GETEM to SAM FY18 Updates

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List of Acronyms

EGS Enhanced Geothermal Systems

GTO Geothermal Technologies Office

GEA Geothermal Energy Association

GETEM Geothermal Electricity Technology Evaluation Model

GTP Geothermal Technologies Program

GWe Gigawatt electric

HX Heat Exchanger

kW Kilowatt

LCOE Levelized Cost of Electricity

NREL National Renewable Energy Laboratory

SAM System Advisor Model

USGS United States Geological Survey

Executive Summary

This report documents the upgrades made to the Geothermal technology (performance + financial) model within NREL’s System Advisor Model (SAM v. 2018.11.11). SAM, available for download at no cost at <https://sam.nrel.gov/>, is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry.

Default input values in SAM’s Geothermal model were updated to match the current default values in the Geothermal Electricity Technology Evaluation Model (GETEM). GETEM is an Excel-based tool, provided by Idaho National Laboratory, and is used to estimate the Levelized Cost of Energy (LCOE) for definable geothermal scenarios. GETEM is the primary tool used by the Geothermal Technologies Office (GTO) in understanding the costs and performances of current U.S. geothermal power systems. The primary objective of the ongoing improvements to the geothermal technology in SAM is to replicate the excel-based GETEM model and thus serve as the desktop application alternative to GETEM.

An option to automatically estimate direct plant cost ($/kW) based on the direct plant cost algorithm in GETEM was developed. A built-in script to optimize overall efficiency of the Binary plant type that minimizes its LCOE was also created. This report describes the algorithm used to calculate direct plant cost and provides a comparison of the results obtained in GETEM versus SAM.

A parametric study was carried out in SAM and GETEM respectively, to compare the direct plant costs calculated in both the models. The average percentage difference between the direct plant cost of a binary calculated in SAM and GETEM was 0.77% with a standard deviation of 0.34%. The average percentage difference of the direct plant cost of a single flash plant type was 3.37% with a standard deviation of 1.23%. And the average percentage difference of the direct plant cost of a dual flash plant type was 3.67% with a standard deviation of 1.24%.

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1 Introduction

Geothermal power plants extract heat from steam produced below the Earth’s surface, in geothermal reservoirs, to drive a thermo-electric power cycle. Two main types of geothermal power plant technologies currently being used to generate electricity from hot hydrothermal fluids are the binary plant and flash plant types. In a binary cycle power plant, naturally sourced hot water from the geothermal reservoir is used to heat a second working fluid with a lower boiling point than water, such as pentane. This binary fluid gets converted to vapor which is then used to turn a turbine to produce electricity. The vapor exiting the turbine is condensed, re-pressurized by a pump and sent back to the heat exchanger to be vaporized by the geothermal fluid again in a closed cycle. In comparison, in a flash plant type, hydrothermal fluid is pumped at high pressures into a tank with a lower pressure resulting in the partial, rapid vaporization of this fluid. This vaporized fluid is then used to turn a conventional steam turbine [1]. In general, binary plants utilize hydrothermal fluids below 200 °C, while flash plants are used for hydrothermal fluids at higher temperatures.

By the end of 2015, the geothermal powerplants in the United States had a cumulative nameplate capacity of 3.7 GW and a net capacity of 2.7 GW [2]. The Geothermal Energy Association (GEA) released a list of geothermal projects expected to come online in the US before the year 2020 that have a cumulative capacity of 6.4 GWe – close to double the current installed capacity. And the United States Geological Survey (USGS) estimates a total hydrothermal resource capacity of 30 GW in the US, which is nearly ten times the current installed capacity [3,4].

Geothermal Electricity Technology Evaluation Model (GETEM) is an Excel-based tool used to estimate the Levelized Cost of Energy (LCOE) for definable geothermal scenarios [5]. This tool was originally developed for the Department of Energy’s (DOE) Geothermal Technologies Program (GTP) to provide a method for quantifying cost of power generation from geothermal energy and assess the impact of technology improvements on generation costs. GETEM also aids the Geothermal Technologies Office (GTO) to evaluate the state of the existing geothermal technology and predict future developments in the U.S. In addition, GTO uses GETEM for informing major policy decisions such as efficient allocation of tax dollars for the research, development, and demonstration of geothermal projects. GETEM only provides assessment capabilities for electrical power generation, and not for geothermal direct-use or geothermal heat pumps.

System Advisor Model (SAM), a performance and financial model developed at the National Renewable Energy Laboratory (NREL), is primarily used to facilitate decision making for people in the renewable energy industry [6]. SAM’s geothermal power model is based on GETEM, and its main capabilities include calculating the annual and lifetime electrical output of a utility-scale geothermal power plant, its LCOE and other economic metrics for both flash and binary conversion plant types. Geothermal systems that SAM can currently model include hydrothermal resources and enhanced geothermal systems (EGS). The primary goal of the ongoing improvements to the geothermal technology in SAM is to replicate the Excel-based GETEM model, and thus serve as a desktop application alternative to GETEM.

As of 2017, SAM is now open source; that is, all the source codes and tools required to build SAM are now freely available to the public. However, NREL will continue to maintain and update the code and regularly release software version updates [7]. Detailed set of instructions to build the open source version of SAM on your desktop using GitHub can be found in [8]. The underlying algorithms for the Geothermal technology of SAM can be found in the SSC project. The 4 main files within the SSC project repository that constitute the Geothermal technology of SAM include:

* ‘shared/lib\_geothermal.h’ - Contains declaration of CGeothermalAnalyzer class
* ‘shared/lib\_geothermal.cpp’ - Contains implementation of CGeothermalAnalyzer class
* ‘ssc/cmod\_geothermal.cpp’ - Interface between the SAM UI and lib\_geothermal.cpp
* ‘ssc/cmod\_geothermal\_costs.cpp’ - Contains calculation of plant baseline cost

This report documents the upgrades made to the Geothermal technology (performance + financial) model within SAM version 2018.11.11. Default values in SAM were updated to match the default values in GETEM v. 2016. A feature was also added that automatically estimates direct plant cost based on the direct plant cost algorithm outlined in GETEM, and a built-in script to optimize overall efficiency of the Binary plant type that minimizes its LCOE was developed. This report describes the algorithm used to calculate direct plant cost and provides a comparison of the results obtained in GETEM versus SAM.

1. Default value updates

The default input values of the Geothermal technology, and for all financial configurations in the latest SAM release (v. 2018.11.11), were updated to match the current default inputs in GETEM v. 2016 which is the most up-to-date version of the model at the time of writing this report.

* 1. Updated Values in Geothermal Resource Tab

Table 1 summarizes the changes made to the default inputs in SAM, to match the current defaults in GETEM 2016. Column labeled ‘Input’ represents user defined inputs in SAM. Column labeled ‘Default Value in GETEM 2016’ contains the default input values in GETEM 2016 - the most recent version of the Excel tool (as of January 2019). Column labeled ‘Old Default Value in SAM’ contains default values of inputs in the ‘Geothermal Resource’ tab of the geothermal technology model of the previous SAM version (v. Version 2017.9.5).

Table 1 Updated Default Values in Geothermal Resource Tab

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Tab in SAM | Block in SAM | Input | Default Value in GETEM 2016 | Old Default Value in SAM | Notes |
| Geothermal Resource | **Resource Characterization** | Resource Type | Hydrothermal | Hydrothermal | - |
| Total Resource Potential | 210 MW | 210 MW | - |
| Resource Temperature | 175 C | 200 C | - |
| Resource Depth | 1500 m | 2000 m | - |
| **Reservoir Parameters** | Hydraulic Drawdown | 0.4 | 0.35 | Exists in SAM as - 'Enter Change in pressure across reservoir…' |
| Width | n/a | 500 m | *No longer inputs in GETEM* |
| Height | n/a | 100 m |
| Permeability | n/a | 0.05 Darcy Units |
| Distance from Injection to Production Wells | n/a | 1500 m |
| Fracture Aperture | n/a | 0.0004 m |
| Number of Fractures | n/a | 6 |
| Fracture Width | n/a | 175 m |
| Fracture Angle | n/a | 15 |
| Subsurface Water Loss | 0% for hydrothermal, 5% for EGS | 2% |  |

Tables A.1 – A.X (see Appendix) summarize the remaining changes made to the default values in SAM v. 2018.11.11.

1. Geothermal Model Updates

The two main core upgrades made to the Geothermal model in SAM v. 2018.11.11 are 1.) the inclusion of an option to automatically estimate direct plant cost based on the direct plant cost algorithm used in GETEM v. 2016, and 2.) a macro to optimize overall efficiency of the Binary plant type that minimizes the project LCOE. This report describes the algorithm used to calculate direct plant cost and provides a comparison of the results obtained in GETEM versus SAM, and discusses the underlying algorithm of the ‘Geothermal Plant Efficiency Optimizer’ macro.

* 1. Direct Plant Cost Calculator

An option to automatically estimate the Geothermal plant cost was installed in the latest version of SAM (v. 2018.11.11) in the System Costs tab of the Geothermal technology (for all financial configurations). As seen in Figure 1, the checkbox labeled *‘Automatically estimate the plant cost per kW’* calculates the geothermal plant cost (for both Binary and Flash plant types) on being checked.

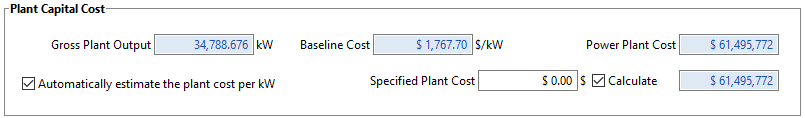


Figure 1 Radio Button to Automatically Estimate Plant Cost Per Kilowatt

The baseline cost ($/kW) of the geothermal plant calculated on clicking the checkbox depends on the set of inputs defined by the user in the active case. Once the checkbox is checked, the baseline cost is automatically updated each time the user redefines the value of any of the underlying inputs used in the calculation of the baseline cost. The source code that implements the GETEM based algorithm of the baseline plant cost (for binary and flash plant types) exists in the SSC project in the following file: ‘ssc/cmod\_geothermal\_costs.cpp.’

* + 1. Binary Plant Direct Cost Model

In GETEM, the baseline cost ($/kW) of the binary plant type is the sum of the costs of the plant’s individual components ($/kW) multiplied by the (construction) installation multiplier; the binary plant type is comprised of the following components:

* **Geofluid Heat Exchangers (HX):**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘hx\_cost’
* **Air-Cooled Condensers (ACC):**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘condenser\_cost’
* **Working Fluid Pumps (WF Pump):**Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘wf\_pump\_cost’
* **Turbine Generator (TG):**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘turbine\_cost’

The (construction) installation cost multiplier is the sum of the following cost multipliers (see Appendix for breakdown of multiplier equations). In SSC, the calculation of the multiplier for both, binary and flash plant types can be found under the comment ‘//Calculating Direct Construction Cost Multiplier:’

* **Corrected Total Material Multiplier:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘corrected\_total\_material\_mult’
* **Corrected Cnstrt Malt’s:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘corrected\_construct\_malts’
* **Plant Size Adjustment:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘plant\_size\_adjustment’
* **Direct Installation Multiplier:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘direct\_installation\_multiplier’
* **Sales Tax:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘sales\_tax’
* **Freight:**  
  Variable name in SSC/cmod\_geothermal\_costs.cpp – ‘freight’

The formula for the baseline cost ($/kW) of the Geofluid Heat Exchanger (HXGF) component of the binary plant type, as per GETEM v. 2016 [5], is given by eq. (1):

(1)

The breakdown of the individual components of eq (1) is shown in Table2.

**Table 2 Formulas Used in Geofluid Heat Exchanger’s (HXGF) Cost Calculation**

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | Units |
|  | User Adjustment *(Constant)* | 1 |  |
|  | Unit Plant Size *(Constant)* | *User Defined Input* | kW |
|  | Reference Plant Size *(Constant)* |  | kW |
|  | Reference Plant’s HX Cost |  | $ |
|  |  |  | ***<not sure>*** |
|  |  |  | *(multiplier)* |
|  | Production Well Head Temperature | (Calculated in ‘*lib\_geothermal.cpp’)* |  |
| C10 | *(constant)* |  | *(multiplier)* |
| C11 | *(constant)* |  | *(multiplier)* |
| C12 | *(constant)* |  | *(multiplier)* |
| C20 | *(constant)* |  | *(multiplier)* |
| C21 | *(constant)* |  | *(multiplier)* |
| C23 | *(constant)* |  | *(multiplier)* |
|  | Second Law Efficiency | (Calculated in ‘*lib\_geothermal.cpp’)* | % |
|  | Size Ratio |  | ratio |
|  | Scaling Factor |  | *(multiplier)* |
|  | *(scaling factor coefficient)* |  | *(multiplier)* |
|  | *(scaling factor coefficient)* |  | *(multiplier)* |
|  | *(scaling factor coefficient)* |  | *(multiplier)* |
|  | Heat Exchanger Cost Index (See Appendix, table A.***<X>*** | **<1.606>** | *(multiplier)* |

The formula for the baseline cost ($/kW) of the of Air-Cooled Condenser (ACC) is given by eq. (2):

(2)

The breakdown of the individual components (, , , , , and ) of eq. (2) is given in table 2. And the calculation of the reference plant’s cost of air-cooled condenser is given in table 3.

Table 3. Calculation of Cost of Reference Plant’s Air-Cooled Condenser

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | Units |
|  | Cost of Reference Plant’s Air-Cooled Condenser ( |  | *$* |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |

The formula for the baseline cost ($/kW) of the of WF Pumps () is given by eq (3):

(3)

The breakdown of the individual components (, , , , and ) of eq (3) is given in Table2. And the calculation of the reference plant’s cost of WF Pumps and is given in Table 3.

Table 3 Calculation of Cost of Reference Plant’s WF Pumps

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | Units |
|  | Cost of Reference Plant’s WF-Pumps |  | *$* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
| C10 | *(constant)* |  | *(multiplier)* |
| C11 | *(constant)* |  | *(multiplier)* |
| C12 | *(constant)* |  | *(multiplier)* |
| C20 | *(constant)* |  | *(multiplier)* |
| C21 | *(constant)* |  | *(multiplier)* |
| C22 | *(constant)* |  | *(multiplier)* |
|  | Production Well Head Temperature | (Calculated in ‘*lib\_geothermal.cpp’)* |  |

The formula for the baseline cost ($/kW) of the of Turbine-Generator () is given by eq. (4):

(4)

The breakdown of the individual components (, , , , and ) of eq (4) is given in table 2. And the calculation of the reference plant’s cost of TG and is given in Table 4.

Table 4. Calculation of Cost of Reference Plant’s Turbine-Generator

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | Units |
|  | Cost of Reference Plant’s TG |  |  |
|  | Cost of Reference Plant’s Turbine (if ) |  |  |
|  | Cost of Reference Plant’s Turbine (if ) |  |  |
|  | TG Size |  |  |
|  | Max Turbine Size |  |  |
|  | Number of turbine-generator sets |  | *ratio* |
|  | Cost of Reference Plant’s Generator |  |  |
|  | Plant Parasitic Losses |  |  |
|  | Second Law Efficiency | (Calculated in ‘*lib\_geothermal.cpp’)* | % |
|  |  |  |  |
|  |  |  |  |
|  | Production Well Head Temperature | (Calculated in ‘*lib\_geothermal.cpp’)* |  |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |
|  | *(constant)* |  | *(multiplier)* |

Therefore, given that the user has selected the Binary Plant type in the Plant and Equipment tab of the Geothermal technology in SAM, clicking the ‘Automatically estimate plant cost’ radio button in SAM (Figure 1) calculates the baseline cost ($/kW) of a binary plant, whose formula is given by eq (5):

(5)

Where eq. (A.1) is the installation multiplier (see Appendix for formula).

* + 1. Flash Plant Direct Cost Model

In GETEM, the baseline cost ($/kW) of the flash plant type is the sum of the costs of the plant’s individual components ($/kW) multiplied by the (construction) installation multiplier; the flash plant type’s baseline cost is comprised of the following component costs:

* Turbine Generator Cost
* Flash Vessels Cost
* Cooling Tower Cost
* Condenser Cost
* Pump Cost
* Non-Condensable Gas (NCG) Removal System Cost
* H2S Removal System Cost

The formula for the baseline cost ($/kW) of the Turbine Generator component of the flash plant type is given by eq (6):

(6)

The breakdown of the individual components of eq (6) is shown in Table 5:

**Table 5. Calculation of Cost of Reference Plant’s Turbine-Generator**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | | Units |
|  | Cost of reference plant’s Turbine Generator set |  |  | |
| UA | User Adjustment *(Constant)* | 1 | *(multiplier)* | |
|  |  |  |  | |
|  | Net Plant Power | (Calculated in ‘*cmod\_geothermal.cpp’)* |  | |

The formula for calculating the baseline cost ($/kW) of the Flash Vessels () is given by eq (7):

(7)

The breakdown of the individual components of eq (7) is given in Table 6:

Table 6. Calculation of Cost of Reference Plant’s Flash Vessel

|  |  |  |  |
| --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | Units |
|  | Cost of reference plant’s Flash Vessel |  |  |
|  | High Pressure Flash Vessel’s Total Cost *(if High Pressure Flash < 75 psia)* |  |  |
|  | High Pressure Flash Vessel’s Total Cost *(if High Pressure Flash > 75 psia)* |  |  |
|  | Total number of flash vessels | *User defined input* |  |
|  | Volume of flash vessel |  |  |
|  | Average area of cross-section of each flash vessel |  |  |
|  | High pressure steam flowrate | (Calculated in *‘lib\_geothermal.cpp’*) |  |
|  | Terminal velocity of high-pressure steam flow |  |  |
|  | High pressure flash vessel’s pressure | (Calculated in *‘lib\_geothermal.cpp’*) |  |
|  | Terminal velocity of flash fluid | *Default value* |  |
|  | Height of flash vessel |  |  |
|  | Diameter of flash vessel |  |  |
|  | Low pressure flash vessel’s total cost *(If number of flash vessels is 1)* |  |  |
|  | Low pressure flash vessel’s total cost *(if low pressure flash vessel’s pressure is < 75 psia)* |  |  |
|  | Low pressure flash vessel’s total cost *(if low pressure flash vessel’s pressure is > 75 psia)* |  |  |

The formula for calculating the baseline cost ($/kW) of the Cooling Tower () is given by eq (8):

(8)

Where, (MMBTU/h) is the total waste heat rejected by the plant (calculated in *‘lib\_geothermal.cpp’)*.

The baseline cost ($/kW) of the condenser (surface type) is given by eq (9). SAM currently only considers the surface type condenser in its calculations.

(9)

Where, is the total area of the condenser, and its calculation is shown in Table 7.

Table 7. Calculation of Total Area of Reference Plant’s Condenser

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | | Units |
|  | Condenser surface area |  |  | |
|  | Total heat rejected from condenser | (Calculated in *‘lib\_geothermal.cpp’*) |  | |
|  | Logarithmic mean temperature difference between hot and cold feeds of condenser |  |  | |
|  | Condenser pinch point | (Calculated in *‘lib\_geothermal.cpp’*) |  | |
|  | Cooling water temperature rise -dt | *(User defined input)* |  | |

The formula for calculating the baseline cost ($/kW) of pumps is given by eq (10):

(10)

The breakdown of the individual components of eq (10) is given in Table 8:

Table 8. Calculation of Cost of Reference Plant’s Turbine-Generator

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | | Units |
|  | Cost of Cooling Water |  |  | |
|  | Cooling water pump power | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  |  |  |  | |
|  | Condensate pump power | (calculated in *‘lib\_geothermal.cpp’)* |  | |

The formula for calculating the baseline cost ($/kW) of non-condensable gas (NCG) removal system is given by eq (11):

(11)

The breakdown of the individual components of eq (11) is given in Table 9:

Table 9. Breakdown of Reference Plant’s NCG Removal System’s Cost

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Symbol | Description *(Notes)* | Formula/Value | | Units |
|  | Cost of vacuum pump |  |  | |
|  | Vacuum pump stage 1 cost (if work done by stage 1 vacuum pump is < 5 MW) |  |  | |
|  | Vacuum pump stage 1 cost (if work done by stage 1 vacuum pump is > 5 MW) |  |  | |
|  | Work done by stage 1 vacuum pump | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Vacuum pump stage 2 cost (if work done by stage 2 vacuum pump is < 5 MW) |  |  | |
|  | Vacuum pump stage 2 cost (if work done by stage 2 vacuum pump is > 5 MW) |  |  | |
|  | Work done by stage 2 vacuum pump | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Vacuum pump stage 3 cost (if work done by stage 3 vacuum pump is < 5 MW) |  |  | |
|  | Vacuum pump stage 3 cost (if work done by stage 1 vacuum pump is > 5 MW) |  |  | |
|  | Work done by stage 3 vacuum pump | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Cost of NCG removal system’s condenser |  |  | |
|  | Area of 1st stage of condenser | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Area of 2nd stage of condenser | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Area of 3rd stage of condenser | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | Cost of NCG removal system’s pump |  |  | |
|  | NCG removal system’s condensate pump | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | NCG removal system’s cooling water pump | (calculated in *‘lib\_geothermal.cpp’)* |  | |
|  | NCG removal system’s cost of ejector (cost is $0 when NCG level is 0) |  |  | |
|  | Ratio of high-pressure flash pressure and 1st stage pressure suction | (calculated in *‘lib\_geothermal.cpp’)* | *ratio* | |
|  | Ratio of high-pressure flash pressure and 2nd stage pressure suction | (calculated in *‘lib\_geothermal.cpp’)* | *ratio* | |
|  | NCG removal flow rate | (calculated in *‘lib\_geothermal.cpp’)* |  | |

The formula for calculating the baseline cost ($/kW) of the H2S Removal System is given by eq (12):

(12)

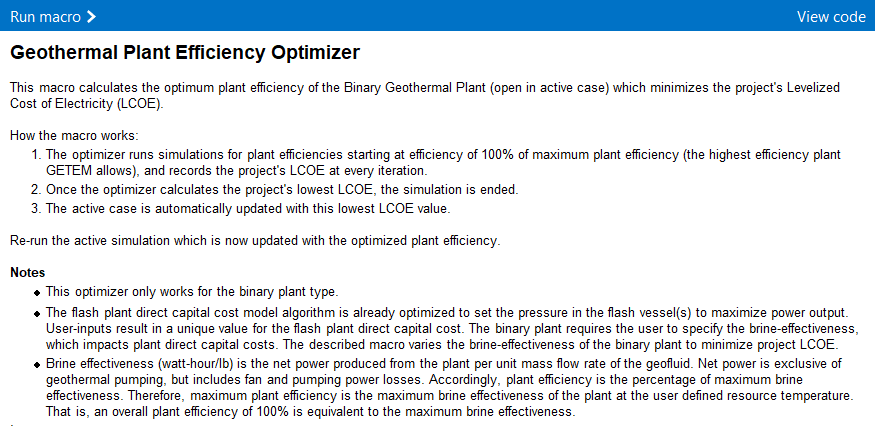
Where, (lb/h) is the rate of removal of Hydrogen Sulfide from the power plant.

Therefore, given that the user has selected the Flash Plant type in the Plant and Equipment tab of the Geothermal technology in SAM, clicking the ‘Automatically estimate plant cost’ radio button in SAM (Figure 1) calculates the baseline cost ($/kW) of a binary plant, whose formula is given by eq (13):

(13)

* 1. Geothermal Plant Efficiency Optimizer

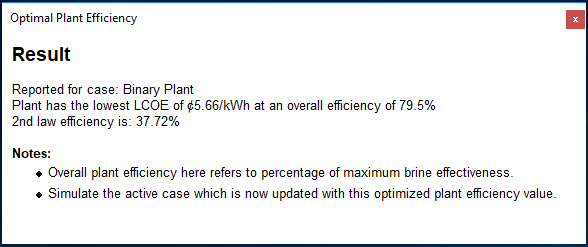
A new macro ‘Geothermal Plant Efficiency Optimizer’ (Figure 2) was added to the geothermal technology of SAM v. 2018.11.11. This macro determines the optimal plant efficiency of a **binary** plant type for which the project has the lowest levelized cost of electricity (LCOE)[[1]](#footnote-1). One of the advantages of recreating the GETEM model in SAM is the enhanced flexibility and ease of adding additional features to the geothermal model, such as the plant efficiency optimizer.



**Figure 2. Geothermal Plant Efficiency Optimizer Macro in SAM v. 2018.11.11**

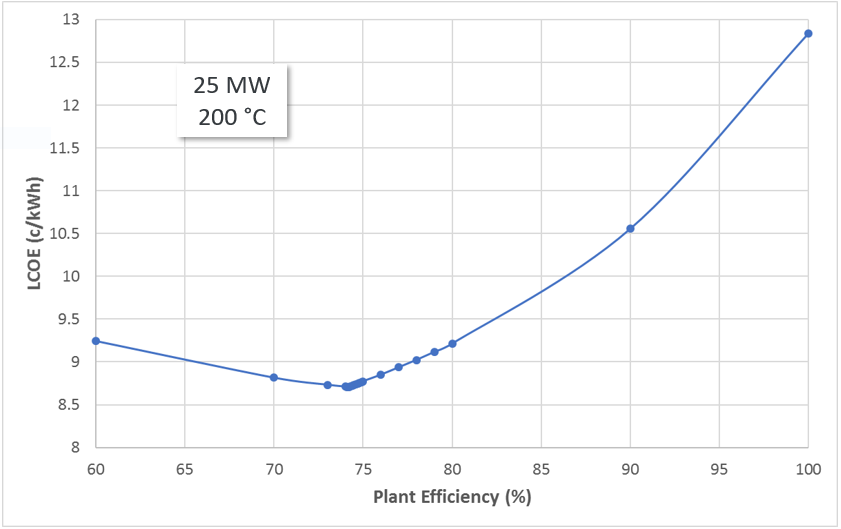
As explained in Figure 2, when the user runs this macro, SAM sets the plant efficiency automatically in the active case and records the LCOE at that efficiency. Once the macro run is completed, a message box displays the lowest LCOE *(* and its corresponding overall plant efficiency (Figure 3).

In GETEM (and the geothermal technology of SAM), the power plant’s performance is characterized by the metric - brine effectiveness (or specific output). Brine effectiveness (watt-hour/lb) is the net power produced from the plant per unit mass flow rate of the geofluid. Net power is exclusive of geothermal pumping, but includes fan and pumping power losses. Accordingly, plant efficiency is the percentage of maximum brine effectiveness. Therefore, maximum plant efficiency is the maximum brine effectiveness of the plant at the user defined resource temperature. That is, an overall plant efficiency of 100% is equivalent to the maximum brine effectiveness. Plant efficiency in other words is the 2nd law efficiency (or exergetic efficiency).[[2]](#footnote-2)

**Figure 3. Message Box Displaying the Optimal Binary Plant Efficiency**

The macro displays the optimal plant efficiency with a one decimal place accuracy. Running a simulation for every iteration of plant efficiency from 0-100% is a time-consuming process, with simulation time exceeding 60 seconds per iteration. Therefore, to speed up this macro’s decision time, it takes advantage of the fact that for a binary power plant, its LCOE v. Plant Efficiency curve roughly follows a convex parabolic relationship (i.e., has a global minimum). The macro runs a simulation beginning at 100%, , plant efficiency and at iterations, , of 10%, keeping track of the curve’s rate of change (in the left-to-right direction). On passing the curve’s inflection point, a flag is turned on to inform the macro that the plant efficiency range in which the minimum occurs has been reached. Once the flag is turned on, the macro simulates for the next and final iteration of plant efficiency to confirm the occurrence of the minimum point was a global minimum as opposed to a local minimum.

This truncates the sample space being searched for an optimum to ( – 100%). However, the sample space can be further trimmed to 10% of the inflection point, resetting the new range being searched to %. The process outlined above is repeated two more times, once at a new sampling frequency of , and finally for = 0.1% to calculate the optimal plant efficiency with a one decimal place accuracy.

**Figure 4. Parabolic Relation of a Generic Binary Plant’s LCOE v. Plant Effiicency**

1. Results and Discussion

A parametric study was done in SAM and GETEM respectively to calculate the plant’s baseline ($/kW) and total cost ($) as a function of its resource temperature (), overall plant efficiency (%), and nameplate capacity (kW) while leaving all other inputs at their new default values. Sections 3.1 and 3.2 compare the results obtained in SAM vs. GETEM for the binary and flash plant types respectively.

* 1. Comparison of Baseline and Total Cost of Binary Plant in SAM vs. GETEM

The parametric study for the binary plant was done for resource temperatures of (150, 175, 200) , overall plant efficiencies of (50, 75, 100) %, and nameplate plant capacities of (5, 25, 50) MWe. The average percentage difference between the baseline cost calculated in SAM and GETEM was 0.77% with a standard deviation of 0.34% (**Figure 5**).

**Figure 5. Comparison of Baseline Cost Calculated in SAM vs. GETEM**

The formula for the total plant cost ($) is given by eq (14):

(14)

Where, baseline cost is in and gross plant output is in (kW). Figure6 below summarizes the difference in total plant cost calculated in SAM and GETEM. The average difference in total cost was 2.43% with a standard deviation of 1.21% (see Appendix for raw data).

**Figure 6. Comparison of Total Plant Cost Calculated in SAM vs. GETEM**

* 1. Comparison of Baseline and Total Cost of Flash Plant in SAM vs. GETEM

The parametric study for the flash plant was done for resource temperatures of (200, 250, 300) , and nameplate plant capacities of (5, 25, 50) MWe. Two types of flash plants studied were the constrained single flash and constrained dual flash plant types.

Figure 7 summarizes the comparison in baseline results obtained for a constrained single flash plant type. The average percentage difference between the baseline cost calculated in SAM and GETEM was 3.37% with a standard deviation of 1.23%.

**Figure 7. Comparison of Baseline Plant Cost Calculated in SAM vs. GETEM for a Constrained Single Flash Plant Type**

Figure 8 below summarizes the difference in total plant cost calculated in SAM and GETEM for the single flash plant type. The average difference in total cost was 2.39% with a standard deviation of 1.13%

Figure 8. Comparison of Total Plant Cost Calculated in SAM vs. GETEM for a Constrained Single Flash Plant Type

Figure 9 summarizes the comparison in baseline cost results obtained for a constrained dual flash plant type. The average percentage difference between the baseline cost calculated in SAM and GETEM was 3.67% with a standard deviation of 1.24%.

Figure 9. Comparison of Baseline Plant Cost Calculated in SAM vs. GETEM for a Constrained Dual Flash Plant Type

Figure 10 summarizes the difference in total plant cost calculated in SAM and GETEM for the constrained dual flash plant type. The average difference in total cost was 0.99% with a standard deviation of 1.13%

Figure 10. Comparison of Total Plant Cost Calculated in SAM vs. GETEM for a Constrained Dual Flash Plant Type

A major source for the discrepancies observed in the baseline and total costs between SAM and GETEM is the differences in the formulas used for calculations of a few technical parameters that characterize the geothermal plant. This includes, and is not limited to, the calculation of the gross plant output, maximum plant efficiency, number of production wells, and exit temperature of the geofluid, to name a few. As seen in equations 1-13, the calculation of baseline and total cost requires a few technical parameters as inputs, which are calculated in two main files, namely, *‘lib\_geothermal.cpp’* and *‘cmod\_geothermal.cpp.’*

As recommended next steps, to fix the discrepancies in cost calculations observed above, the underlying geothermal performance model in SAM will need to be compared to that in GETEM v. 2016 to make any necessary updates.

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Appendix

* 1. Default Values Updates

Table A. 1 Updated Default Values in Plant and Equipment Tab

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Tab in SAM | Block | Input | Default Value in GETEM 2016 | Old Default Value in SAM | Notes |
| Plant and Equipment | Plant Configuration | Toggle: |  |  |  |
| Specify Plant Output | 30,000 kW | 15,000 kW |  |
| Use exact number of wells | 1 | 3 | Default in GETEM is 1, but isn't realistic. Left in SAM as 3 |
| Conversion Plant Type | Binary | Binary |  |
| Plant Efficiency | n/a | 95% | Not an input in GETEM. Value lowered to 80% in SAM - more realistic. |
| Enter Plant Design Temperature | n/a |  | Not an input in GETEM. |
| Automatically set to Resource Temp | n/a | No (Unchecked) | Set to Yes (Checked) in SAM v. 2018.11.11 |
| Availability and Curtailment | Constant Loss | n/a | 0 | Unchanged in new SAM v. 2018.11.11 |
| Hourly Losses | n/a | None |
| Custom Periods | n/a | None |
| Temperature Decline (EGS only) | Specify Temp Decline | 0.50% | 3%/yr | This is the option selected in SAM |
| Max temp decline before reservoir replacement | 30 C | 30 C |  |
| Flash Technology | Wet Bulb Temperature | 15.56 C / 60 F | 15 C |  |
| Ambient Pressure | n/a | 14.7 psi | No longer an input in GETEM |
| Pumping Parameters | Production Well Flow Rate | [Hydrothermal: 110 kg/s for binary plant] [Flash Plant: 80 kg/s] [EGS: 40 kg/s (binary and flash)] | 70 kg/s |  |
| Pump Efficiency | 67.50% | 60% |  |
| Pressure Difference Across Surface Equipment | 40 | 25 psi |  |
| Excess Pressure at Pump Suction | 50 | 50.76 psi |  |
| Production Well Diameter | 12.25 | 10 inches |  |
| Production Pump Casing Size | 9.625 | 9.625 inches |  |
| Injection Well Diameter | 12.25 | 10 inches |  |
| Specify Pump Work | n/a | Unchecked | Unchanged in new SAM v. 2018.11.11 |
| Specified Pump Work | n/a | 0 MW |

Table A. 2 Updated Default Values in Power Block Tab

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Tab in SAM | Block | Input | Default Value in GETEM 2016 | Old Default Value in SAM | Notes |
| Power Block | **Power Block Design Point** | Rated Cycle Conversion Efficiency | n/a | 0.17 | Unchanged in SAM 2018.11.11 |
| Design Outlet Temperature | n/a | 90 C |
| Boiler Operating Pressure | n/a | 2 Bar |
| Steam Cycle Blowdown Fraction | n/a | 0.013 |
| **Cooling System** | Condenser Type | Hybrid | Evaporative |
| Ambient Temperature at Design | n/a | 15 C |
| Ref. Condenser Water dT | n/a | 10 C |
| Approach Temperature | n/a | 5 C |
| ITD at Design Point | n/a | 16 C |
| Condenser Pressure Ratio | n/a | 1.0028 |
| Minimum Condenser Pressure | n/a | 1.25 Hg |
| Cooling System Part Load Levels | n/a | 8 |
| Hybrid Dispatch: Periods 1-8 | n/a | 0 |

Table A. 3 Updated Default Values in System Costs Tab

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Tab in SAM | Block | Input | Default Value in GETEM 2016 | Old Default Value in SAM |
| System Costs | Number of Wells to Drill | % of Confirmation Wells Used for Production | 50% | 50% |
| Ratio of Injection Wells to Production Wells | 0.75 | 0.5 |
| Drilling and Associated Costs | Exploration |  |  |
| Cost Multiplier | not an input in Excel anymore | 0.5 |
| # of Wells | not an input in Excel anymore | 2 |
| Non-Drilling Cost | not an input in Excel anymore | $750,000.00 |
| Confirmation |  |  |
| Cost Multiplier | 1.2 | 1.2 |
| # of Wells | 4 | 2 |
| Non-Drilling Cost | not an input in Excel anymore | $250,000 |
| Production |  |  |
| Cost Curve | not an input in Excel anymore | Med |
| Injection |  |  |
| Cost Curve | not an input in Excel anymore | Med |
| Non-Drilling Cost | $150,000 (but not an input in Excel anymore) | $250,000.00 |
| Surface Equipment Installation | Calculated. | $125,000 / well |
| Stimulation Cost | Hydrothermal: $0 EGS: $2,500,000/well (injection wells only) | $1,000,000.00 |
| Specified Total Drilling, Surface Equipment, and Stimulation Cost | Calculated | Checked (Calculate) |

1. The flash plant direct capital cost model algorithm is already optimized to set the pressure in the flash vessel(s) to maximize power output. User-inputs result in a unique value for the flash plant direct capital cost. The binary plant requires the user to specify the brine-effectiveness, which impacts plant direct capital costs. The described macro varies the brine-effectiveness of the binary plant to minimize project LCOE. [↑](#footnote-ref-1)
2. Where exergy is the maximum theoretical work done by a system as it interacts and reaches equilibrium with its surroundings. Exergetic efficiency is defined as the ratio of exergy output and exergy input. [↑](#footnote-ref-2)