Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines

Preprint

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Presented at the 41st Geothermal Resource Council Annual Meeting
Salt Lake City, Utah
October 1–4, 2017

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Conference Paper
NREL/CP-6A20-68747
November 2017

Contract No. DE-AC36-08GO28308

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Clean Energy Manufacturing Analysis Center, National Renewable Energy Laboratory

Keywords

Value Chain, Manufacturing Cost Model, ORC Turboexpander, Steam Turbine

ABSTRACT

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). Currently, geothermal project developers customize the size of the power plant to fit the resource being developed. In particular, 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, 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 steam turbines used in geothermal power plants. 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). MSP is the minimum price that a company must sell its product for in order to pay back the capital and operating expenses during the plant lifetime (CEMAC, 2017). 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. Sensitivity analysis indicated these savings come largely from reduced labor costs for design and engineering and manufacturing setup.

1. Introduction

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 and issues 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.

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, 2017). 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). 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 is 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. Given the breadth of existing plants and known information about proposed projects and resource assessments, that continued development raises the question of the potential value of 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 manufacturing costs in the U.S.

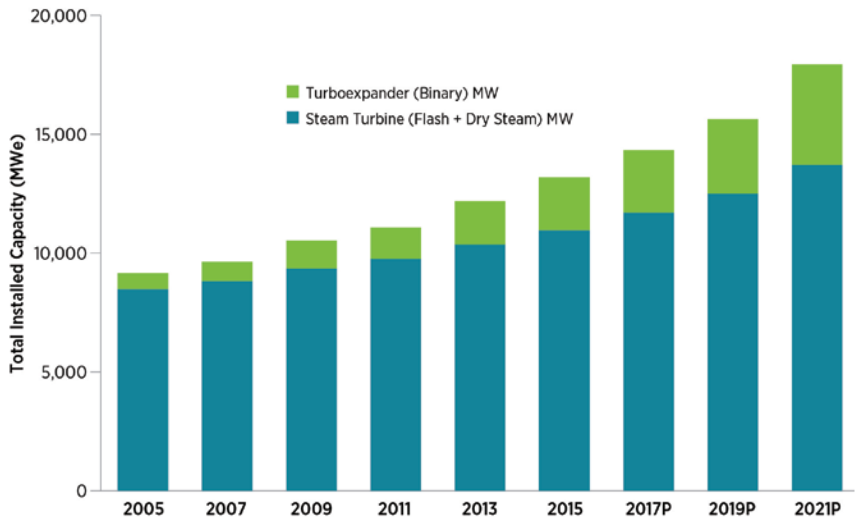


Figure 1 Historical, current, and projected global installations of geothermal power plant turbines. Data displayed represent the median figures which have been compiled from GEA (2016), BNEF (2016), and Bertani (2016). (P = projection)

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), Biomass (biogas and landfill gas), and Concentrating Solar Power (CSP)—over the last decade. While biomass 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), biomass and WHR follows with 15% and 13.7% respectively (Tartiere, 2016).

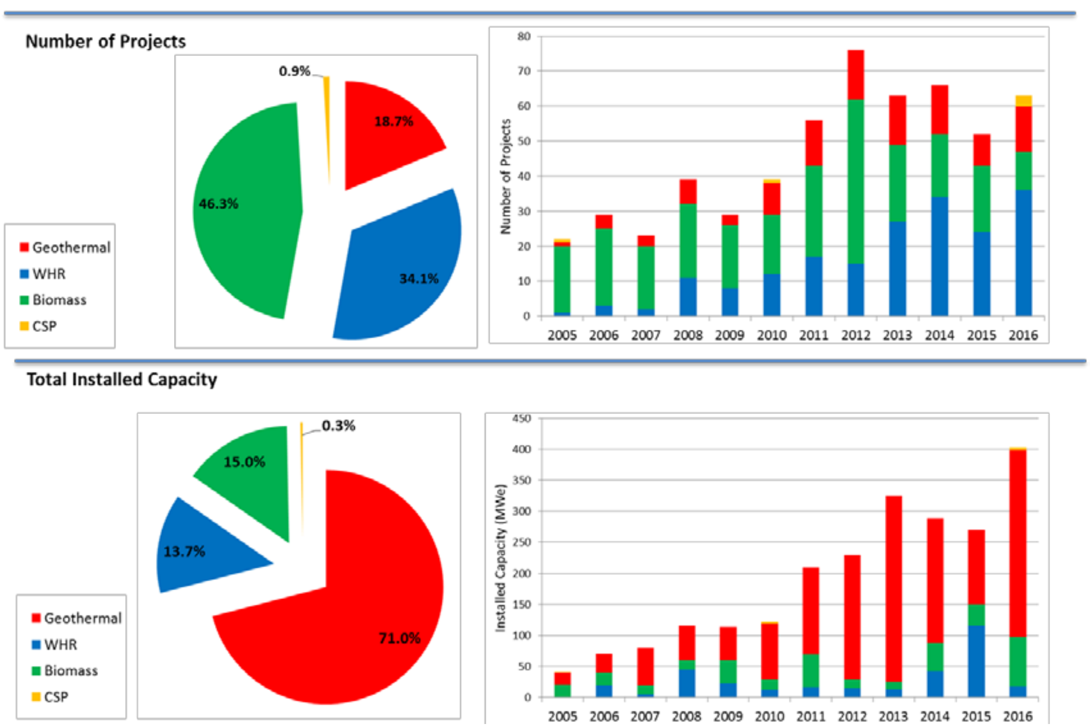


Figure 2 Overview of global ORC turboexpander market between 2005 and 2016 (Data modified from Tartiere (Tartiere 2016); lab-scale prototypes and installed capacity lower than 50 kWe have not been included)

2. Global Value Chain and Trade Flow Analysis

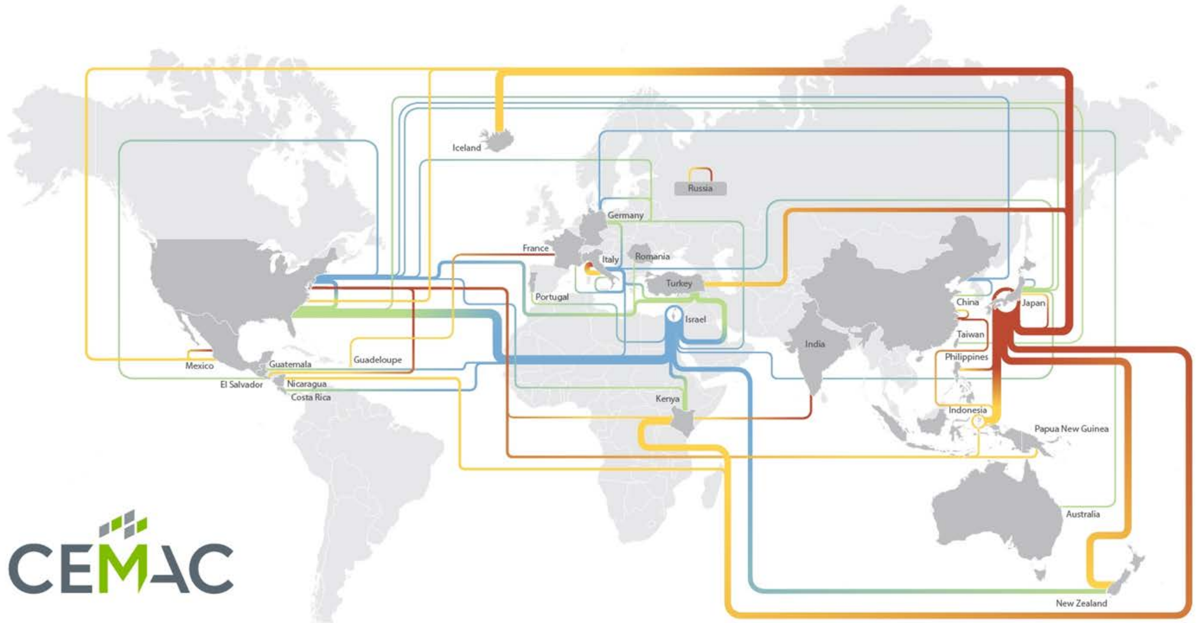
Geothermal project developers customize the size of the power plant to fit the resource being developed. The steam turbine in particular is designed and sized to optimize efficiency and resource utilization for electricity production; most often, other power plant components are then chosen to complement the turbine design. For example, in the Imperial Valley, Southern California USA, the Salton Sea Unit 5 geothermal steam turbine is designed and optimized for 58.32MWe (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 industry expert's interviews, 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, 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 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 includes 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).



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

Trade Flow
Turbine Capacity (MW)
1,200
600
300
150
50
≤1

Turbine Type & Trade Status

Exporter	Importer	
		Binary Cycle
		Dry Steam/Flash Cycle

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

3. Methodology for 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.

Manufacturing processes for subcomponents include casting, forging, and machining. For casting and forging, an electric arc furnace and forging press are required. The modeling method 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 5). 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).

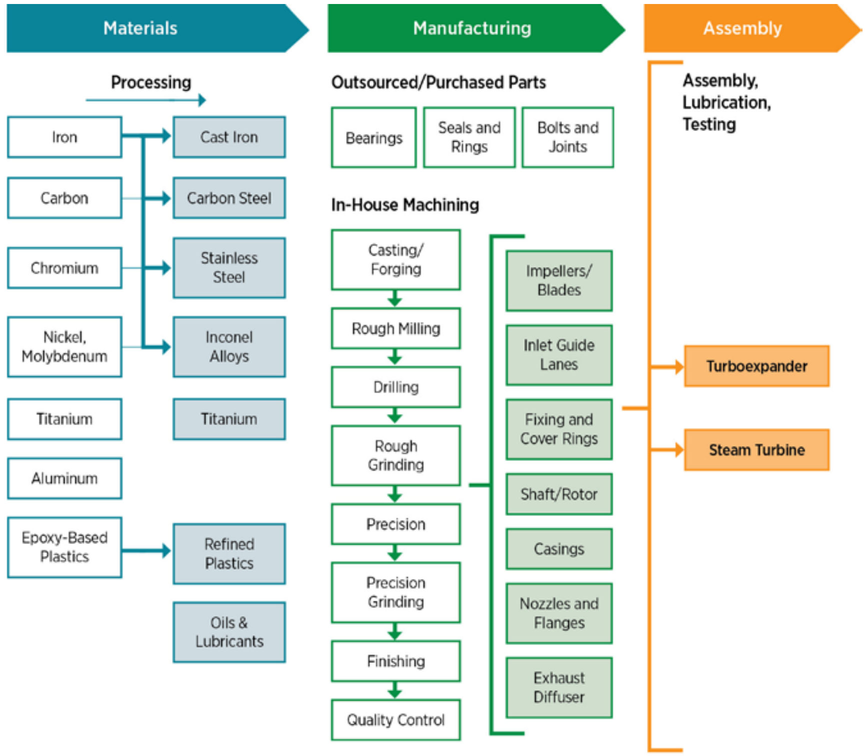


Figure 4 Manufacturing process flow diagram for geothermal power plant turbines

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 5 Machine inventory for the custom factory model

The factory model developed estimates a minimum machining rate for each machine based on annual maximum allowable working hours (MAWH) and operation hours with and without setup time.

MAWH is set as 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 a number of 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.

Machining times for each process were estimated using Design for Manufacturing and Assembly (DMFA®) software. The DFMA® tool has built-in libraries for materials and the machining/processing steps; however, DFMA® also allows users to enter new materials or manufacturing processes if not available in the libraries. DFMA® allows the user to calculate a primary manufacturing cost for each component within the overall product/assembly (Dewhurst, 2016).

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 1). We selected a manufacturing volume of 50 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.

Table 1 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

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 stamping, sand casting, and forging; it also takes into account tool wear and lifetime. The impellers were either CNC machined from titanium or stainless steel plates; the shaft were produced from initial forgings of nickel alloy (Inconel) and subsequently machined to the final dimensions. Figure 6 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 6, a custom design could be ~$4,000/unit, compared to ~$1,000/unit with the standard design. If we take the same yield rate of custom design in material as an assumption, 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	

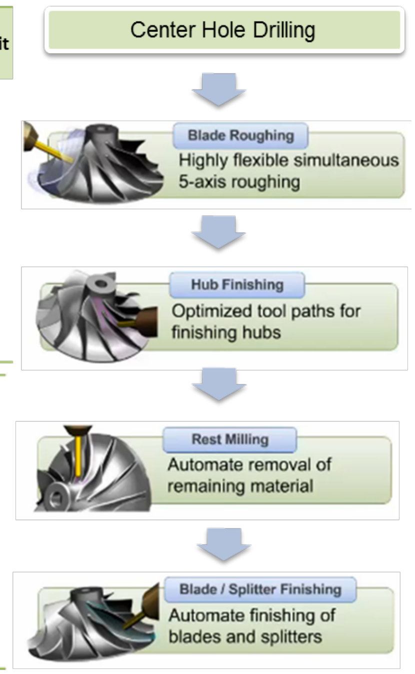


Figure 6 Representative material and machining cost estimates of a typical impeller for both custom design and standard design (at a volume of 10 units per year) 5 MWe Turboexpander.

4. 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 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 are able to account for several additional 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 2 summarizes the input parameters for the DCF analysis and MSP calculation.

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

Table 2 Summary of input parameters for DCF analysis and MSP calculations

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 in (debt + equity)	**64**	%
Replacement equip. target capital structure, % of debt in (debt + equity)	**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

Multiple iterations of the techno-economic model were developed to represent and evaluate U.S. manufacturing costs. In doing so, variations in manufacturing cost for that particular product and MSP in different manufacturing volumes were broken down by cost factors. The cost breakdown includes materials, labor, capital (equipment and facilities), energy and utilities, outsourced parts, D&E, SG&A.

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.

In scenarios 1 and 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 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 7). Similarly, 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 8).

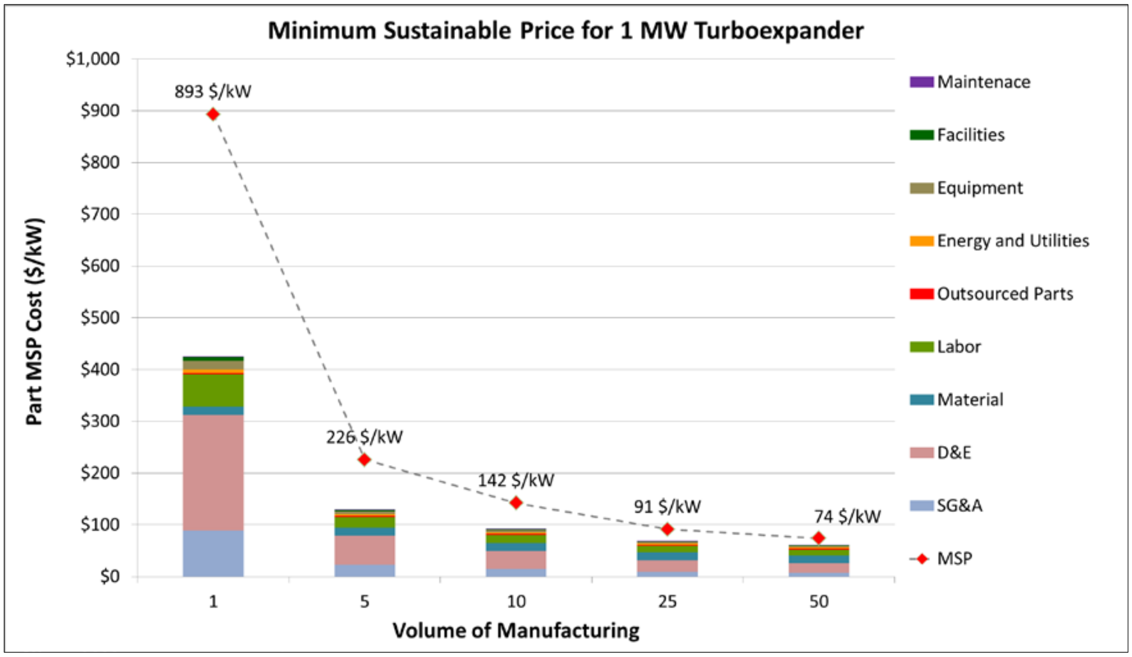


Figure 7 Calculated MSP and manufacturing cost breakdown for a 1 MWe ORC turboexpander in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC cost analysis.

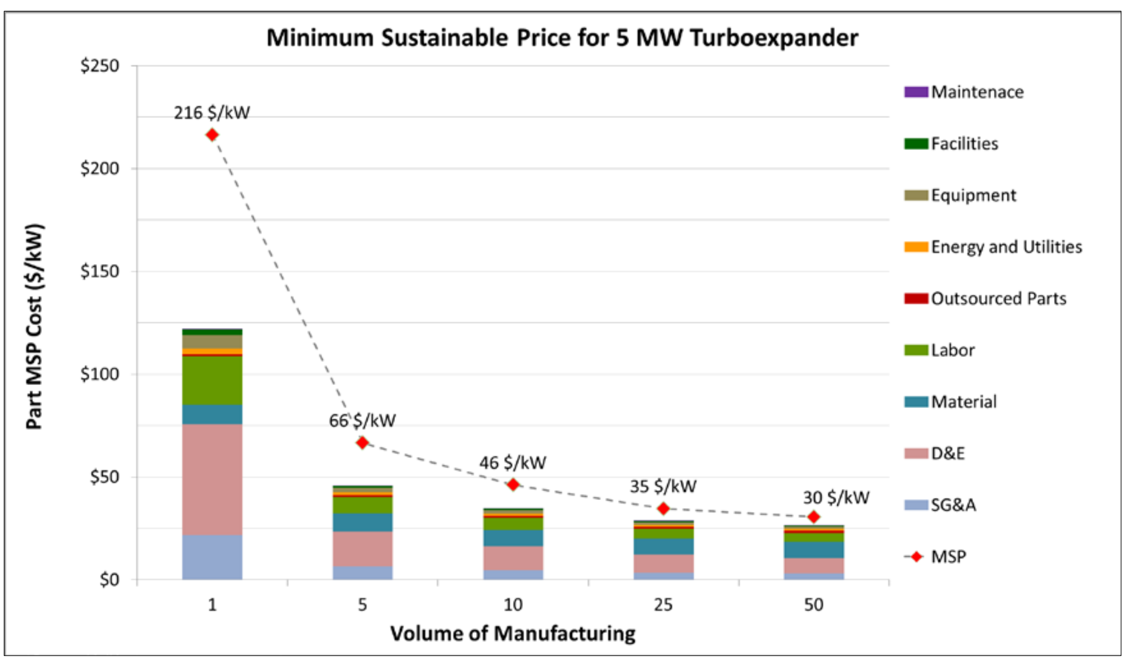


Figure 8 Calculated MSP and manufacturing cost breakdown for a 5 MWe ORC turboexpander in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC cost analysis.

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 MW steam turbine is calculated as 135 $/kW at an annual production rate of 5 unit/year (Figure 9).

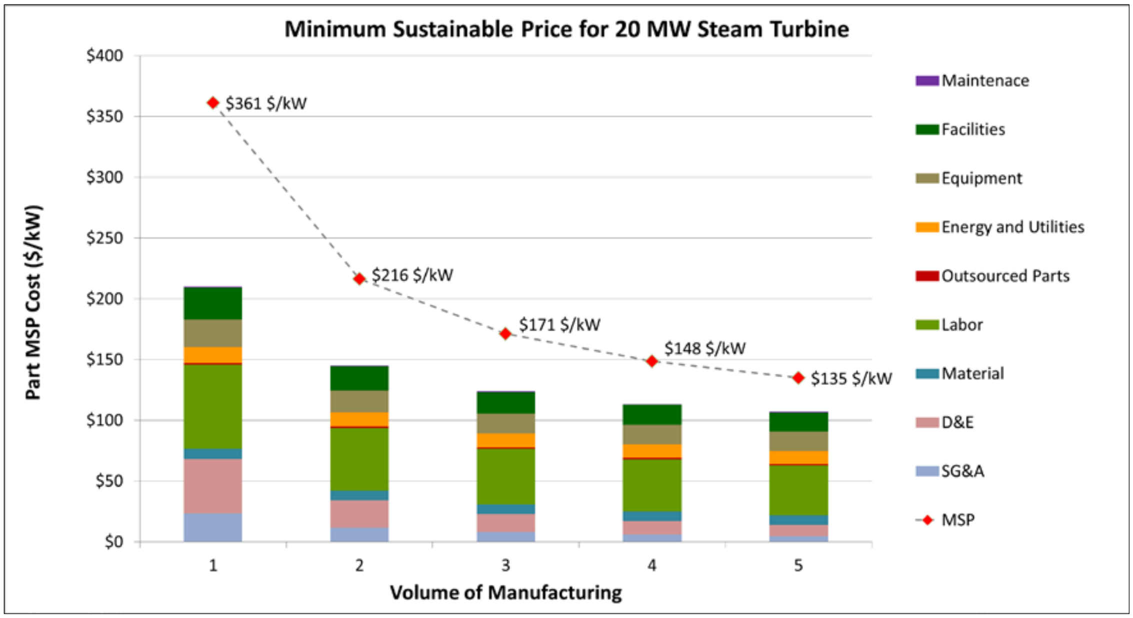


Figure 9 Calculated MSP and manufacturing cost breakdown for a 20 MWe geothermal steam turbine in different volumes of manufacturing in the United States. Data is taken from an ongoing CEMAC cost analysis.

5. 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 at a custom design unit due to time spent on tailor made design for each custom unit (Figure 10). 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 11).

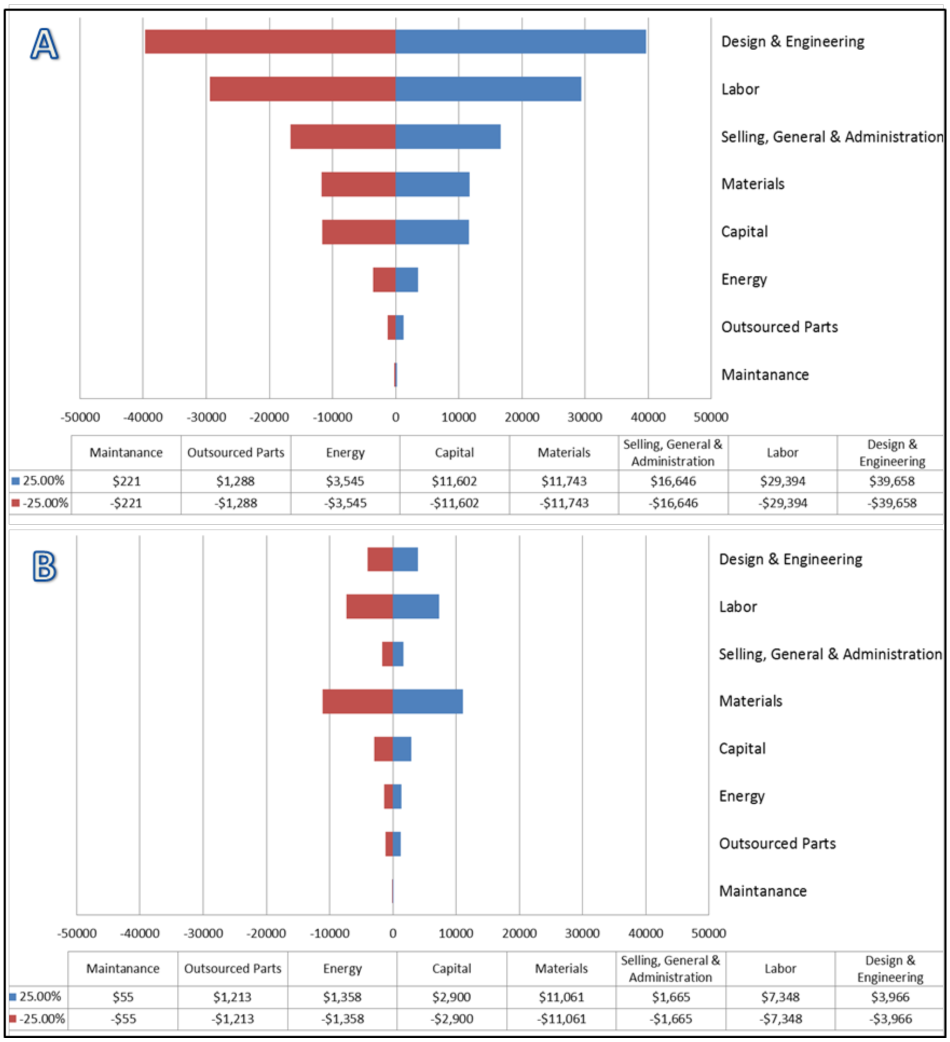


Figure 10 Sensitivity analysis for 5 MWe turboexpander based on A) Manufacturing volume of 1 unit/year (Custom Design) and B)) Manufacturing volume of 10 units per year (Standard Design) in the United States (Data is from an ongoing CEMAC cost analysis).

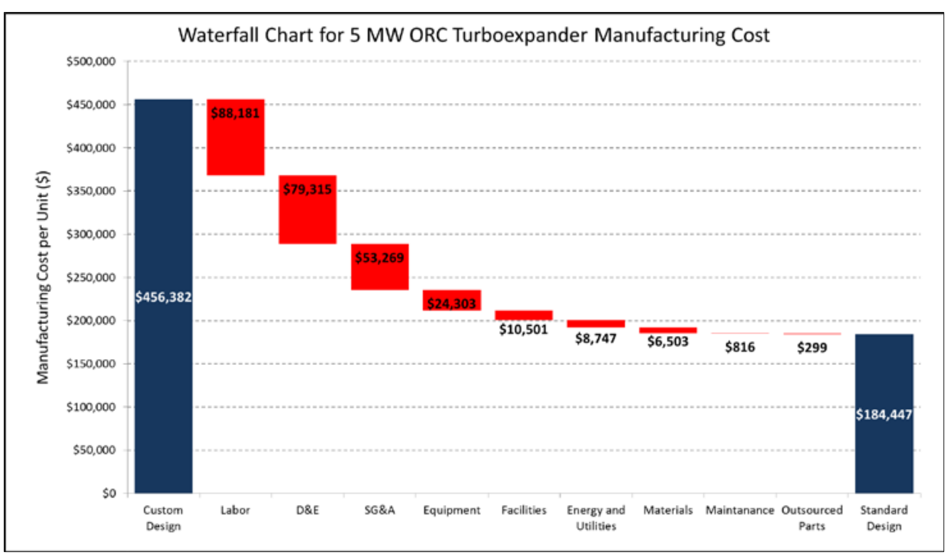
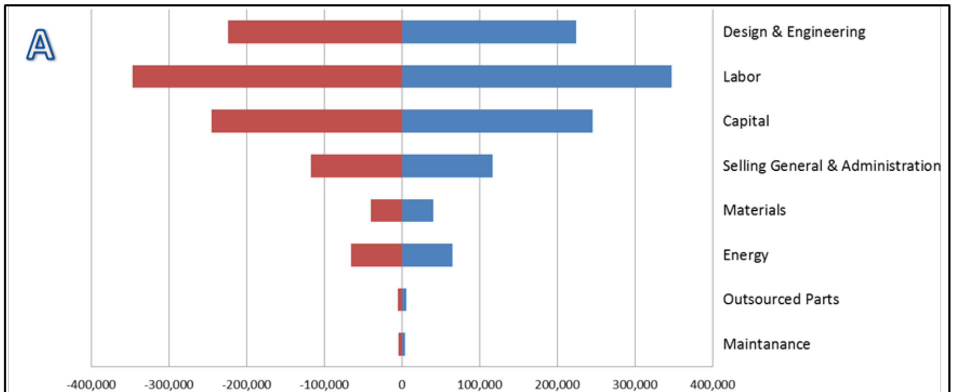
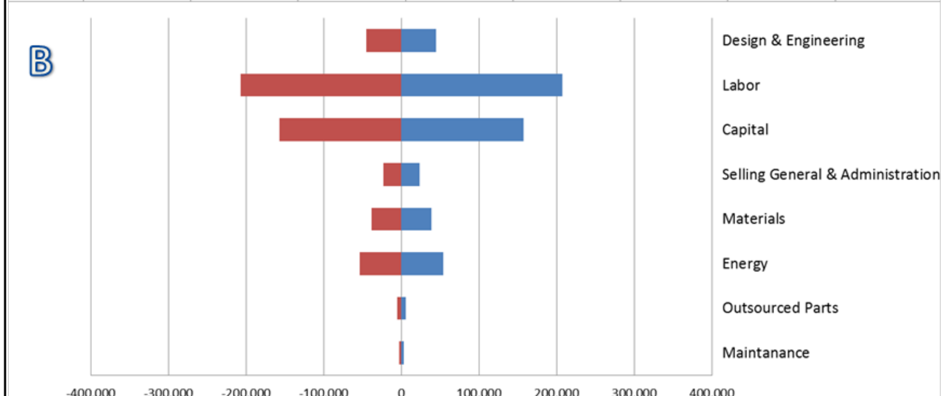


Figure 11 Manufacturing cost drop by cost factor for a standard design (10 units) 5 MWe ORC turboexpander (Data: ongoing CEMAC cost analysis)

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 12). 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 unit 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 H2S, and CO2 and have multiple pressure stages. 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 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 13).



	Maintanance	Outsourced Parts	Energy	Materials	Selling General & Administration	Capital	Labor	Design & Engineering
25.00%	$4,267	$5,737	$65,304	$40,545	$116,960	$245,231	$346,994	$224,640
-25.00%	-$4,267	-$5,737	-$65,304	-$40,545	-$116,960	-$245,231	-$346,994	-$224,640



	Maintanance	Outsourced Parts	Energy	Materials	Selling General & Administration	Capital	Labor	Design & Engineering
25.00%	$2,993	$5,727	$54,063	$38,883	$23,392	$157,636	$207,200	$44,928
-25.00%	-$2,993	-$5,727	-$54,063	-$38,883	-$23,392	-$157,636	-$207,200	-$44,928

Figure 12 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).

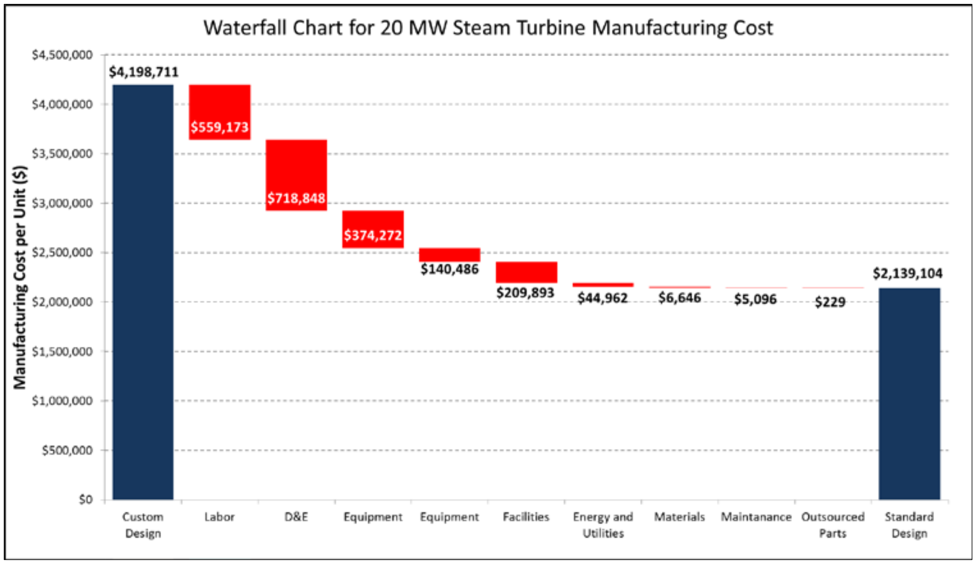


Figure 13 Manufacturing cost drop by cost factor for a standard design (5 units) 20 MWe steam turbine (Data: ongoing CEMAC cost analysis)

6. Discussion

The geothermal turbine market is expected to continue growing substantially both for steam turbine and turboexpander technologies. In Europe and the United States, binary cycle projects are the main power plant type under construction. In regions such as East Africa, Southeast Asia, and the South Pacific, numerous flash and dry steam power plant projects are under development. The countries in which geothermal capacity is growing the fastest are Indonesia, Turkey, and Kenya. These developing projects are expected to create an annual average demand of 1 GW for a diverse mix of geothermal turbine types (BNEF, 2016; GEA, 2016).

The U.S. geothermal market had a challenging year in 2016 and did not grow significantly. However, there are potential opportunities on the horizon that could help the sector grow and expand. 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 third 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 capacity is 1,400 MWe. Considering the ambitious plans by the government of Indonesia for geothermal development of 6,500 MWe by 2025 a targeted geothermal market analysis of Indonesia is a worthwhile endeavor (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).

Turkey has 851 MW of installed capacity as of May 2017 and a capacity target of 1,700 MWe including the projects in the pipeline (Enerji Atlasi, 2017). Turkey implemented a long-awaited 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 which 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 impressive construction pipeline of new projects in several 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).

The emerging geothermal markets discussed above show that there may be an opportunity for using standardized turbines to reduce plant capital costs. In addition to labor cost associated to direct processes of machining, machine set up time and time spent on design and engineering stages are two of the most important factors affecting manufacturing costs when turbines are manufactured as custom designs. Standard design turbines could lower these cost components a significant amount. CEMAC uses a model, which assumes facility cost based on minimum required working area per machine; equipment cost associated with machinery based on annual straight line depreciation, labor cost based on operational hours with setup time. The model does not include storage and shipping costs. Every manufacturer has its own factory cost model and supply chain. This may result in differences between the MSP`s calculated in this study and actual industry costs. However, the concept of standard design and manufacturing cost saving would be similar. The MSP`s would have a significant drop at increased volume of manufacturing. One more benefit of standard design turbines could be on lead times. Based on our industry interviews, total lead time could be lowered from 18 months to 8 months including shipping and installation by utilizing off-the-shelf units.

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 manufacturing cost analysis above shows that even applying a standard design to a relatively small number of units, as few as five, can have significant cost savings. Issues not addressed by the analysis are the potential for lower efficiencies and decreased electricity generation from a standard turbine operating at off-design conditions, and the potential for a standard unit size to be undersized for a given resource versus a custom designed turbine. Given that the turbine makes up a small portion of overall project capital costs, does the lower turbine cost and possible shorter lead times compensate for less revenue from lost electricity generation? An analysis of the economic tradeoffs is required to answer this question, and is planned as future work in this study.

7. Conclusions

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. The MSP calculations and sensitivity analysis for 1 MWe and 5 MWe turboexpanders and a 20 MWe steam turbine 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 spread among multiple units. It is also cheaper to manufacture one larger unit versus many smaller units, at least for the sizes explored. 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. 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.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory (NREL). The authors wish to thank reviewers for their comments and suggestions including Doug Arent, Jill Engel-Cox, Emily Newes, Samantha Reese, and Ahmad Mayyas from NREL. The authors also thank to Billy Roberts from NREL for his help on mapping. All errors and omissions are the responsibility of the authors.

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