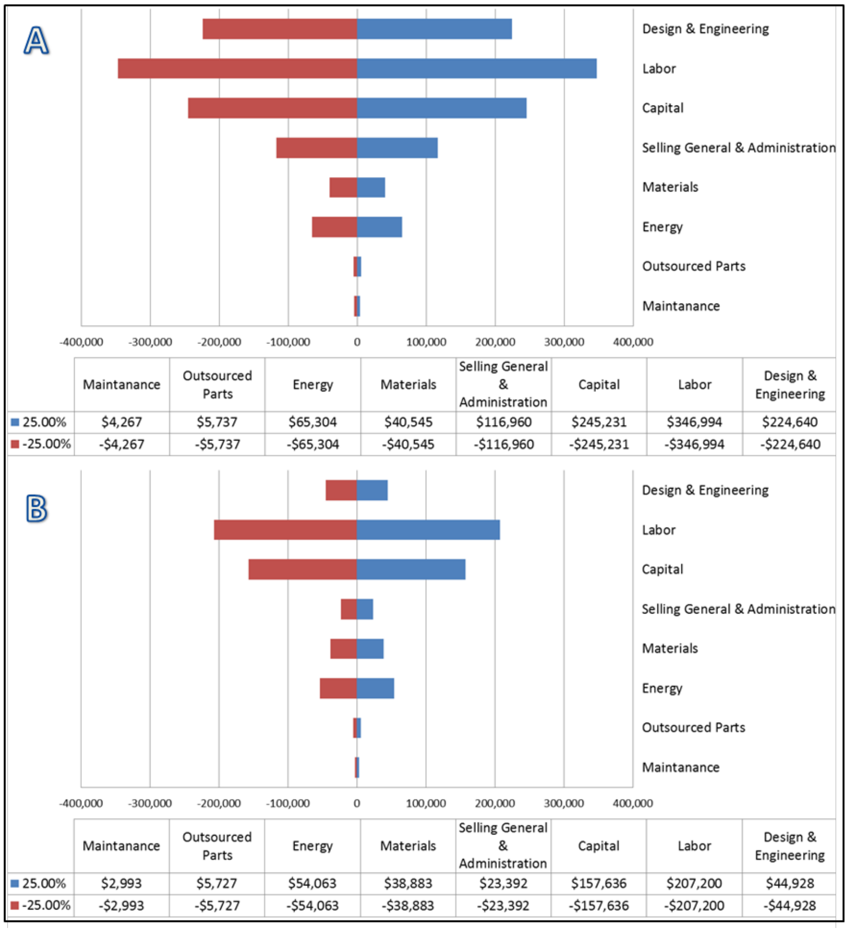


Figure 14 Sensitivity analysis for 20 MWe turboexpander based on A) Manufacturing volume of 1 unit per year (Custom Design) and B) Manufacturing volume of 5 units per year (Standard Design) in the United States (Data is from an ongoing CEMAC cost analysis).

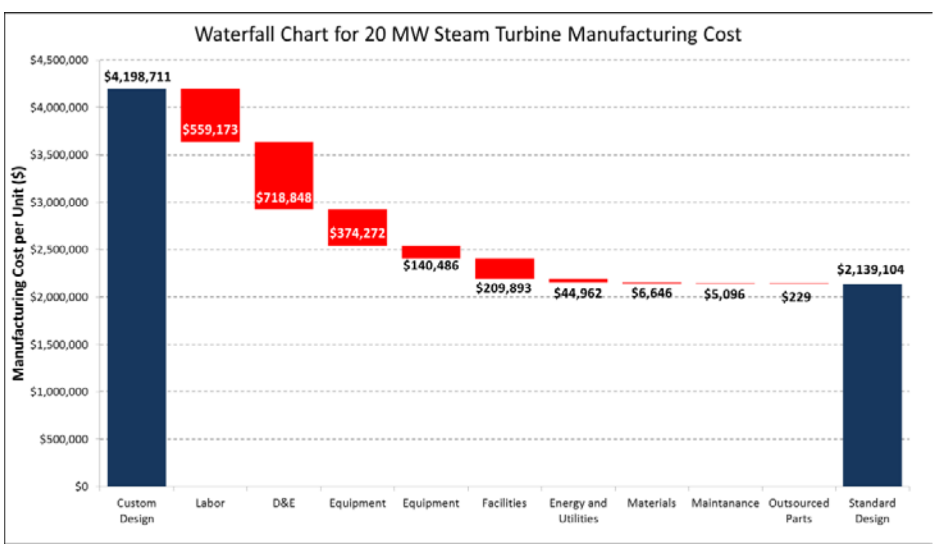


Figure 15 Manufacturing cost drop by cost factor for a standard design (5 units) 20 MWe steam turbine (Data: ongoing CEMAC cost analysis)

A comparison of MSP analysis for all three cases can be found in Table 4. The manufacturing cost of custom design 5 MW ORC turboexpander is only $187,000 more than a custom design 1 MW ORC turboexpander. This shows that the size of the turbine does not have a significant effect on the total cost of turbine/turboexpander. However, if we look at the unit cost per MW for both custom and standard design cases, we see that the manufacturing cost savings are significant (667 $/kW for 1 MW turboexpander and 150 $/kW for 5 MW turboexpander).

Table 4 Comparison of MSPs for standard and custom design turbines

MSP	Custom Design Single Unit		Standard Design Volume of 5 Units		Standard Design Volume of 50 Units	
1 MW Turboexpander	$893,000	893 $/kW	226,000 $	226 $/kW	$74,000	74 $/kW
5 MW Turboexpander	$1,080,000	216 $/kW	332,000 $	66 $/kW	$152,000	30 $/kW
20 MW Steam Turbine	$6,350,000	361 $/kW	2,790,000 $	135 $/kW	N/A	N/A

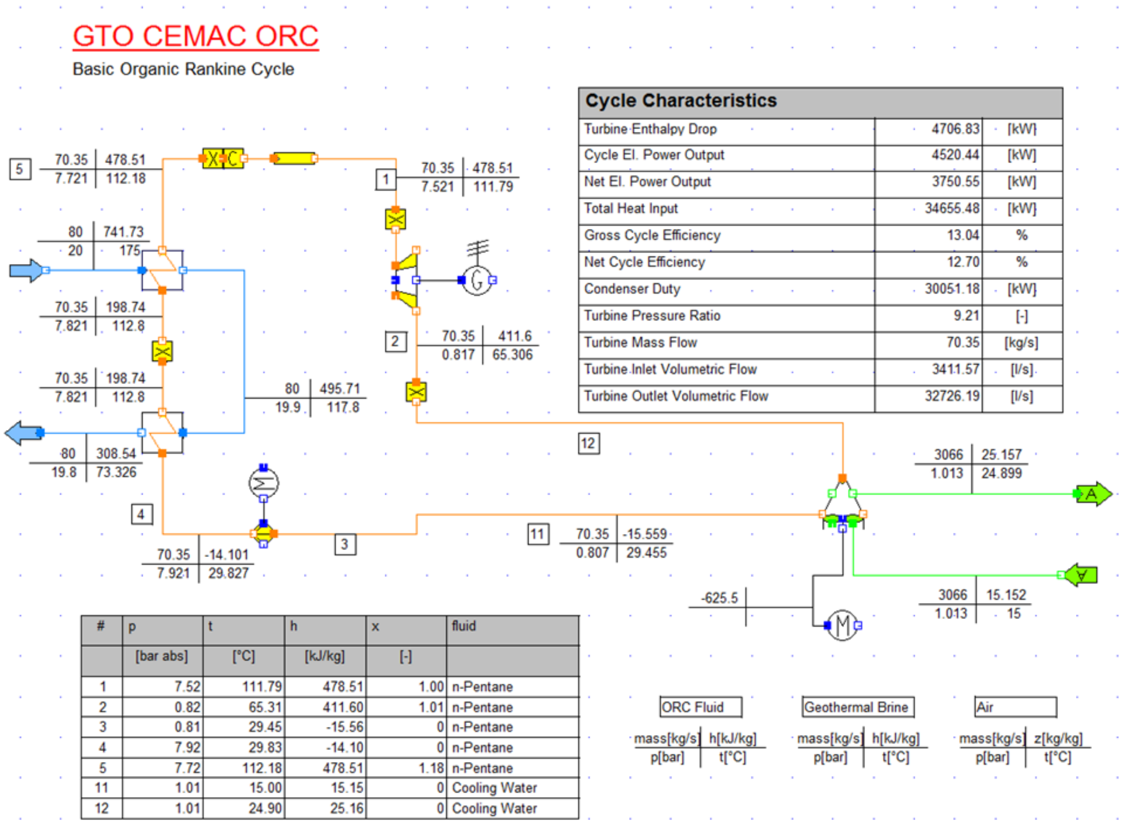
5 Power Plant Design and Performance Analysis

The purpose of the turbine performance analysis is to determine the commercially favorable operating range of a standard ORC compared to custom-designed ORC equipment. We created a process flow model for an ORC Geothermal Power Plant at a given design point of the standard size (5 MW) turbine by using IPSEpro software (Figure 16). Balance of plant (BOP) is optimized to maximize power generation. In other words, the BOP, including Heat Exchanger (HX), air cooled condenser (ACC), pumps, and piping, can be designed to optimize turbine output. The design assumptions for the optimized system include; 1) the pinch point temperature difference in heat exchanger, 2) vapor quality into the turbine and 3) turbine efficiency.

We selected the design point at 175°C inlet brine temperature and 80 kg/s brine mass flow rate for the standard turbine. Then, we ran an optimization algorithm to optimize BOP and operating conditions by adjusting the pressure before and after turbine for maximum turbine output at given geothermal inputs. The performance of the standard turbine is compared to a custom design turbine by running off-design models for varying geothermal resource temperatures (between 160°C and 190°C), and brine flow rates (between 40 kg/s and 120 kg/s). A turbine off-design efficiency curve[1] provided by a reliable manufacturer as a function of mass flow rate of the working fluid is used to evaluate the impact on power generation of the standard versus custom design (Figure 17). The design point isentropic efficiency is selected as 80%.

One important parameter that we use in the plant performance analysis is the Brine Effectiveness (BE). Simply, BE is the amount of energy that you can extract per pound of geothermal brine or steam, which is defined as net plant output divided by the brine flow rate (w-hr/lb). The use of BE to describe plant performance comes from the Geothermal Technology Evaluation Model (GETEM, 2016) on which the SAM geothermal module is based.

[1] Due to the proprietary nature of turbine performance curves, we could not obtain a full set of turbine performance curves. The turbine efficiency curve we used shows relative efficiency as a function of relative working fluid mass flow rate at a constant isentropic enthalpy drop across the turbine. The curve does not account for changes in isentropic enthalpy drop. in the IPSEpro modeling, both the working fluid mass flow rate and isentropic enthalpy drop across the turbine vary. However, the turbine model only considers working fluid mass flow rate when adjusting turbine isentropic efficiency. The resulting efficiency curve is likely not representative of actual turbine performance and is used only for illustrative purposes in this report. Turbine manufacturers and project developers have access to actual turbine performance curves and can use the methodology in this report to assess potential benefits of a standard turbine design.



Cycle Characteristics		
Turbine Enthalpy Drop	4706.83	[kW]
Cycle El. Power Output	4520.44	[kW]
Net El. Power Output	3750.55	[kW]
Total Heat Input	34655.48	[kW]
Gross Cycle Efficiency	13.04	%
Net Cycle Efficiency	12.70	%
Condenser Duty	30051.18	[kW]
Turbine Pressure Ratio	9.21	[-]
Turbine Mass Flow	70.35	[kg/s]
Turbine Inlet Volumetric Flow	3411.57	[l/s]
Turbine Outlet Volumetric Flow	32726.19	[l/s]

#	p	t	h	x	fluid
	[bar abs]	[°C]	[kJ/kg]	[-]	
1	7.52	111.79	478.51	1.00	n-Pentane
2	0.82	65.31	411.60	1.01	n-Pentane
3	0.81	29.45	-15.56	0	n-Pentane
4	7.92	29.83	-14.10	0	n-Pentane
5	7.72	112.18	478.51	1.18	n-Pentane
11	1.01	15.00	15.15	0	Cooling Water
12	1.01	24.90	25.16	0	Cooling Water

Figure 16 Process Flow Diagram of Standard Size ORC Power Plant

In SAM, BE is set by adjusting the plant efficiency input. According to IPSEpro modeling results, the BE of binary plants studied varies between 3.3 and 7.5 w-hr/lb (Figure 18). This value is 5.9 w-hr/lb for the standard turbine at its design point in IPSEpro. The BE value determines the more conventional thermal to electric conversion efficiency (TE) of the plant. TE varies as a function of inlet geothermal brine temperature and mass flow rate (Figure 19). TE is calculated as 10.83% at the design point for the base case IPSEpro model.

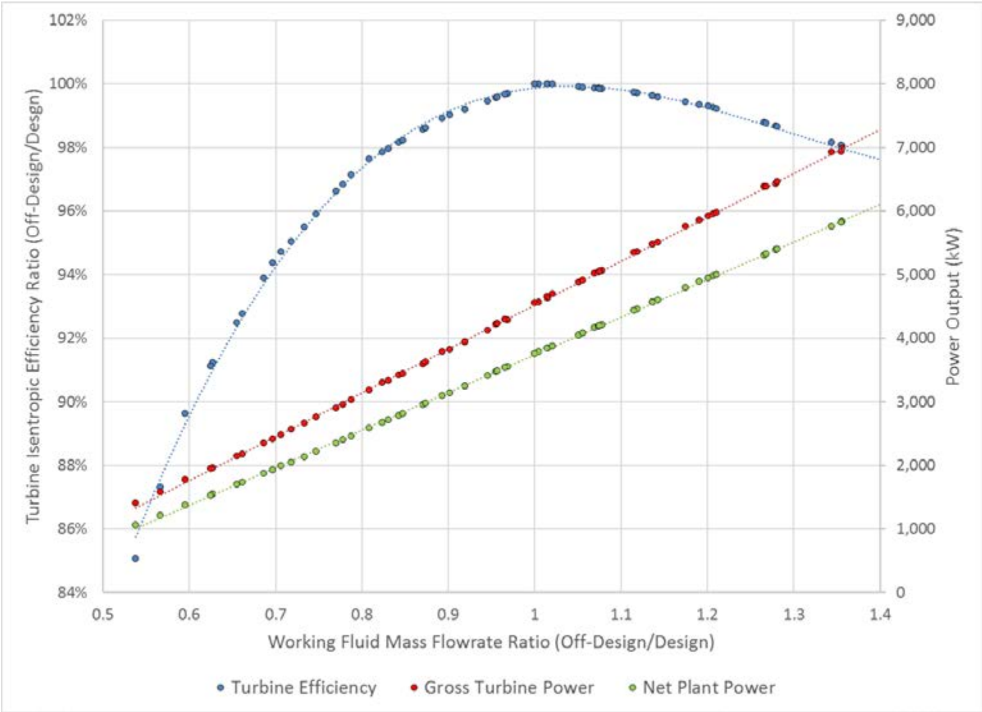


Figure 17 Off-Design Turbine Efficiency Curve

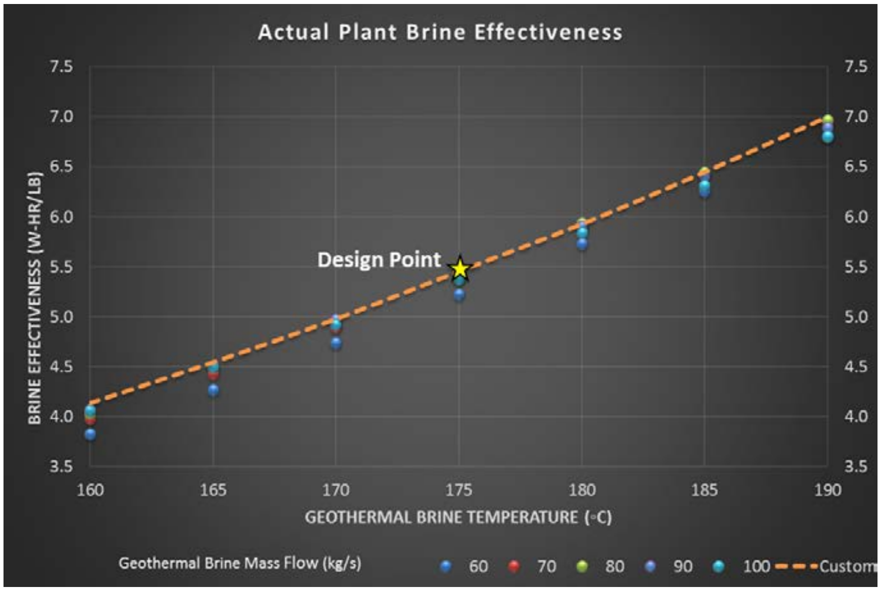


Figure 18 Actual Plant Brine Effectiveness

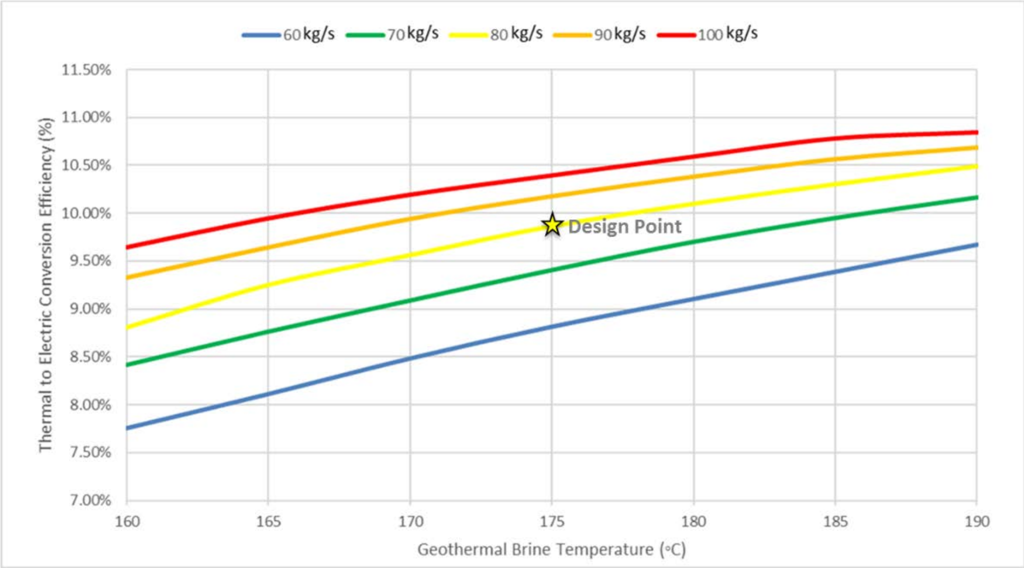


Figure 19 Thermal to electric conversion efficiency for 5 MWe ORC turbine

6 Economic Analysis

We focused on monetizing the processes developed in power plant performance modeling for our economic analysis, which helped us to convert performance calculations and power output into a DCF analysis of plant operations and financing, thereby creating representative techno-economic models of a total geothermal power plant. We used SAM and performed DCF analysis of standard and custom design turbines using results from IPSEpro over the range of geothermal resource temperatures and flow rates of interest. We applied the base case inputs for geothermal resource to SAM inputs and established a base case model (Table 5). A single owner PPA financial model was selected for financial analysis.

Table 5 Base Case Geothermal Resource Characterization for SAM financial Model

Parameter	Unit	Value
Resource Temperature	C	175
Reservoir pressure change per 1000 lb	psi-h	0.35
Reservoir Depth	m	2000
Temperature Decline Rate	%/yr.	0.3
Number of Production Wells	-	1
Production Well Flow Rate	kg/s	80
Number of Injection Wells	-	1

To compare projects and results on a common basis, the “exact number of wells” option is chosen in SAM and the number of production wells is set at one. For the base case, this results in a gross turbine output power capacity (nameplate capacity) of ~5 MW, so that the power plant cost values from the MSP analysis can be used.

SAM allows the user to set “Plant Efficiency (%)”, which sets the plant BE as a percentage of the Maximum Brine Effectiveness (limit from GETEM). Setting Plant Efficiency to 100% gives plant with BE equal to the maximum brine effectiveness. Setting Plant Efficiency to 50% gives a plant with brine effectiveness equal to 50% of max BE. Using this data, we back-calculated the Plant Efficiency needed to match BE values from IPSEpro runs. We set the binary plant efficiency to 65.1% to match to IPSEpro BE results in w-hr/lb for the base case.

We developed system cost scenarios for custom design and standard design turbines. The SAM version of GETEM does not currently include the ability to automatically estimate plant cost, but the Excel version of GETEM does. Therefore, we used GETEM to estimate the plant costs and imported those values in SAM. For the custom design scenarios, the plant size and efficiency results from the IPSEpro model were used as inputs to GETEM to estimate the plant costs. Plant costs in GETEM are determined by estimating the individual costs for the major plant components (turbine, heat exchangers, condenser and working fluid pump) and using a direct-cost multiplier to account for piping, instrumentation, etc. and construction costs. This value was then used as the input for the “Specified Plant Cost” in SAM. For the standard design scenarios, the same individual component costs and direct cost multiplier were used, but the turbine cost was decreased by $150/kW to reflect the cost savings from using a standard turbine design (see Table 4). Results from IPSEpro were used as the BE (plant efficiency) inputs in SAM for the custom and standard scenarios to account for the reduced efficiency of the standard turbine (compared to the custom turbine) when it operates at off-design conditions.

For the DCF analysis, we developed a business model with standard financial assumptions for all scenarios (Table 6). Changes in financial parameters would affect the NPV of costs. The simplest business model is a 100% equity model in which the developer pays cash for the project at the time of start of operations. In this case, the standard turbine is not competitive compared to a custom turbine. Realistically, the more you defer costs to the future (debt) or offset costs in the future (depreciation, tax advantages), the more the custom turbine design would be favored. In our model, we selected 60% debt ratio to optimize NPV calculations.

Table 6 Financial parameters for SAM Model

Parameter	Unit	Value
PPA price	¢/kWh	10.00
Annual escalation rate	%	1.00
IRR Target	years	20.00
Project debt ratio	%	60.00
Real discount rate	%/yr	5.5
Inflation rate	%	2.5
Nominal Discount Rate	%/yr	8.15
Annual interest rate	%	7.00
Incentives (PTC/ITC)	$	0.00
Depreciation Structure (5 Years MACRS)	%	100.00

6.1 Decision Criteria used in SAM Financial Model

The decision criteria of the SAM financial model are functions of:

- Electricity generated
- PPA price
- Analysis period
- Project equity investment amount
- Annual project costs
- Discount rate

PPA price is the bid price in a power purchase agreement (PPA) and is the price that the project receives for each unit of electricity that the system generates. Levelized PPA uses the discount rate to determine the present value of the project's PPA revenue over its lifetime. For the PPA models, SAM assumes that the project sells all the electricity generated by the system at a price negotiated through a power purchase agreement (PPA). A financially viable project is likely to have a levelized cost that is equal to or less than the levelized PPA price to cover project costs and meet internal rate of return (IRR) requirements.

The internal rate of return (IRR) is a measure of the project's profitability and is defined as the nominal discount rate that corresponds to a net present value of zero (Mendelsohn et al, 1995; Short et al, 2012). Using "Specify IRR Target" makes SAM uses a search algorithm to find the PPA price required to meet the target IRR. SAM reports IRRs and NPVs for the project.

The NPV is the present value of the after-tax cash flow discounted to year one using the nominal discount rate. PPA price determines annual revenue. Net capital cost is the sum of the total installed cost and debt, other financing fees, and reserve funding from the Financial Parameters page, less investment-based and capacity-based incentives. SAM also allows the user to specify parameters for up to five construction loans to approximate interest during construction (IDC) that SAM considers to be a cost to the project. The Project Term Debt input variables determine the size of debt or amount borrowed and debt-related costs. Real Discount Rate is a measure of the time value of money expressed as an annual percentage. SAM's financial model results are very sensitive to the real discount rate input (Mendelsohn et al, 1995; Short et al, 2012).

The levelized cost of Electricity (LCOE) calculator uses a simple method to calculate the project's LCOE. The user provides the installation cost, operating costs, and a fixed charge rate as input, and the model calculates the LCOE based on the annual energy generated by the system. The calculator can also calculate the fixed charge rate when you provide basic financial parameters. The list of financial parameters which are required to calculate financial outputs can be found in Table 7.

Table 7 Summary of financial parameters used to calculate financial outputs

	PPA (revenue)	Discount Rate	Project Costs	Expenditures	Electricity Generation	IRR Target Year	Analysis Period
IRR	X		X	X		X	
NPV	X	X	X	X			X
LCOE	X	X	X	X	X		X
Levelized PPA	X	X			X		X

6.2 SAM Model Results and Discussions

To start with, we ran the SAM model for the custom design and standard design turbine for the base case (175 °C temperature and 80 kg/s mass flow rate), where it is assumed that the standard and custom turbine designs have identical performance. Net electricity generation capacity is used to calculate annual revenue from electricity sales. The results showed that the standard design turbines provide savings at the net capital cost and result in a higher NPV and IRR for the project at the given base case conditions (Table 8). While the net capital cost saving may reach up to +$2,312,300, the difference between the NPV of standard design and custom design turbines could reach up to +$1,440,410.

Table 8 Comparison of SAM financial model results for custom and standard design scenarios

Metric		Custom Design (Base Case)	Standard Design (Base Case)
Levelized COE (nominal)	¢/kWh	10.49	9.82
Levelized COE (real)	¢/kWh	8.13	7.61
Net present value (NPV)	$	$1,346,430	$2.786.840
Internal rate of return (IRR)	%	7.20%	11.99%
Year IRR is achieved	year	20	20
IRR at end of project	%	10.03%	13.66%
Net capital cost (NCC)	$	$24,456,800	$22,144,500
Equity	$	$9,782,720	$8,857,800
Size of debt	$	$14,674,080	$13,286,700
NCC Difference	$		**+$2,312,300**
NPV Difference	$		**+$1,440,410**

Then, we extended the financial analysis over 63 off-design cases by changing inlet geothermal brine temperature (between 160 °C and 190 °C) and inlet mass flow rate (between 40 kg/s and 120 kg/s). The standard turbine's power generation capacity is taken as 5 MW with off design power outputs ranging between 1.4 MW and 6.9 MW gross. The results for standard turbines operating at off-design conditions showed that:

- Net capital cost in $/kW significantly decreases with respect to increasing geothermal brine temperature and mass flow rate (Figure 20).

- The standard turbines are competitive over a wide range of temperatures and flow rates and give positive NPV for cases near the design point (Figure 21)

- Standard turbines are more cost effective than custom turbines near the design point, and less cost effective away from it. Because the standard turbine cannot perform at higher isentropic efficiency than the custom turbine. It can only be equal or less.

- The NPV difference between standard and custom design scenarios show 45 of 63 test cases that resulted in positive values where standard design turbines are favorable (Figure 22).

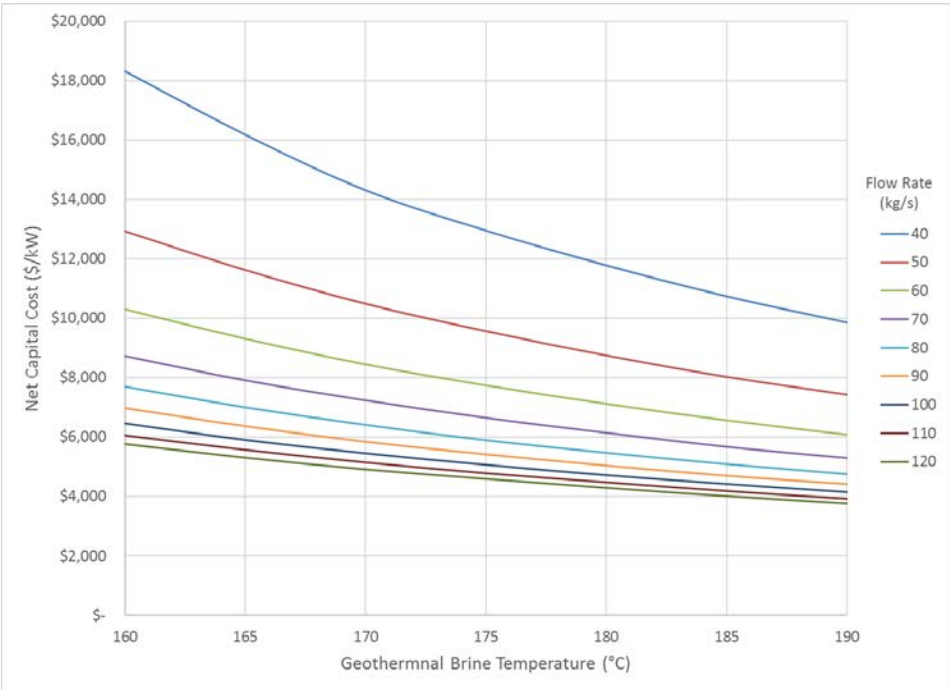


Figure 20 Net capital cost per kW for different off-Design cases of the standard turbine

Using a standard turbine design results in an NPV that is higher than using a custom turbine design over a large range of geothermal brine temperatures and flow rates, as shown in Figure 22. The highest relative NPV results tend to be at elevated geothermal brine temperatures and flow rates. The figure does not consider practical limitations on the power output from the standard turbine. The actual output from the model can be much larger than the design output of 5,000 kW as shown in Figure 23. In practice, a turbine would not be able to operate at this high an output above its design point. We do not have the technical information to estimate exactly what the cut off output would be for the standard design, but we can conclude that a large portion of the upper right part of Figure 22 is not in the practical operating range of the standard turbine design. Turbine manufacturers and project developers should keep these limitations in mind when evaluating the results of this study.

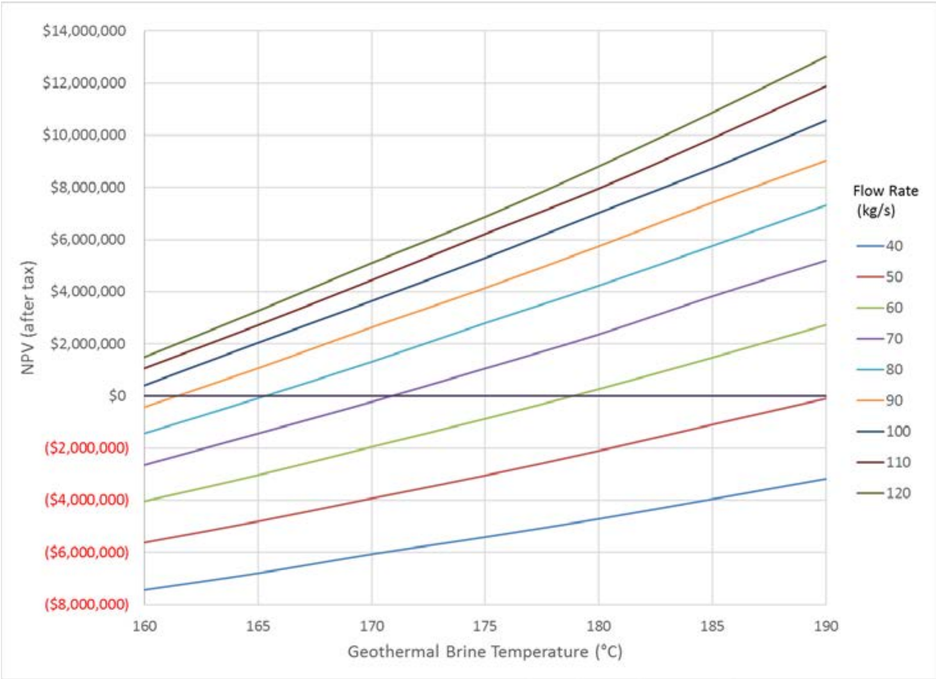


Figure 21 NPV after tax for different off-design cases of the standard turbine

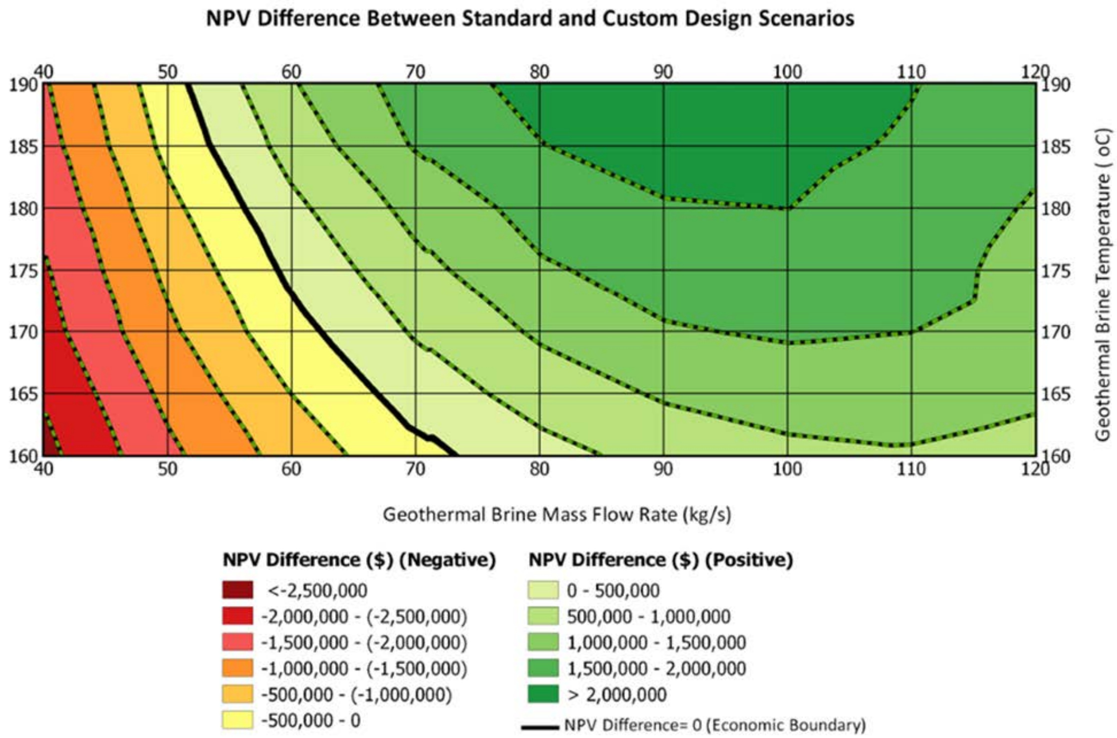


Figure 22 NPV difference between custom and standard design scenarios for given resource conditions. Green colored areas with positive values represent cases where standard design turbines are favorable. Black solid line represents the economic boundary of standard turbines where NPV difference is zero.

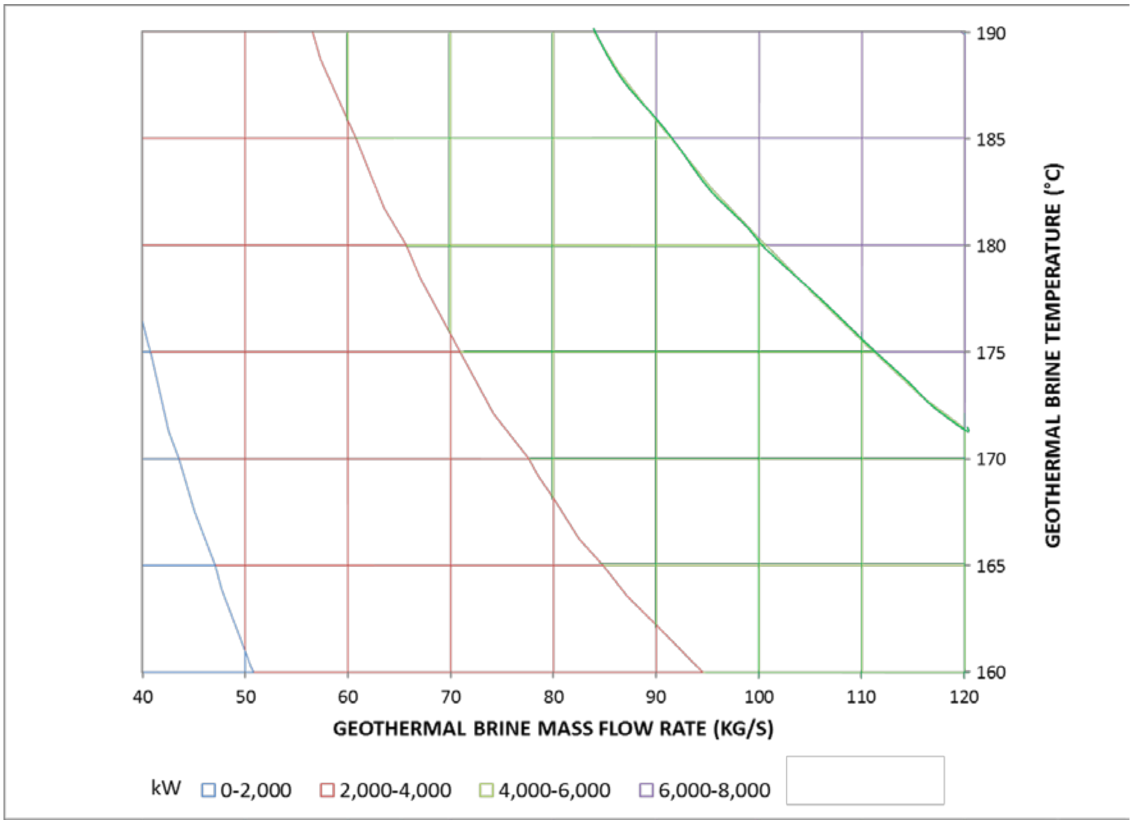


Figure 23 Standard turbine design gross turbine output in kW as a function of geothermal brine temperature and flow rate. Standard turbine design output (nameplate capacity) is 5,000 kW.

6.2.1 Sensitivity Analysis

As described in Section 5, we did not have access to a full turbine performance curve for this analysis. Therefore, the results above are only illustrative of the relative costs and performance of standard and custom turbine designs. Although we did not have the data to accurately model off-design turbine performance, we did have the information necessary to determine the relative efficiency at which a standard turbine design is cost competitive with a custom turbine design. We conducted a sensitivity analysis on the impact of turbine performance on the NPV of the power plant. We iteratively varied geothermal brine temperature and flow rate to calculate the isentropic turbine efficiency at the break-even NPV point (Figure 23). In other words, we set the relative isentropic efficiency of the turbine to achieve the NPV of the custom plant equal the NPV of the plant with a standard turbine. This is the economic boundary between the standard design and custom design turbines.

For the sensitivity analysis, 63 test case scenarios are taken, and 1008 observation points are generated for different relative isentropic efficiencies with respect to the design point ranging between 85% and 100%. The results for select cases (minimum, design, and maximum geothermal brine temperature and flow rates) are shown in Figure 24 and for all cases in Figure 25. In these figures, the standard turbine design is cost competitive at a given relative isentropic efficiency if the NPV difference (standard design NPV minus custom design NPV) is positive. There is a large range of relative isentropic efficiencies over which the standard turbine design is cost competitive for the maximum and design geothermal brine temperatures and flow rates (Figure 24). For the lowest geothermal brine flow rate and temperature, the standard design is not competitive, even at 100% relative efficiency.

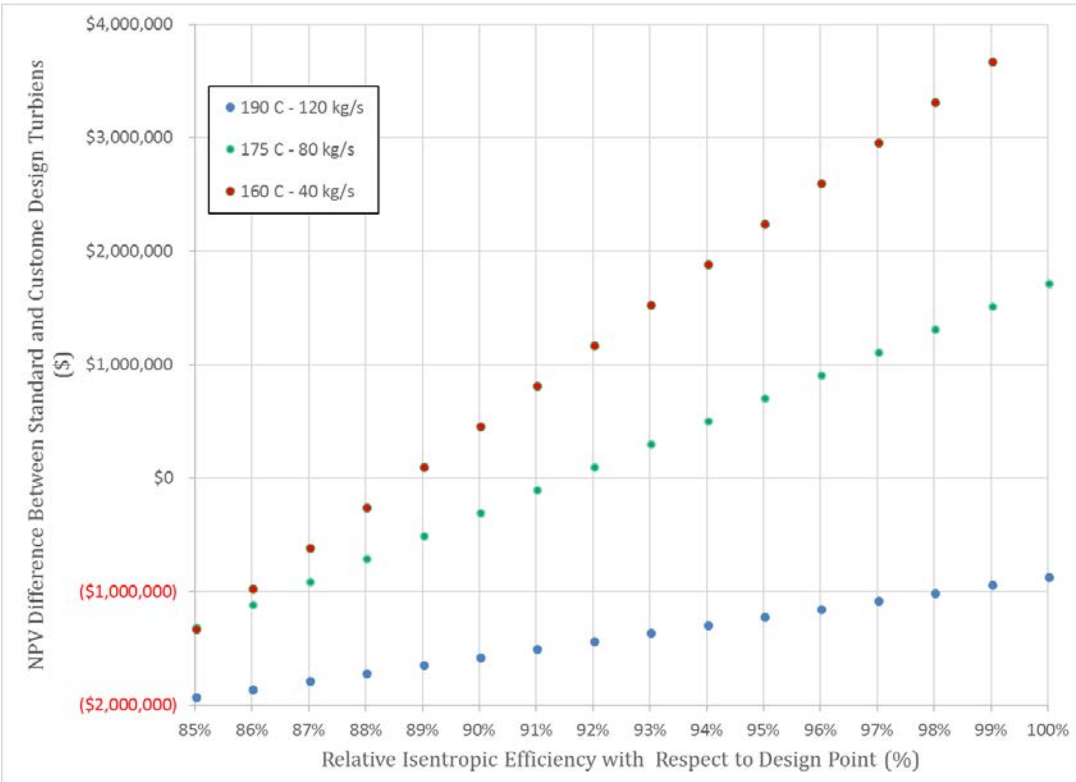


Figure 24. Sensitivity analysis for NPV difference with respect to relative isentropic efficiencies for select cases

The correlation between the NPV difference vs. relative efficiency is linear (Figure 25). By fitting a linear curve to each case and calculating the relative efficiency where the NPV is zero, we determined the breakeven isentropic efficiency for each case, or the relative isentropic efficiency of the standard turbine necessary to make the project cost competitive with a custom turbine design.

The results of this analysis are shown in Figure 26. The results showed that the NPV of the project is sensitive to turbine isentropic efficiency. This also implies that a detailed turbine efficiency analysis is needed for more precise economic analysis.

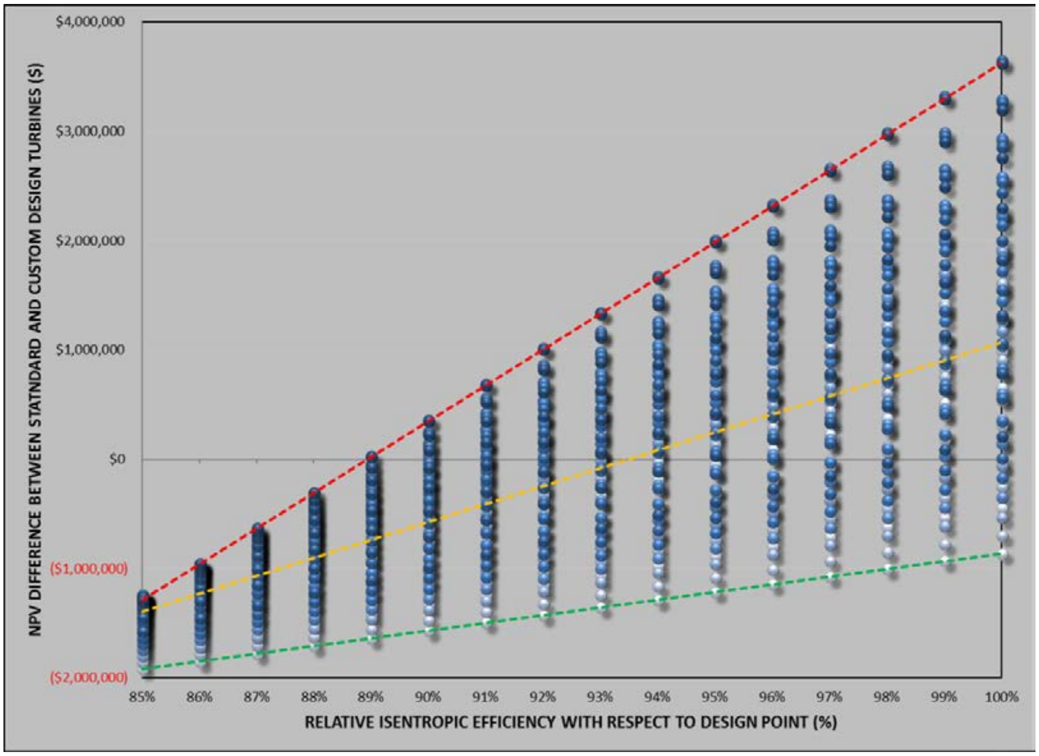


Figure 25 Sensitivity analysis for NPV difference with respect to relative isentropic efficiencies for all cases (Green, yellow and red dashed lines represent the lower limit, median and upper limit respectively.)

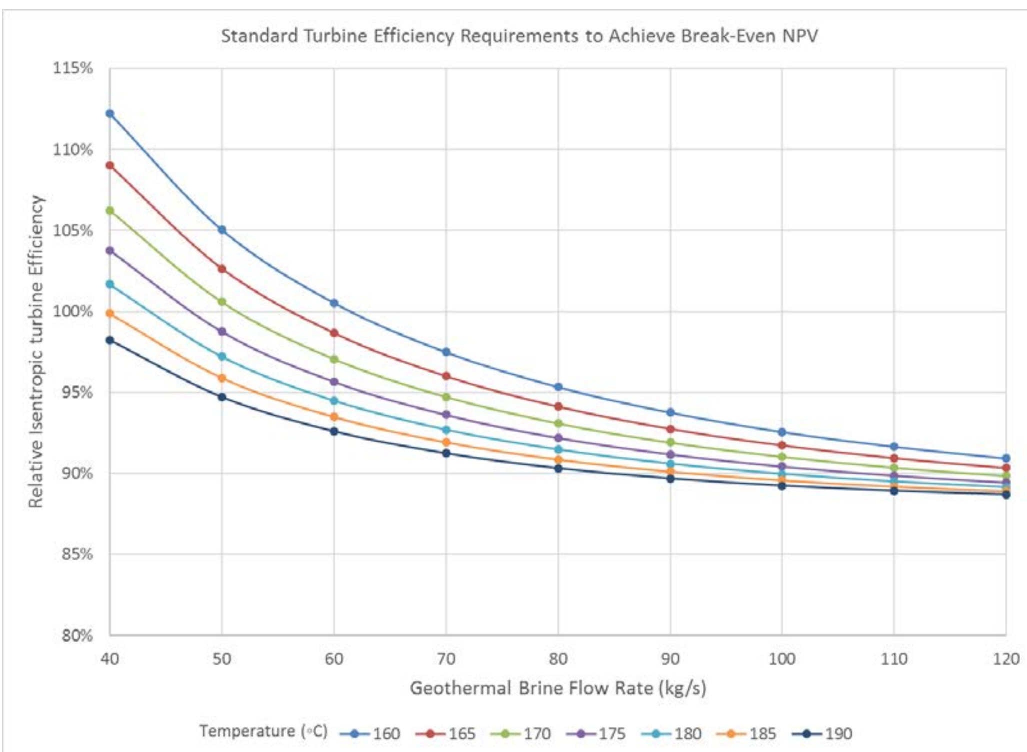


Figure 26 The required isentropic efficiency of the standard turbine relative to a custom turbine to get a break-even NPV.

Figure 26 shows that for lower temperature and flow rates, a standard turbine requires an isentropic efficiency greater than zero to be cost competitive. The reason for this is illustrated by Figure 27, which shows the total plant cost savings from using a standard turbine design vs. a custom turbine design for each case. The standard turbine cost is fixed for each case, while the custom turbine cost depends on its size and efficiency. At low geothermal brine temperatures and flow rates, where the plant power output is lower, the plant cost for the custom turbine is lower than for the standard turbine because of the small turbine size. To compensate, the standard turbine would have to operate at a higher efficiency and generate more electricity than the custom turbine to be cost competitive. This illustrates that at some point, building a smaller custom turbine at a higher $/kW cost offsets the cost savings from a standard (but oversized) turbine. This is the type of information that a manufacturer would need to consider when deciding on what sizes or design power generation capacity to choose for a series of standard turbine designs.

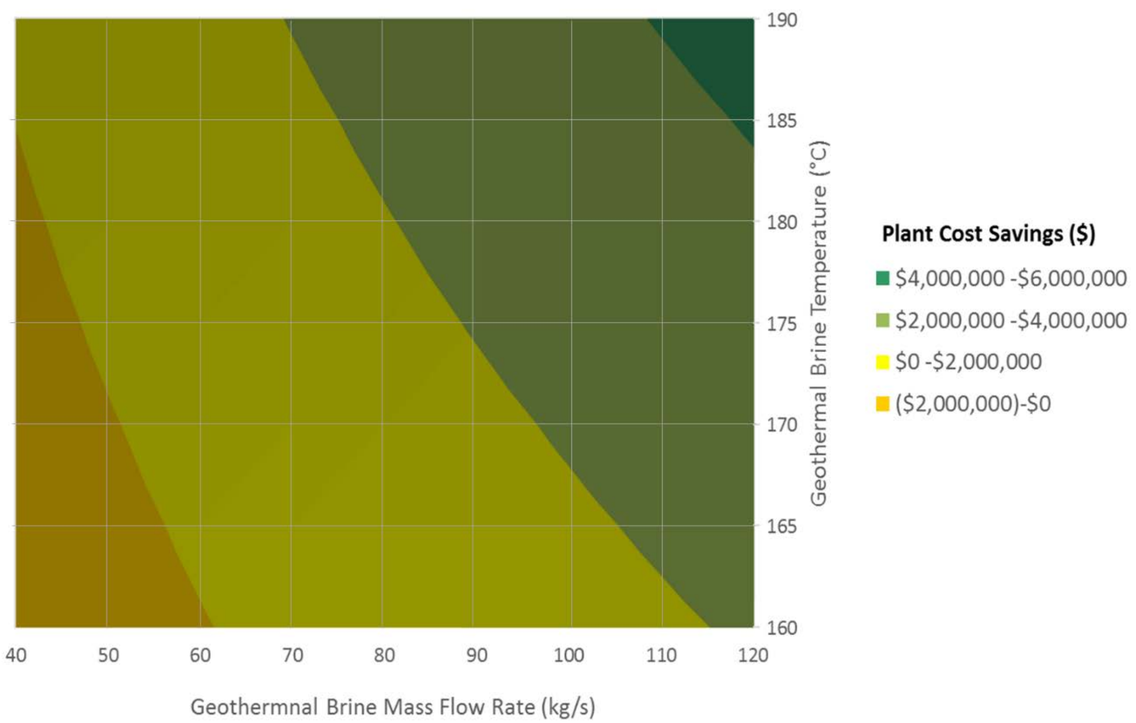


Figure 27 Plant cost savings (standard minus custom) as a function of geothermal brine temperature and flow rate

7 Discussions and Conclusions

Currently, the geothermal turbine market is driven by developer demand for plant efficiency and consists of custom turbines designed specifically for the varying conditions encountered at different geothermal fields. Some degree of custom design may always be required. For example, geothermal steam turbines often require custom materials due to corrosion issues at different sites. However, the MSP analysis in this study showed that even applying a standard design to a relatively small number of units, as few as five, can have significant cost savings. The MSP calculations and sensitivity analysis for 1 MWe and 5 MWe turboexpanders and a 20 MWe steam turbine showed that MSP could highly vary between 893 $/kW and 30 $/kW based on turbine size, standardization and volume of manufacturing. The analysis also showed that the economy of scale applies both to the size of the turbine and the number manufactured in a single run. As an example, the unit price of a 5 MW standard design turbine could be 150 $/W cheaper than the custom design. Sensitivity analysis showed that the main costs are associated with labor and D&E for a custom designed unit. Manufacturing costs decrease significantly with volume due to shorter machine set up time, and D&E is spread among multiple units. There is a significant opportunity for turbine manufacturers to realize manufacturing cost savings due to labor and D&E by switching from custom to standard design at larger volumes. If manufacturers at all steps of the supply chain can successfully operate their facilities similar to the presented manufacturing model, it could result in up to 60% manufacturing cost savings. While the manufacturing cost model developed in this study is limited to the turbine component of a geothermal power plant, it can also be applied to other important components such as heat exchangers and air-cooled condensers.

In practice, a standard turbine design would likely operate at off-design conditions, resulting in lower efficiencies, less electricity generation, and less revenue than a custom turbine design. The second half of the study focused on determining whether and under what conditions the upfront capital cost savings from a standard turbine design could offset future revenue losses. To compare the economics of standard and custom turbine designs, we developed a model of a 5 MW geothermal power plant project using a standard turbine design optimized to maximize power generation for a 175 °C, 80 kg/s geothermal resource. Then, we varied the geothermal resource over a range of temperatures and flow rates and compared power generation of the standard turbine operating at off-design conditions to a custom turbine operating a constant isentropic efficiency. We used these performance calculations and power output results in a DCF analysis of plant operations, costs and financing. The results of off-design performance analysis and financial calculations showed that NPV for lower efficiencies and decreased electricity generation from a standard turbine operating at off-design conditions could be higher than the NPV for a standard unit size to be undersized for a given resource versus a custom designed turbine. The results showed that the net capital cost savings from a standard design vs. a custom design turbine at the standard turbine design point for the modeled 5 MW case study may reach up to $2.3 million, while the difference in NPV could reach up to $1.4 million. For this study, we did not have an accurate turbine performance curve to assess off-design turbine performance. Instead, we used information relating turbine efficiency to working fluid flow rate to approximate off-design performance. The trends from that analysis show that standard turbine designs could be competitive over a wide range of temperatures and flow rates. A calculation of the standard turbine efficiencies at off-design conditions that give the same NPV as a project using a custom turbine showed that the range of off-design efficiencies support this conclusion.

The study shows that developing and using standard turbine designs may be an effective strategy for lowering geothermal power project costs. Ideally, these turbines would be designed to be flexible and operate over a wide range of conditions with minimal decreases in efficiency. The strategy requires that multiple turbines be built at once and then warehoused until sold. The study did not take into account the cost of financing and storing turbines until they are purchased for a project. A significant barrier to implementing this strategy is the demand for these technologies at high volumes. However, as the global geothermal market continues to grow, opportunities in new markets will continue to increase. The emerging geothermal markets discussed above show that there may be an opportunity for using standardized turbines to reduce plant capital costs.

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Appendix: List of Global Geothermal Power Plants

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Germany	Traunereut	2015	5.5	Binary	Geothermischen Kraftwerksgesellschaft Traunreut mbH (GKT)	Turboden	Italy
Japan	Oguni Matsuya	2015	0.06	Binary	N/A	Toshiba	Japan
Japan	Tsuchiyu onsen	2015	0.4	Binary	Tsuchiyu Onsen Energy Co.	ORMAT	Israel
Japan	Sugawara Binary Cycle	2015	5.5	Binary	Kyushu Electric Power	Turboden	Italy
Turkey	Alasehir 1-2	2015	45	Single Flash	ZORLU	Toshiba	Japan
Turkey	Tosunlar	2015	3.81	Binary	Akca Holding	EXERGY	Italy
Turkey	Umurlu 1-2	2015	12	Binary	Karadeniz Holding	EXERGY	Italy & Turkey
Turkey	Pamukoren-2	2015	22.5	Binary	Çelikler Jeotermal Elektrik	Atlas Copco, EXERGY	USA
Turkey	Efe-2	2015	22.5	Binary	GURIS	ORMAT	Israel
Turkey	Efe-3	2015	22.5	Binary	GURIS	ORMAT	Israel
Turkey	Efe-4	2015	22.5	Binary	GURIS	ORMAT	Israel
Turkey	Babadere	2015	8	Binary	MTN Enerji	ORMAT	Israel
USA	Don A. Campbell (Wild Rose) II	2015	22.5	Binary	ORMAT	ORMAT	Israel
USA	McGinness Expansion	2015	48	Binary	ORMAT	ORMAT	Israel
Kenya	Olkaria GEG (OW 914)	2015	27.8	Single Flash	Green Energy Group (GEG)	Hindustan Turbomacinery	India
Kenya	Olkaria GEG (OW43)	2015	12.8	Single Flash	KenGen	Hindustan Turbomacinery	India
Japan	Tsuchiyu onsen	2015	0.4	Binary	Tsuchiyu onsen energy Co.	ORMAT	Israel
Mexico	Los Azufres III - 1	2015	53	Single Flash	Comision Federal de Electricidad	Mitsubishi	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Paisley	2014	2	Binary	Surprise Valley Electric Co.	TAS	USA
USA	OIT-2	2014	1.5	Binary	OIT	Pratt & Whitney	USA
Kenya	Olkaria I unit-4	2014	70	Single Flash	KenGen	Toyota Tsusho	Japan
Kenya	Olkaria I unit-5	2014	70	Single Flash	KenGen	Toyota Tsusho	Japan
Kenya	Olkaria III	2014	40	Binary	ORMAT	ORMAT	Israel
Kenya	Olkaria IV	2014	70	Single Flash	KenGen	Toyota Tsusho	Japan
Kenya	Olkaria IV	2014	70	Single Flash	KenGen	Toyota Tsusho	Japan
Turkey	Yilmazkoy (Ken Kipas)	2014	24	Binary	KIPAS	EXERGY	Italy
Turkey	Alasehir	2014	24	Binary	Turkeler	ORMAT	Israel
Turkey	Kerem	2014	24	Binary	MAREN	ORMAT	Israel
Kenya	Olkaria3-Plant3	2014	24	Binary	ORMAT	ORMAT	Israel
Turkey	Kizildere-2 Binary	2014	20	Binary	ZORLU	TAS	USA
Turkey	Dora3-U2	2014	17	Binary	MENDERES	ORMAT	Israel
Turkey	Gumuskoy-2	2014	6.6	Binary	BM	TAS (repowerd by ORMAT)	USA
Germany	Oberhaching-Laufzorn / Grünwald	2014	4.3	Binary	Daldrup & Sohne AG (EGS)	Atlas Copco/Energas, GMK	Germany
Japan	Hagenoyu	2014	2	Binary	Keiyo Plant Engineering Co, Waita Geothermal Power Plant, Chuo Electric Power Co	Toshiba	Japan
Japan	Ibusuki	2014	1.5	Binary	Geonext Co.	ORMAT	Israel
Japan	Beppu Spring	2014	0.5	Binary	N/A	Toshiba	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Japan	Goto-en	2014	0.09	Binary	N/A	Toshiba	Japan
Japan	Yumura Spring	2014	0.03	Binary	N/A	Kawasaki	Japan
Japan	Shichimi Spring	2014	0.02	Binary	N/A	Kawasaki	Japan
Kenya	Olkaria III	2014	18	Binary	N/A	ORMAT	Israel
Kenya	Olkaria GEG (OW37)	2014	5	Single Flash	N/A	Hindustan Turbomacinery	India
Germany	Taufkirchen/ Oberhaching	2014	4	Binary	N/A	Atlas Copco/Energas, GMK	Germany
Germany	Sauerlach	2014	5	Binary	N/A	Turboden	Italy
Turkey	Gümüsköy-1	2014	6.6	Binary	BM	TAS (Repowerd by ORMAT)	USA
Indonesia	Cibuni	2014	2	Single Flash	PLN	Elliot TurboMachinery	USA
Indonesia	Ndunga	2014	5	Single Flash	PLN	Elliot TurboMachinery	USA
Indonesia	Ulumbu	2014	10	Single Flash	PLN	Elliot TurboMachinery	USA
Indonesia	Patuha Unit 1	2014	55	Single Flash	PT. Geo Dipa Energy	Toshiba	Japan
Italy	Bagnore 4	2014	40	Single Flash	Enel Green Power	Ansaldo/Tosi	Italy
Philippines	Nasulo	2014	49.4	Single Flash	Energy Development Corporation	Fuji	Japan
USA	Patua	2013	48	Binary	Gradient Resources	TAS	USA
USA	Lightening Dock	2013	4.4	Binary	Cyrq Energy	Kaishan	China
USA	Don A. Campbell	2013	22.5	Binary	N/A	ORMAT	Israel
USA	Cove Fort 1-2	2013	25	Binary	N/A	ORMAT	Israel
Nicaragua	San Jacinto-Tizate	2013	36	Single Flash	N/A	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Turkey	Efe-1	2013	47.4	Double Flash	N/A	Mitsubishi	Japan
Turkey	Kizildere-2	2013	60	Double Flash	N/A	Fuji	Japan
Germany	Durrhaar	2013	7	Binary	N/A	Turboden	Italy
Turkey	Pamukören-1	2013	67.5	Binary	Çelikler Jeotermal Elektrik	Atlas Copco, EXERGY	USA
Turkey	Dora3-U1	2013	17	Binary	MENDERES	ORMAT	Israel
USA	Desert Peak (EGS)	2013	1.7	Binary	N/A	ORMAT	Israel
Germany	Kirchstockach	2013	7	Binary	N/A	Turboden	Italy
USA	Chena-2	2013	0.4	Binary	N/A	Turboden	Italy
Australia	Habanero-EGS	2013	1	Binary	N/A	Siemens	Germany
Japan	Abo-tunnel	2013	0.003	Binary	N/A	Kawasaki	Japan
USA	Mammoth Complex Repowering	2013	7.5	Binary	ORMAT	ORMAT	Israel
Indonesia	Mataloko	2013	2.5	Single Flash	PLN	Elliot TurboMachinery	USA
Mexico	Los Humeros II Phase 2	2013	26.7	Single Flash	Comision Federal de Electricidad	Alstom	Mexico
New Zealand	Ngatamariki	2013	82	Binary	Mighty River Power	ORMAT	Israel
New Zealand	Te Mihi	2013	166	Double Flash	Contact Energy	Toshiba	Japan
New Zealand	TOPP1	2013	25	Binary	Nagati Tuwharetoa Geothermal	ORMAT	Israel
Philippines	Maibarara	2013	20	Single Flash	Maibarara Geothermal (JV PetroEnergy, Trans-Asia Oil, and PNOC Renewables)	Fuji	Japan
Nicaragua	San Jacinto-Tizate	2012	36	Single Flash	Ram Power	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Hudson Ranch I	2012	50	Triple Flash	EnergySource	Fuji	Japan
Germany	Dürrnhaar	2012	5.5	Binary	Municipality Germany	Turboden	Italy
Germany	Insheim	2012	4.3	Binary	Municipality Germany	Turboden	Italy
USA	McGinness Hill	2012	48	Binary	ORMAT	ORMAT	Israel
USA	Tuscarora	2012	24	Binary	ORMAT	ORMAT	Israel
Turkey	DENIZ	2012	24	Binary	MAREN	ORMAT	Israel
Turkey	SINEM	2012	24	Binary	MAREN	ORMAT	Israel
USA	Neal Hot Springs	2012	33	Binary	US Geothermal	TAS	USA
USA	San Emidio	2012	12	Binary	US Geothermal	TAS	USA
Germany	Sauerlach	2012	5	Binary	Municipality Germany	Turboden	Italy
Japan	Niigata	2012	2	Binary	Wasabi	EcoGen	USA
USA	Florida Canyon Mine	2012	0.1	Co-Production	Electratherm	Electratherm	USA
Romania	Oradea	2012	0.5	Binary	Electratherm	Electratherm	USA
Taiwan	Qingshui	2012	0.1	Binary	SSNE (Kalina Cycle)	Energent Turbine	USA
China	YangYi-2	2012	0.4	Binary	Jiangxi HuanDian Electric Co.	Jiangxi HuanDian Electric Co.	China
Indonesia	Ulumbu	2012	2.5	Single Flash	Pertamina Geothermal Energy	Elliot TurboMachinery	USA
Indonesia	Ulumbu	2012	2.5	Single Flash	Pertamina Geothermal Energy	Elliot TurboMachinery	USA
Indonesia	Ulubelu Unit 1	2012	55	Dry Steam	PLN	Fuji	Japan
Indonesia	Ulubelu Unit 2	2012	55	Dry Steam	PLN	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Italy	Bagnore 3 Binary	2012	1	Binary	Enel Green Power	Exergy	Italy
Italy	Rancia 2	2012	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
USA	Dixie Valley Binary	2012	6.2	Binary	Terra Gen	TAS	USA
Mexico	Los Humeros	2012	26.7	Single Flash	Comision Federal de Electricidad	Alstom	Mexico
China	Yangyi	2011	0.9	Single Flash	Jiangxi Huadian Electric	Jiangxi HuanDian Electric Co.	China
Kenya	Eburru	2011	2.5	Single Flash	KenGen	Elliot Turbomachinery	USA
Costa Rica	Las Pailas	2011	21	Binary	Instituto Costarricense de	ORMAT	Israel
Costa Rica	Las Pailas	2011	21	Binary	Instituto Costarricense de	ORMAT	Israel
Turkey	IREM	2011	20	Binary	MAREN	ORMAT	Israel
USA	Puna Expansion	2011	12	Binary	ORMAT	ORMAT	Israel
USA	Beowave-2	2011	3.6	Binary	Beowawe Power Terra Gen	TAS	USA
China	YangYi-1	2011	0.5	Binary	Jiangxi HuanDian Electric Co.	Jiangxi HuanDian Electric Co.	China
Indonesia	Lahendong Unit 4	2011	20	Single Flash	Pertamina Geothermal Energy	Fuji	Japan
Iceland	Hellisheidi 5	2011	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Hellisheidi 5	2011	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Italy	Chiusdino 2	2011	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Nuova Radicondoli	2011	20	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Kenya	Olkaria II	2010	35	Single Flash	KenGen	Mitsubishi	Japan
USA	Jersey Valley	2010	22.5	Binary	ORMAT	ORMAT	Israel

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Turkey	Dora-2	2010	9.5	Binary	MENDERES	ORMAT	Israel
Turkey	Tuzla	2010	7.5	Binary	Dardanel	ORMAT	Israel
China	Longyuan	2010	1	Binary	Longyuan Co	Longyuan Co	China
China	North Oil Field (Huabei)	2010	0.4	Binary	Jiujiang Power	Jiujiang Power	China
Italy	Chiusdino 1	2010	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Radicondoli 2	2010	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Kenya	Olkaria II	2010	35	Single Flash	KenGen	Mitsubishi	Japan
New Zealand	Nga Awa Purua	2010	139	Triple Flash	Mighty River Power	Fuji	Japan
New Zealand	Te Huka	2010	23	Binary	Top Energy	ORMAT	Israel
Kenya	Olkaria III	2009	52	Binary	ORMAT (upgraded)	ORMAT	Israel
Turkey	Germencik (Galip Hoca)	2009	47.4	Double Flash	GURMAT	Mitsubishi	Japan
USA	OIT-1	2009	0.3	Binary	OIT	Pratt & Whitney	USA
USA	Faulkner	2009	63.9	Binary	Nevada Geothermal	ORMAT	Israel
USA	Stillwater	2009	47.3	Binary	Enel Green Power	Atlas Copco / Mafi-Trench	USA
USA	Salt Wells	2009	18.1	Binary	Enel Green Power	Atlas Copco / Mafi-Trench	USA
USA	Thermo Hot Spring	2009	14	Binary	Raser Technologies	Turboden	Italy
Germany	Unterhaching	2009	3.4	Binary	Municipality (Kalina Cycle)	Siemens	Germany
Germany	Bruchsal	2009	0.55	Binary	Municipality (Kalina Cycle)	Energent Turbine	USA
Indonesia	Lahendong Unit 3	2009	20	Single Flash	PLN	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Indonesia	Wayang Windu Unit 2	2009	117	Single Flash	Star Energy Ltd	Fuji	Japan
Italy	Nuova Lagoni Rossi	2009	20	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Sasso 2	2009	20	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
USA	North Brawley	2008	50	Binary	ORMAT	ORMAT	Israel
USA	Galena III	2008	30	Binary	ORMAT	ORMAT	Israel
USA	Raft River	2008	18	Binary	US Geot hermal	ORMAT	Israel
El Salvador	Berlin	2008	9.4	Binary	LaGeo/Enel Green Power	Enex-GE-Rotoflow	USA
Turkey	Kizildere Binary (Bereket)	2008	6.8	Binary	BEREKET	ORMAT	Israel
France	Soultz-sous-Forêts	2008	1.5	Binary	European EGS Interest	Turboden	Italy
USA	Heber South	2008	16	Binary	ORMAT	ORMAT	Israel
Indonesia	Darajat	2008	110	Dry Steam	Chevron	Mitsubishi	Japan
Indonesia	Lahendong Unit 2	2008	20	Single Flash	PLN	Fuji	Japan
Iceland	Hellisheidi 3	2008	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Hellisheidi 3	2008	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
New Zealand	Kawerau	2008	95.72	Double Flash	Mighty River Power	Fuji	Japan
New Zealand	KA24	2008	8.3	Binary	Savage Papakainga Trust	ORMAT	Israel
New Zealand	Ngawha 2	2008	15	Binary	Top Energy	ORMAT	Israel
Papua New Guinea	Lihir	2007	20	Single Flash	Lihir Gold Ltd mine	General Electric	USA
Nicaragua	San Jacinto-Tizate	2007	10	Back Pressure	Polaris	Alstom	France

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Germany	Landau	2007	3	Binary	Municipality	ORMAT	Israel
Guatemala	Amatitlán	2007	24	Binary	ORMAT	ORMAT	Israel
USA	Galena II	2007	13.5	Binary	ORMAT	ORMAT	Israel
USA	Blundell-2	2007	12	Binary	Pacific Corporation	ORMAT	Israel
USA	GEM Bottoming Cycle	2007	9	Binary	ORMAT	ORMAT	Israel
Kenya	Oserian	2007	2	Binary	Oserian Flower co	Elliot Turbomachinery	USA
USA	Steamboat Hills	2007	5.5	Binary	ORMAT	ORMAT	Israel
USA	Ormesa II (Upgrade)	2007	4.3	Binary	ORMAT	ORMAT	Israel
Indonesia	Kamojang Unit 4	2007	60	Dry Steam	PLN	Fuji	Japan
Indonesia	Sibayak	2007	5.65	Single Flash	Dizamatra Powerindo	Harbin	China
Indonesia	Sibayak	2007	5.65	Single Flash	Dizamatra Powerindo	Harbin	China
Iceland	Hellisheidi 2b	2007	33	Single Flash	Orkuveita Reykjavikur	Toshiba	Japan
Mexico	Los Humeros	2007	5	Back Pressure	Comision Federal de Electricidad	Mitsubishi	Japan
New Zealand	Mokai 3	2007	17	Binary	Tuaropaki Power Co.	ORMAT	Israel
Russia	Mendeleevskaya	2007	1.8	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Russia	Okeanskaya	2007	1.8	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Russia	Okeanskaya	2007	1.8	Single Flash	SC Geotherm	Kaluga Turbine	Russia
El Salvador	Berlin	2006	44	Single Flash	LaGeo/Enel Green Power	General Electric	USA
USA	Desert Peak II (Brady Complex)	2006	26	Binary	ORMAT	ORMAT	Israel

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Portugal	Pico Vermelho	2006	13.5	Binary	Electricidade dos Açores	ORMAT	Israel
USA	Goulds-1	2006	10.5	Binary	ORMAT	ORMAT	Israel
Turkey	Dora-1	2006	7.9	Binary	MENDERES	ORMAT	Israel
Japan	Hatchobaru	2006	2	Binary	Kyushu Electric Power	ORMAT	Israel
USA	Chena-1	2006	0.7	Binary	Chena Hot Springs	Turboden	Italy
Iceland	Hellisheidi 1	2006	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Hellisheidi 2a	2006	45	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Reykjanes Unit 2	2006	50	Single Flash	Hitaveita Sudurnesja & HS Orka	Fuji	Japan
Japan	Kirishima Geotherm	2006	0.22	Binary	Fuji	Fuji	Japan
Japan	Suginoi	2006	1.9	Single Flash	Suginoi Hotel	Fuji	Japan
Papua New Guinea	Lihir	2005	30	Single Flash	Lihir Gold Ltd mine	General Electric	USA
USA	Goulds-2	2005	16	Binary	ORMAT	ORMAT	Israel
USA	Galena I (Richard Burdett)	2005	30	Binary	ORMAT	ORMAT	Israel
Guadalope	Bouillante 2	2005	11	Single Flash	ORMAT	Alstom	France
Iceland	Nesjavellir	2005	30	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Reykjanes Unit 1	2005	50	Single Flash	Geothermie Bouilante	Fuji	Japan
Iceland	Svartsengi Unit 6	2005	33	Dry Steam	Hitaveita Sudurnesja & HS Orka	Fuji	Japan
Italy	Nuova Larderello	2005	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Nuova San Martino	2005	40	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
New Zealand	Mokai 2	2005	19	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 2	2005	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 2	2005	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 2	2005	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 2	2005	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Wairakei Binary	2005	14.4	Binary	Contact Energy	ORMAT	Israel
USA	Brady (Brady Complex)	2004	5.3	Binary	ORMAT	Ormat	Israel
Kenya	Oserian	2004	2	Binary	Oserian Flower co	ORMAT	Israel
New Zealand	Tasman BP	2004	8	Back Pressure	Norske Skog Tasman	Elliot TurboMachinery	USA
Russia	Goryachii Plyazh	2004	2.6	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Russia	Mutnovskaya	2004	50	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Kenya	Olkaria II	2003	35	Single Flash	KenGen	Mitsubishi	Japan
USA	Ormesa I (Ormesa Complex)	2003	26.2	Binary	ORMAT	Ormat	Israel
Costa Rica	Miravalles 5	2003	17	Binary	Instituto Costarricence de Electricidad	ORMAT	Israel
Mexico	Los Azufres	2003	26.5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Los Azufres	2003	26.5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Los Azufres	2003	26.5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Los Azufres	2003	26.5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Los Humeros	2003	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
New Zealand	Rotokawa	2003	6	Binary	Mighty River Power	ORMAT	Israel
Indonesia	Lahendong Unit 1	2002	20	Single Flash	PLN	Alstom	France
Austria	Altheim	2002	1	Binary	Marktgemeinde Altheim GmbH	Turboden	Italy
Italy	Nuova Gabbro	2002	20	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Nuova Lago	2002	10	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Nuova Molinetto	2002	20	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Nuova Monterotondo	2002	10	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Nuova Radicondoli	2002	40	Dry Steam	Enel Green Power	General Electric- Nuovo Pignone	Italy
Italy	Nuova Serrazzano	2002	60	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Sesta	2002	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Travale 4	2002	40	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Mexico	Las Tres Virgenes	2002	5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Las Tres Virgenes	2002	5	Single Flash	Comision Federal de Electricidad	Alstom	France
Mexico	Las Tres Virgenes	2002	2	Binary	Comision Federal de Electricidad	ORMAT	Israel
Austria	Blumau	2001	0.2	Binary	Municipality	Ormat	Israel
Iceland	Nesjavellir	2001	30	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Papua New Guinea	Lihir	2001	6	Single Flash	Lihir Gold Ltd mine	General Electric	USA
USA	CE Turbo	2000	11.5	Single Flash	CalEnergy Generation	Fuji	Japan
USA	Salton Sea V	2000	58.32	Double Flash	CalEnergy Generation	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Indonesia	Wayang Windu Unit 1	2000	110	Single Flash	Star Energy Ltd	Fuji	Japan
Costa Rica	Miravalles 3	2000	29.5	Single Flash	Instituto Costarricence de Electricidad	Mitsubishi	Japan
Iceland	Husavik Kalina	2000	2	Binary	Orkuveita Husavikur	Enex-GE-Rotoflow	USA
Italy	Nuova Castelnuovo	2000	14.5	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Travale 3	2000	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Japan	Kuju	2000	0.99	Single Flash	Kuju Kanko Hotel	Kawasaki	Japan
Mexico	Cerro Prieto 4	2000	25	Single Flash	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Cerro Prieto 4	2000	25	Single Flash	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Cerro Prieto 4	2000	25	Single Flash	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Cerro Prieto 4	2000	25	Single Flash	Comision Federal de Electricidad	Mitsubishi	Japan
Russia	Pauzhetskaya	2000	11	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Russia	Verkhne-Mutnovskaya	2000	4	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Indonesia	Darajat	1999	95	Dry Steam	Chevron	Mitsubishi	Japan
El Salvador	Berlin I Unit 1	1999	28.12	Single Flash	LaGeo	Fuji	Japan
El Salvador	Berlin I Unit 2	1999	28.12	Single Flash	LaGeo	Fuji	Japan
Ethiophia	Aluto-Langano 1-2	1999	7.5	Binary	Ethiopian Electric Power Corporation	ORMAT	Israel
Guatemala	Zunil	1999	24	Binary	ORMAT	ORMAT	Israel
Guadalope	Bouillante 1	1999	4	Double Flash	ORMAT	Alstom	France
Iceland	Svartsengi Unit 5	1999	30	Single Flash	Hitaveita Sudurnesja & HS Orka	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Japan	Hachijojima	1999	3.3	Single Flash	Tokyo Electric Power	Fuji	Japan
New Zealand	Mokai 1	1999	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 1	1999	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 1	1999	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 1	1999	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 1	1999	5	Binary	Tuaropaki Power Co.	ORMAT	Israel
New Zealand	Mokai 1	1999	30	Single Flash	Tuaropaki Power Co.	ORMAT	Israel
Nicaragua	Momotombo	1999	22	Single Flash	Momotombo Power Group	Ansaldo/Tosi	Italy
Philippines	Mindanao 2	1999	52.4	Double Flash	FDC Misamis	Mitsubishi	Japan
Russia	Verkhne-Mutnovskaya	1999	4	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Indonesia	Dieng	1998	60	Single Flash	PT. Geo Dipa Energy	Ansaldo/Tosi	Italy
Costa Rica	Miravalles 2	1998	55	Single Flash	Instituto Costarricence de Electricidad	Ansaldo/Tosi	Italy
Iceland	Nesjavellir	1998	30	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Iceland	Nesjavellir	1998	30	Single Flash	Orkuveita Reykjavikur	Mitsubishi	Japan
Italy	Bagnore 3	1998	20	Single Flash	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Carboli 1	1998	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
New Zealand	Ngawha	1998	5	Binary	Top Energy	ORMAT	Israel
New Zealand	Ngawha	1998	5	Binary	Top Energy	ORMAT	Israel
Philippines	Bacman LowLoad	1998	1.5	Single Flash	National Power Corporation	Mitsubishi	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Russia	Verkhne-Mutnovskaya	1998	4	Single Flash	SC Geotherm	Kaluga Turbine	Russia
Indonesia	Gunung Salak	1997	60	Single Flash	PLN	Fuji	Japan
Indonesia	Gunung Salak-IPP Unit 4	1997	55	Single Flash	Chevron	Fuji	Japan
Indonesia	Gunung Salak-IPP Unit 5	1997	55	Single Flash	Chevron	Fuji	Japan
Indonesia	Gunung Salak-IPP Unit 6	1997	55	Single Flash	Chevron	Fuji	Japan
Iceland	Krafla	1997	30	Double Flash	Geothermie Bouilante	Mitsubishi	Japan
Italy	Carboli 2	1997	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Monteverdi 1	1997	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Monteverdi 2	1997	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Selva	1997	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
New Zealand	Rotokawa	1997	14	Single Flash	Mighty River Power	General Electric	USA
Philippines	Mahanagdong A-Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Mahanagdong A-Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Mahanagdong B-Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Mahanagdong B-Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Malitbong \ Bottoming Binary	1997	16.7	Binary	Energy Development Corporation	ORMAT	Israel
Philippines	Tongonan 1 - Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Tongonan 1 - Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Tongonan 1 - Binary	1997	6.5	Binary	Energy Development Corporation	Ormat	Israel

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Philippines	Mahanagdong A	1997	60	Single Flash	Energy Development Corporation	Toshiba	Japan
Philippines	Mahanagdong A	1997	60	Single Flash	Energy Development Corporation	Toshiba	Japan
Philippines	Mahanagdong B	1997	60	Single Flash	Energy Development Corporation	Toshiba	Japan
Philippines	Malitbong Unit 1	1997	77.5	Single Flash	Energy Development Corporation	Fuji	Japan
Philippines	Malitbong Unit 2	1997	77.5	Single Flash	Energy Development Corporation	Fuji	Japan
Philippines	Malitbong Unit 3	1997	77.5	Single Flash	Energy Development Corporation	Fuji	Japan
Indonesia	Sibayak	1996	2	Back Pressure	Pertamina Geothermal Energy	Kawasaki	Japan
Italy	Le Prata	1996	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Nuova Sasso	1996	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Japan	Takigami	1996	27.5	Single Flash	Kyushu Electric Power	Mitsubishi	Japan
Japan	Kakkonda	1996	30	Single Flash	Tohoku Electric Power	Toshiba	Japan
Japan	Ogiri	1996	30	Single Flash	Kyushu Electric Power	Mitsubishi	Japan
USA	Salton Sea IV	1996	51	Double Flash	CalEnergy Generation	General Electric	USA
New Zealand	Poihipi	1996	55	Dry Steam	Contact Energy	Fuji	Japan
Philippines	Upper Mahiao-1	1996	34.12	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Upper Mahiao-2	1996	34.12	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Upper Mahiao-3	1996	34.12	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Upper Mahiao-4	1996	34.12	Binary	Energy Development Corporation	Ormat	Israel
Philippines	Upper Mahiao Binary	1996	5.5	Binary	Energy Development Corporation	Ormat	Israel

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Costa Rica	Miravalles Boca de pozo	1995	5	Single Flash	Instituto Costarricence de Electricidad	Mitsubishi	Japan
Italy	Farinello	1995	60	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Japan	Yamakawa	1995	30	Single Flash	Kyushu Electric Power	Mitsubishi	Japan
Japan	Sumikawa	1995	50	Single Flash	Tohoku Electric Power	Mitsubishi	Japan
Japan	Yanaizu-Nishiyama	1995	65	Single Flash	Tohoku Electric Power	Toshiba	Japan
Philippines	Mak-Ban D	1995	20	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban D	1995	20	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban E	1995	20	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban E	1995	20	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mindanao 1	1995	52.4	Single Flash	FDC Misamis	Mitsubishi	Japan
Indonesia	Darajat	1994	55	Dry Steam	Chevron	Mitsubishi	Japan
Indonesia	Gunung Salak	1994	60	Single Flash	PLN	Ansaldo/Tosi	Italy
Indonesia	Gunung Salak	1994	60	Single Flash	PLN	Ansaldo/Tosi	Italy
Costa Rica	Miravalles 1	1994	55	Single Flash	Instituto Costarricence de Electricidad	Toshiba	Japan
Italy	Cornia 2	1994	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Piancastagnaio 5	1994	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Japan	Uenotai	1994	28.8	Single Flash	Tohoku Electric Power	Toshiba	Japan
Mexico	Los Humeros	1994	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy
Philippines	Mak-Ban Binary1	1994	3	Binary	Aboitiz Power Corp	Ormat	Israel

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Philippines	Mak-Ban Binary1	1994	3	Binary	Aboitiz Power Corp	Ormat	Israel
Philippines	Mak-Ban Binary2	1994	3	Binary	Aboitiz Power Corp	Ormat	Israel
Philippines	Mak-Ban Binary2	1994	3	Binary	Aboitiz Power Corp	Ormat	Israel
Philippines	Mak-Ban Binary3	1994	3	Binary	Aboitiz Power Corp	Ormat	Israel
Philippines	Mak-Ban Binary3	1994	0.75	Binary	Aboitiz Power Corp	Ormat	Israel
Philippines	Bacman 2 (Cawayan)	1994	20	Single Flash	National Power Corporation	Mitsubishi	Japan
Philippines	Palimpinon 2 (Sogongon)	1994	20	Single Flash	National Power Corporation	Fuji	Japan
Philippines	Palimpinon 2 (Sogongon)	1994	20	Single Flash	National Power Corporation	Fuji	Japan
Philippines	Palimpinon 2 Unit 2 (Nasuji)	1994	20	Single Flash	National Power Corporation	Fuji	Japan
Portugal	Ribeira Grande	1994	15	Binary	Electricidade dos Açores	ORMAT	Israel
USA	Heber II (Heber Complex) Second Imperial	1993	48	Binary	Ormat	Ormat	Israel
Philippines	Bacman 1	1993	60	Single Flash	National Power Corporation	Ansaldo/Tosi	Italy
Philippines	Bacman 1	1993	60	Single Flash	National Power Corporation	Ansaldo/Tosi	Italy
Philippines	Palimpinon 2 Unit 1 (Okoy)	1993	20	Single Flash	National Power Corporation	Fuji	Japan
China	Yangbajian North Unit-4	1992	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
USA	Brady Hot Spring (Brady Complex)	1992	26.1	Double Flash	Ormat	ORMAT	Israel
USA	Puna	1992	35	Binary	Ormat	Ormat	Israel
USA	Steamboat 2 (Steamboat Complex)	1992	18.2	Binary	Ormat	Ben Holt	USA

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Steamboat 3 (Steamboat Complex)	1992	18.2	Binary	Ormat	Ben Holt	USA
Mexico	Los Azufres	1992	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Makrotek	Italy
Mexico	Los Humeros	1992	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy
China	Yangbajian North Unit-3	1991	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
Italy	Piancastagnaio 4	1991	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Valle Secolo	1991	60	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Italy	Valle Secolo	1991	60	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
USA	Soda Lake 2	1991	18	Binary	Cyrq Energy	Ormat	Israel
Mexico	Los Humeros	1991	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy
Mexico	Los Humeros	1991	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy
Italy	Piancastagnaio 3	1990	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
Japan	Hatchobaru Unit 2	1990	55	Double Flash	Kyushu Electric Power	Mitsubishi	Japan
USA	Mammoth II (Mammoth Complex)	1990	40	Binary	Ormat	Ben Holt	USA
USA	Leathers	1990	35.8	Double Flash	CalEnergy Generation	Fuji	Japan
USA	Salton Sea II	1990	20	Double Flash	CalEnergy Generation	Mitsubishi	Japan
Mexico	Los Azufres	1990	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Japan
Mexico	Los Humeros	1990	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy
Mexico	Los Humeros	1990	5	Back Pressure	Comision Federal de Electricidad	Ansaldo/Tosi	Italy

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
China	Yangbajian North Unit-2	1989	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Iceland	Svartsengi Binary	1989	1.2	Binary	Hitaveita Sudurnesja & HS Orka	ORMAT	Israel
Japan	Takenaka Corp.	1989	0.045	Single Flash	Takenaka Corp.	Fuji	Japan
USA	Aidlin Unit 1	1989	12.5	Dry Steam	Calpine	Fuji	Japan
USA	Aidlin Unit 2	1989	12.5	Dry Steam	Calpine	Fuji	Japan
USA	Honey Lake	1989	1.5	Binary	HL Power Company	General Electric	USA
USA	Del Ranch (Hoch)	1989	35.8	Double Flash	CalEnergy Generation	Fuji	Japan
USA	Elmore	1989	35.8	Double Flash	CalEnergy Generation	Fuji	Japan
USA	GEM II (Ormesia Complex)	1989	21.6	Double Flash	Ormat	Mitsubishi	Japan
USA	GEM III (Ormesia Complex)	1989	21.6	Double Flash	Ormat	Mitsubishi	Japan
USA	Navy II Unit 1	1989	30	Double Flash	Terra Gen	Fuji	Japan
USA	Navy II Unit 2	1989	30	Double Flash	Terra Gen	Fuji	Japan
USA	Navy II Unit 3	1989	30	Double Flash	Terra Gen	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Salton Sea III	1989	54	Double Flash	CalEnergy Generation	Mitsubishi	Japan
New Zealand	Ohaaki	1989	46	Single Flash	Contact Energy	Mitsubishi	Japan
New Zealand	Ohaaki	1989	11.2	Back Pressure	Contact Energy	Mitsubishi	Japan
New Zealand	Ohaaki	1989	11.2	Back Pressure	Contact Energy	General Electric	USA
Thailand	Fang	1989	0.3	Binary	Electricity Generating Authority of Thailand	ORMAT	Israel
China	Yangbajian North Unit-1	1988	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
USA	Amedee (Wendel)	1988	3	Binary	Amedee Geothermal Venture (Oski Energy)	Barber Nichols	USA
USA	Ormesa IH (Ormesa Complex)	1988	8.8	Binary	Ormat	Ormat	Israel
USA	Steamboat IA (Steamboat Complex)	1988	2	Binary	Ormat	Ormat	Israel
USA	Bear Canyon	1988	24.4	Dry Steam	Calpine	Mitsubishi	Japan
USA	BLM Unit 1	1988	30	Double Flash	Terra Gen	Fuji	Japan
USA	BLM Unit 2	1988	30	Double Flash	Terra Gen	Fuji	Japan
USA	BLM Unit 3	1988	30	Double Flash	Terra Gen	Fuji	Japan
USA	Dixie Valley	1988	60.5	Double Flash	Terra Gen	Fuji	Japan
USA	Steamboat Hills	1988	14.6	Single Flash	Ormat	ORMAT	Israel
USA	West Ford Flat	1988	38	Dry Steam	Calpine	Mitsubishi	Japan
Mexico	Los Azufres	1988	50	Single Flash	Comision Federal de Electricidad	General Electric	Japan
New Zealand	Ohaaki	1988	46	Single Flash	Contact Energy	Mitsubishi	Japan
Indonesia	Kamojang	1987	55	Dry Steam	PLN	Mitsubishi	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Indonesia	Kamojang	1987	55	Dry Steam	PLN	Mitsubishi	Japan
Italy	Pianacce	1987	20	Dry Steam	Enel Green Power	Ansaldo/Tosi	Italy
USA	Soda Lake 1	1987	5.1	Binary	Cyrq Energy	Ormat	Israel
USA	Wabuska II	1987	1.6	Binary	Home Stretch Geothermal	Ormat	Israel
USA	Navy I	1987	102.4	Double Flash	Terra Gen	Fuji	Japan
USA	Ormesa II (Ormesa Complex)	1987	24	Double Flash	Ormat	Mitsubishi	Japan
Mexico	Cerro Prieto 2	1987	110	Double Flash	Comision Federal de Electricidad	Toshiba	Japan
China	Yangbajian North Unit-5	1986	3.18	Double Flash	Electric Power Tibet	Fuji	Japan
USA	Steamboat I	1986	2.4	Binary	Ormat	Ormat	Israel
USA	Vulcan	1986	40	Double Flash	CalEnergy Generation	Mitsubishi	Japan
Mexico	Cerro Prieto 2	1986	110	Double Flash	Comision Federal de Electricidad	Toshiba	Japan
Mexico	Cerro Prieto 3	1986	110	Double Flash	Comision Federal de Electricidad	Toshiba	Japan
Mexico	Cerro Prieto 3	1986	110	Double Flash	Comision Federal de Electricidad	Toshiba	Japan
Mexico	Los Azufres	1986	5	Back Pressure	Comision Federal de Electricidad	Toshiba	Japan
Kenya	Olkaria I	1985	15	Single Flash	KenGen	Mitsubishi	Japan
China	Yangbajian South Unit-3	1985	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
USA	Wineagle	1985	0.7	Binary	Wineagle Development	Barber Nichols	USA
USA	Beowawe	1985	17	Double Flash	Terra Gen	Mitsubishi	Japan
USA	Bottle Rock	1985	55	Dry Steam	AltaRock Energy Inc	Fuji	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Grant	1985	118	Dry Steam	Calpine	Toshiba	Japan
USA	Heber I (Heber Complex)	1985	52	Double Flash	Ormat	Mitsubishi	Japan
USA	NCPA II	1985	110	Dry Steam	Northern California Power Agency	Toshiba	Japan
USA	Quicksilver	1985	118	Dry Steam	Calpine	Toshiba	Japan
Turkey	Kizildere-1	1984	15	Double Flash	ZORLU	Ansaldo/Tosi	Italy
USA	Wabuska I	1984	1.6	Binary	Home Stretch Geothermal	Ormat	Israel
USA	Blundell 1	1984	26.1	Single Flash	Pacific Corporation	General Electric	USA
USA	Calistoga	1984	110	Dry Steam	Calpine	Toshiba	Japan
Philippines	Mak-Ban C	1984	55	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban C	1984	55	Single Flash	Aboitiz Power Corp	Mitsubishi	Japan
USA	NCPA I No. 2	1983	110	Dry Steam	Northern California Power Agency	Fuji	Japan
USA	Socrates	1983	118	Dry Steam	Calpine	Toshiba	Japan
USA	Sonoma	1983	78	Dry Steam	Calpine	Mitsubishi	Japan
Indonesia	Kamojang	1983	30	Dry Steam	PLN	Mitsubishi	Japan
Japan	Kirishima International	1983	0.1	Single Flash	Kirishima International	Fuji	Japan
Philippines	Palimpinon I Unit 1	1983	37.5	Single Flash	National Power Corporation	Fuji	Japan
Philippines	Palimpinon I Unit 2	1983	37.5	Single Flash	National Power Corporation	Fuji	Japan
Philippines	Palimpinon I Unit 3	1983	37.5	Single Flash	National Power Corporation	Fuji	Japan
Philippines	Tongonan 1	1983	37.5	Double Flash	Unified Leyte Geothermal Energy, Inc. (ULGEI) (turned over from PSALM)	Mitsubishi	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Philippines	Tongonan 1	1983	37.5	Double Flash	Trans-Asia Oil and Energy Development Corp. (turned over from PSALM)	Mitsubishi	Japan
Philippines	Tongonan 1	1983	37.5	Double Flash	Aboitiz Energy Solutions (turned over from PSALM)	Mitsubishi	Japan
USA	Lake View	1982	118	Dry Steam	Calpine	Toshiba	Japan
USA	Salton Sea I	1982	10	Single Flash	CalEnergy Generation	Fuji	Japan
Kenya	Olkaria I	1982	15	Single Flash	KenGen	Mitsubishi	Japan
China	Yangbajian South Unit-2	1982	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
Japan	Mori	1982	25	Double Flash	Hokkaido Electric Power	Toshiba	Japan
Mexico	Cerro Prieto 1	1982	30	Double Flash	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Los Azufres	1982	5	Back Pressure	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Los Azufres	1982	5	Back Pressure	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Los Azufres	1982	5	Back Pressure	Comision Federal de Electricidad	Mitsubishi	Japan
Mexico	Los Azufres	1982	5	Back Pressure	Comision Federal de Electricidad	Mitsubishi	Japan
Philippines	Tiwi C	1982	57	Single Flash	AP Renewables Inc	Toshiba	Japan
Philippines	Tiwi C	1982	57	Single Flash	AP Renewables Inc	Toshiba	Japan
Kenya	Olkaria I	1981	15	Single Flash	KenGen	Mitsubishi	Japan
China	Yangbajian South Unit-1	1981	3	Double Flash	Electric Power Tibet	Qingdao Jieneng	China
El Salvador	Ahuachapan No. 3	1981	35	Double Flash	LaGeo	Fuji	Japan
Iceland	Svartsengi BP	1981	6	Single Flash	Hitaveita Sudurnesja & HS Orka	Fuji	Japan
USA	Sulfur Springs	1980	113	Dry Steam	Calpine	Toshiba	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
USA	Big Geyser	1980	97	Dry Steam	Calpine	General Electric	USA
Philippines	Mak-Ban B	1980	63.2	Double Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban B	1980	63.2	Double Flash	Aboitiz Power Corp	Mitsubishi	Japan
Russia	Pauzhetskaya	1980	11	Single Flash	SC Geotherm	Kaluga Turbine	Russia
USA	Cobb Creak	1979	110	Dry Steam	Calpine	Toshiba	Japan
Mexico	Cerro Prieto 1	1979	37.5	Single Flash	Comision Federal de Electricidad	Toshiba	Japan
Mexico	Cerro Prieto 1	1979	37.5	Single Flash	Comision Federal de Electricidad	Toshiba	Japan
Philippines	Mak-Ban A	1979	63.2	Double Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Mak-Ban A	1979	63.2	Double Flash	Aboitiz Power Corp	Mitsubishi	Japan
Philippines	Tiwi A	1979	60	Single Flash	AP Renewables Inc	Toshiba	Japan
Philippines	Tiwi A	1979	60	Single Flash	AP Renewables Inc	Toshiba	Japan
Iceland	Krafla	1978	30	Double Flash	Landsvirkjun	Mitsubishi	Japan
Japan	Kakkonda	1978	50	Single Flash	Tohoku Electric Power	Toshiba	Japan
Japan	Hatchobaru	1977	55	Double Flash	Kyushu Electric Power	Mitsubishi	Japan
El Salvador	Ahuachapan No. 2	1976	30	Single Flash	LaGeo	Mitsubishi	Japan
USA	Eagle Rock	1975	110	Dry Steam	Calpine	Toshiba	Japan
El Salvador	Ahuachapan No. 1	1975	30	Single Flash	LaGeo	Mitsubishi	Japan
Japan	Onikobe	1975	15	Single Flash	J-Power	Kawasaki	Japan
Japan	Onuma	1974	9.5	Single Flash	Mitsubishi Material	Mitsubishi	Japan

Country	Plant Name	Year	Capacity	Type	Project Developer/Owner/Operator	Turbine Manufacturer	Manufacturing Location
Mexico	Cerro Prieto 1	1973	37.5	Single Flash	Comision Federal de Electricidad	Toshiba	Japan
Mexico	Cerro Prieto 1	1973	37.5	Single Flash	Comision Federal de Electricidad	Toshiba	Japan
USA	Ridgeline	1972	110	Dry Steam	Calpine	Toshiba	Japan
USA	McCabe	1971	110	Dry Steam	Calpine	Toshiba	Japan
Iceland	Bjarnarflag	1969	3	Single Flash		Mitsubishi	Japan
Japan	Otake	1967	12.5	Single Flash	Kyushu Electric Power	Mitsubishi	Japan
Japan	Matsukawa	1966	23.5	Dry Steam	Tohoku Hydropower and Geothermal Energy	Toshiba	Japan
Russia	Pauzhetskaya	1966	5	Single Flash	SC Geotherm	Kaluga Turbine	Russia
New Zealand	Wairakei	1958	117	Single Flash	Contact Energy	General Electric	USA

NOTICE

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