2018 RESEARCH HIGHLIGHT IN MANUFACTURING ANALYSIS

Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines

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SUMMARY OF FINDINGS

This project analyzed the geothermal turbine market (including trade flows, detailed manufacturing costs, economies of scale, standardization, and off-design performance) to reduce the plant cost and optimize performance.

SNAPSHOT:
Standardized geothermal turbines could reduce plant capital costs.

- 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). In this new capacity, the share of flash cycle plants is 49.5% and the shares of binary cycle and dry steam plants are 38.7% and 11.8%, respectively (Bertani 2016).
- Binary cycle geothermal turbines have the greatest quantity of installations and mostly utilize organic rankine cycle (ORC) turboexpanders. Geothermal ORC power plants contributed 71% of all ORC-installed capacity in the world between 2005 and 2016 (Tartière, 2016).
- Currently, the geothermal turbine market is driven by developer demand for plant efficiency and consists of custom turbines designed specifically for the varying conditions 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.
- The minimum sustainable price (MSP) calculations and sensitivity analysis for 1-MWe and 5-MWe turboexpanders and a 20-MWe steam turbine showed that the MSP could vary greatly between $893/kW and $30/kW based on turbine size, standardization, and volume of manufacturing. If manufacturers can successfully operate their facilities with the presented manufacturing model, it could result in up to 60–70% manufacturing cost savings.
- 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. However, the upfront capital cost savings could offset future revenue losses. The results showed that the net capital cost savings from a standard design versus a custom design turbine at the standard design turbine point for the modeled 5-MW case study may reach up to $2.3 million, while the difference in net present value (NPV) could reach up to $1.4 million.

CEMAC
Clean Energy Manufacturing Analysis Center

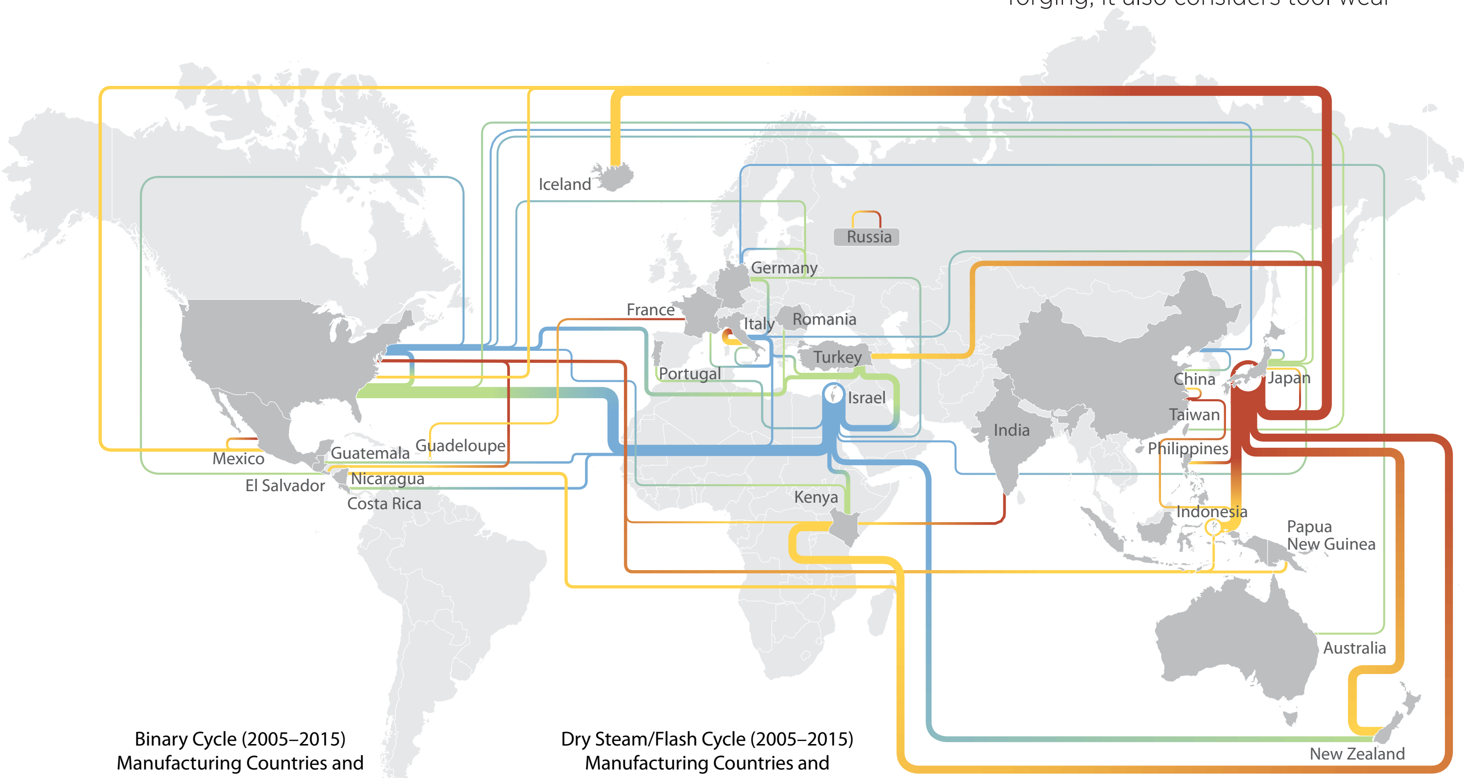
Global Value Chain and Trade Flow

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 plays an important role both as exporter and importer in the global trade flow of geothermal turbines (Figure 1).

Manufacturing Cost Model Analysis

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 Clean Energy Manufacturing Analysis Center (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 2).

To calculate the machining cost of key and high-value components, such as impellers and shafts, Design for Manufacture and Assembly (DFMA®) software was used. We produced detailed projected costs of the components, based on the volume of materials needed, the machines and process steps, machine setup time, and tooling. Tooling investment is calculated for processes such as stamping, sand casting, and forging; it also considers tool wear



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

Country	Manufact.	Exports	Imports	Installed
Israel	1,240.0	1,240.0	-	-
USA	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

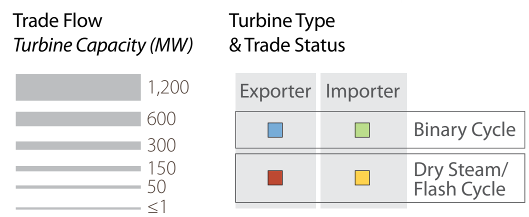


Figure 1. Global trade flow map of geothermal turbines, 2005–2015. (Akar et al, 2018; GEA 2015; GEA 2016; BNEF 2013, BNEF; 2014, BNEF; 2015, BNEF 2016; and Bertani (2016))

and lifetime. Then, we took the manufacturing cost components into a detailed financial model for the discounted cash flow (DCF) of a manufacturing facility. 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) costs; and warranty coverage (Goodrich et al. 2013).

We analyzed the manufacturing cost and MSP for three different scenarios: (1) a 1-MWe ORC turboexpander; (2) a 5-MWe ORC turboexpander; and (3) a 20-MWe steam turbine. Each scenario considered five volumes of manufacturing—1, 5, 10, 25, and 50 units/year—assuming U.S. production facilities and costs. The results of MSP analysis showed that, the manufacturing cost of a custom design 5-MW turboexpander is 21% more expensive than custom design 1-MWe Turboexpander. Also, the unit MSP per kW for the standard design turbines could be 60-70% cheaper than custom design turbines at larger volumes of manufacturing (Table 1). As an example, manufacturing unit cost ($/kW) breakdown for a typical 5-MWe geothermal ORC turboexpander, up to a volume of 50 units per year, can be found in Figure 3.

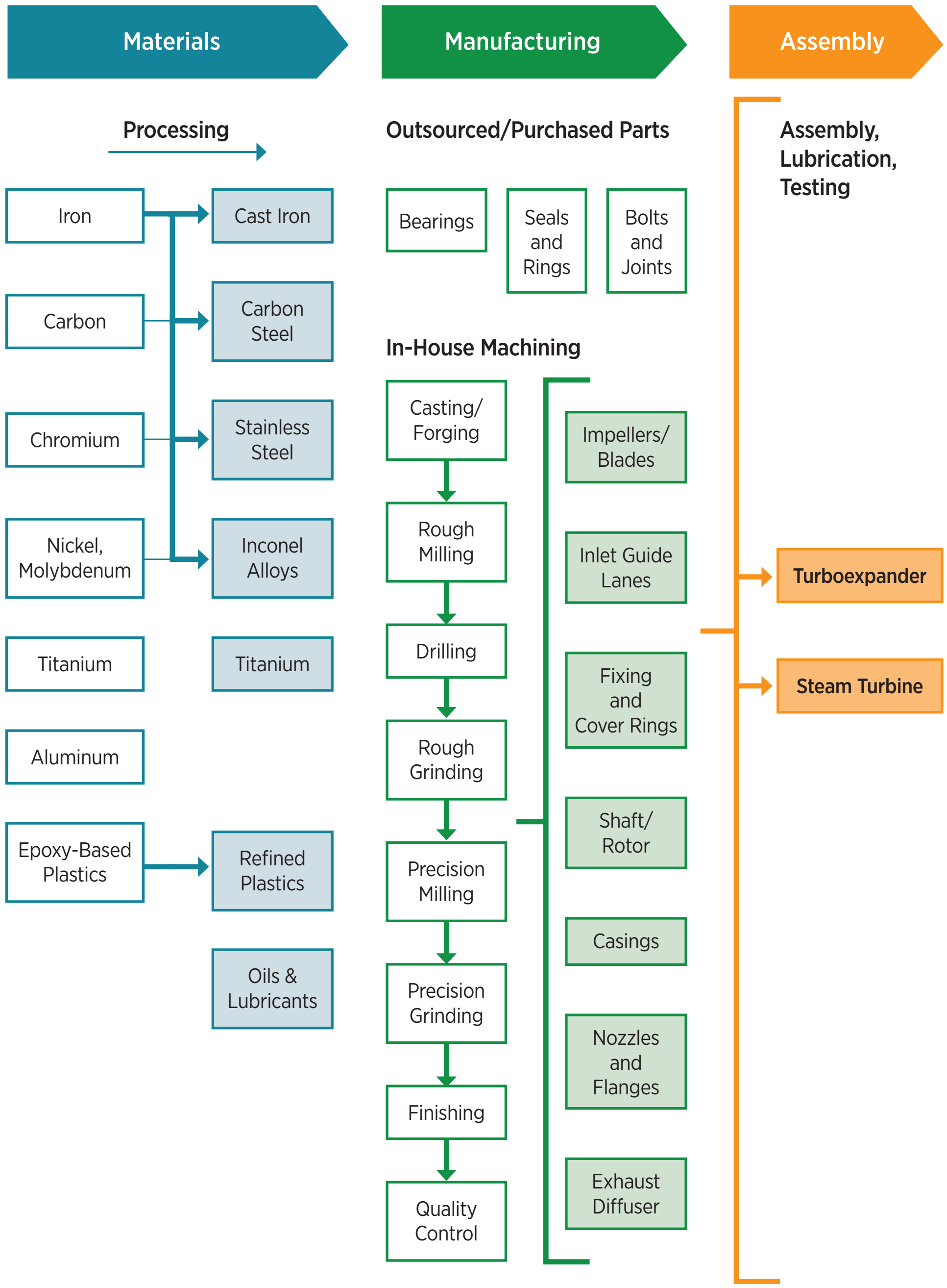


Figure 2. Manufacturing process flow diagram for geothermal power plant turbines

Table 1. 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

Performance and Economics of Standard Versus Custom Design Turbines

To determine the commercially favorable operating range of a standard ORC compared to custom design 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. We selected the design point at a 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 Balance of Plant (BOP) and operating conditions by adjusting the pressure before and after 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 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 4).

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 the System Advisor Model (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 ran SAM for the custom design and standard design turbine for the base case (175°C and 80 kg/s mass flow rate), where it is assumed that the standard and custom design turbines have identical performance. The results showed that the standard design turbines provide savings at the net capital cost and result in a higher NPV and internal rate of return (IRR) for the project at the given base case conditions (Table 2). While the net capital cost savings may reach up to +$2,312,300, the difference between the NPV of standard and custom design turbines could reach up to +$1,440,410.

We extended the financial analysis over 63 off-design cases by changing inlet geothermal brine temperature (between 160°C and 190°C) and inlet

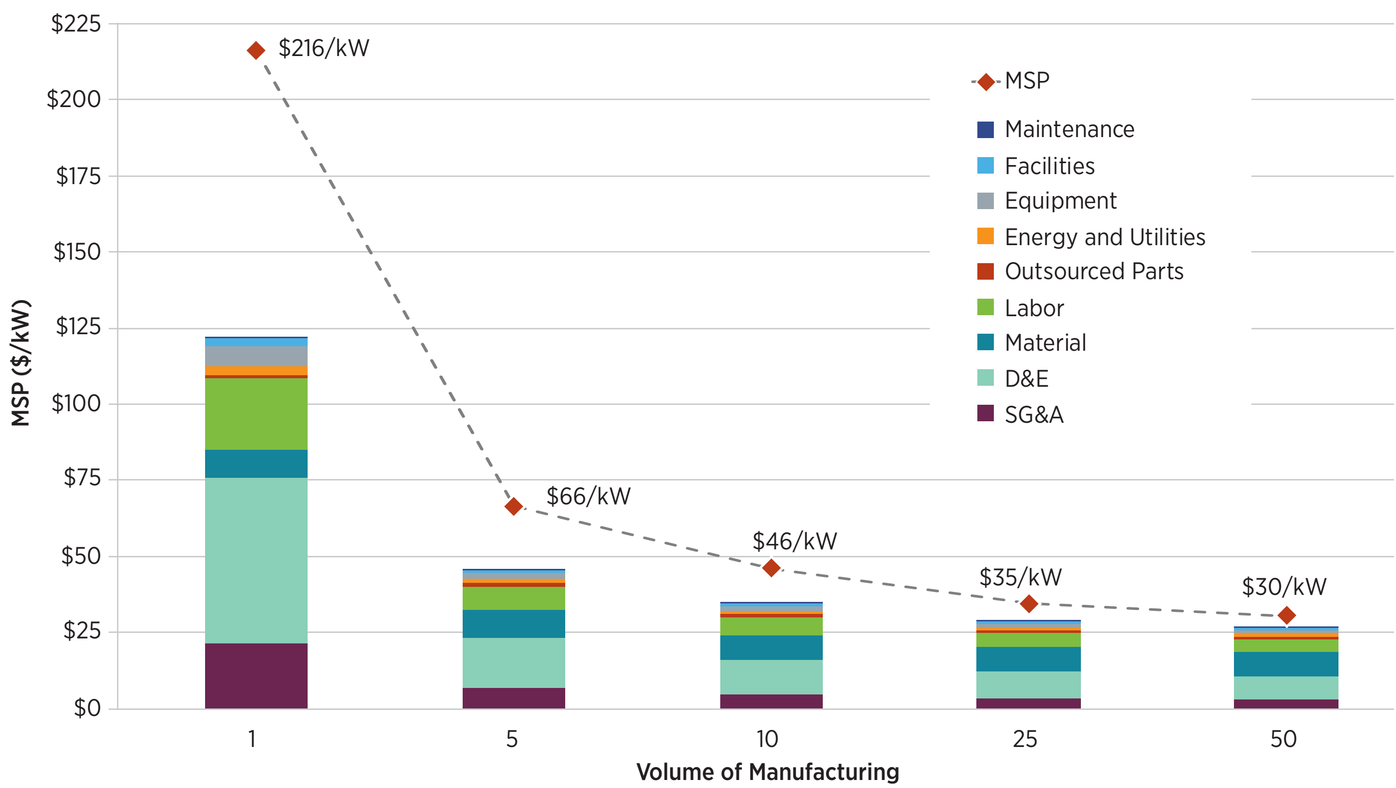


Figure 3. Manufacturing cost drop by cost factor for a standard design (10 units) 5-MWe ORC turboexpander

Table 2. Comparison of SAM Results for Custom and Standard Design Scenarios

Metric		Custom Design (Base Case)	Standard Design (Base Case)
Levelized Cost of Energy (LCOE) (nominal)	¢/kWh	10.49	9.82
LCOE (real)	¢/kWh	8.13	7.61
NPV	$	$1,346,430	$2,786,840
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**

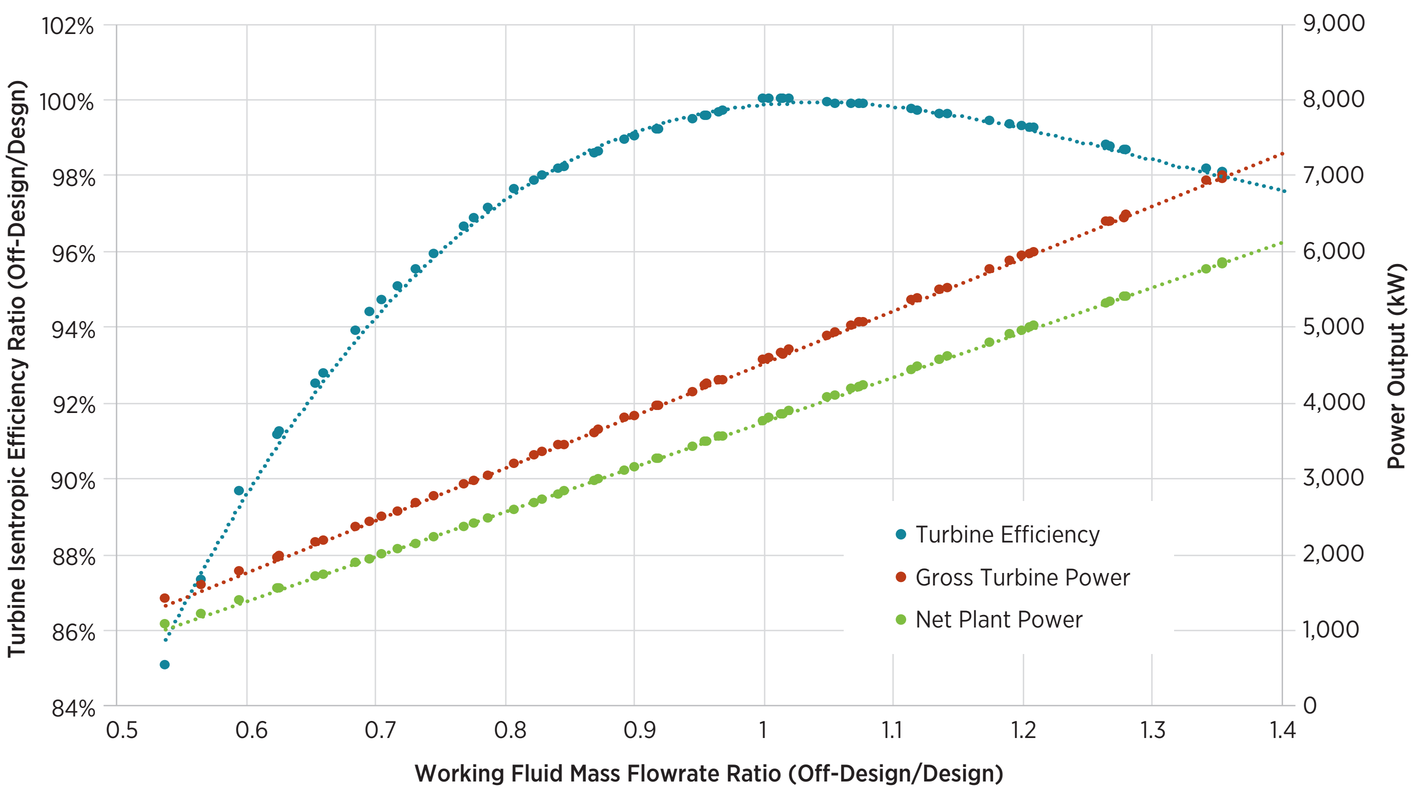


Figure 4. Off-Design Turbine Efficiency Curve for 5 MW Geothermal ORC Turbine

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 the standard turbines are competitive over a wide range of temperatures and flow rates and give positive NPV for cases near the design point. 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 5).

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. We do not have the technical information to estimate exactly what the cutoff output would be for the standard design, but we can conclude that a large portion of the upper right part of Figure 4 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.

The total plant cost savings from using a standard design versus a custom design turbine for each case can be found in Figure 5. 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 dollar-per-kilowatt cost would offset the cost savings from a standard (but oversized) turbine. This is the type of information that a manufacturer would need to consider when deciding what sizes or design power generation capacity to choose for a series of standard turbine designs.

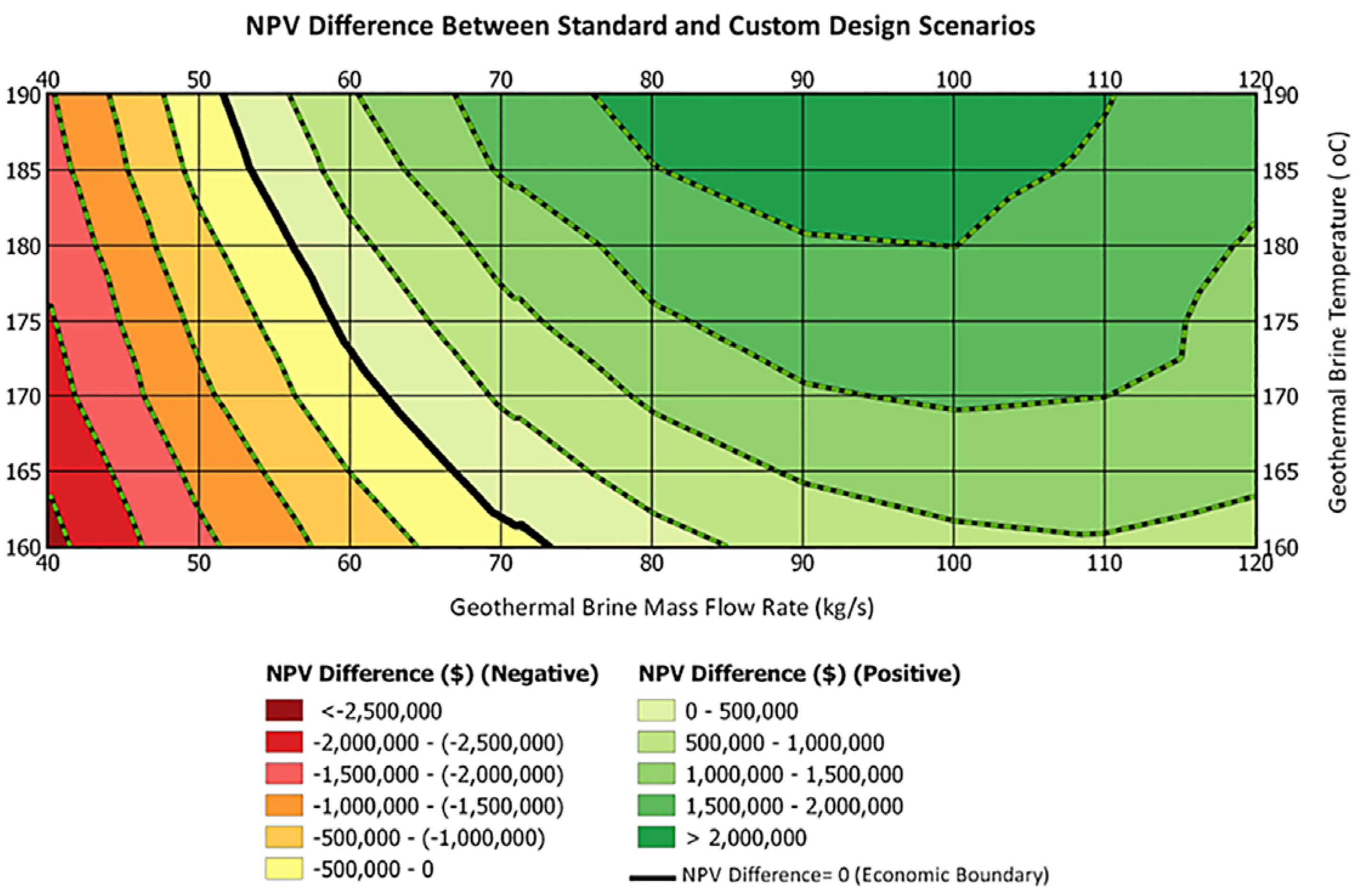


Figure 5. NPV difference between standard and custom design scenarios for given resource conditions

Learn More

See the technical report on this work titled Global Value Chain and Manufacturing Analysis on Geothermal Turbines (Akar et al. 2018).

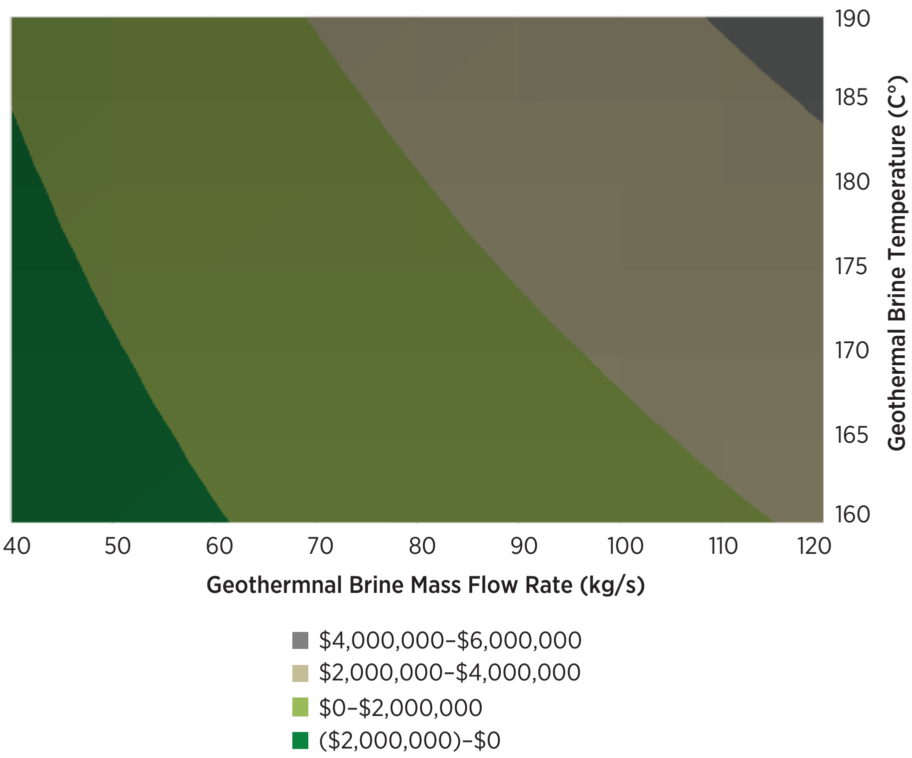


Figure 6. Plant cost savings (standard minus custom) as a function of geothermal brine temperature and flow rate

References

Akar S., Augustine C., Kurup P., Mann M. 2018. *Global Value Chain and Manufacturing Analysis on Geothermal Turbines.* NREL/TP-6A20-71128. Golden, CO: National Renewable Energy Laboratory.

Bertani, R. 2016. "Geothermal Power Generation in the World 2010–2014 Update Report." *Geothermics* 60: 31–43. https://doi.org/10.1016/j.geothermics.2015.11.003

BNEF, 2013, Q2 2013 *Geothermal Market Outlook Report*, Bloomberg New Energy Finance

BNEF, 2014, H2 2014 *Geothermal Market Outlook Report*, Bloomberg New Energy Finance

BNEF, 2015, H1 2015 *Geothermal Market Outlook Report*, Bloomberg New Energy Finance

BNEF, 2016, *Geothermal Market Outlook Report*, Bloomberg New Energy Finance

CEMAC. 2017. "Minimum Sustainable Price: Understanding Sustainable Business Practices in Clean Energy Technology." Accessed May 5, 2017. http://www.manufacturingcleanenergy.org/blog-20160510.html

GEA. 2015. "2015 Annual U.S. & Global Geothermal Power Production Report." Geothermal Energy Agency, Washington DC, USA, http://geo-energy.org/reports/2015/2015%20Annual%20US%20%20Global%20Geothermal%20Power%20Production%20Report%20Draft%20final.pdf

GEA. 2016. "2016 Annual U.S. & Global Geothermal Power Production Report." Geothermal Energy Agency, Washington DC, USA. http://geo-energy.org/reports/2016/2016%20Annual%20US%20Global%20Geothermal%20Power%20Production.pdf

GETEM. 2016. "Geothermal Electricity Technology Evaluation Model." Accessed July 8, 2018. https://www.energy.gov/eere/geothermal/geothermal-electricity-technology-evaluation-model

Goodrich, A., P. Hacke, Q. Wang, B. Sopori, R. Margolis, T.L. James, and M. Woodhouse. 2013. "A Wafer-Based Monocrystalline Silicon Photovoltaics Road Map: Utilizing Known Technology Improvement Opportunities for Further Reductions in Manufacturing Costs." *Solar Energy Materials and Solar Cells* 114:110–35. https://doi.org/10.1016/j.solmat.2013.01.030

Sandor, D., D. Chung, D. Keyser, M. Mann, and J. Engel-Cox. 2017. *Benchmarks of Global Clean Energy Manufacturing*, Clean Energy Manufacturing Analysis Center (CEMAC). NREL/TP-6A50-65619. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy17osti/65619-ES.pdf

Tartière T., 2016. *ORC Market: A World Overview*, http://orc-world-map.org/index.html

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