GEOPHIRES v2.0 User Manual | January 15th, 2019

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Contents

1. Introduction

This manual helps the user run geothermal techno-economic simulations with the software tool GEOPHIRES v2.0. The manual provides a short overview of the tool (Section 2), a quick start guide (Section 3), an overview of the included example problems (Section 4), the format required to enter input values (Section 5), and a list of all input parameters (Section 6) with corresponding description, units, allowable values (or range of values), and default values.

The latest version of GEOPHIRES, this manual and example simulations can be downloaded from the GEOPHIRES GitHub folder: https://github.com/NREL/GEOPHIRES-v2

If case of questions or comments or if you find a bug, please contact Koenraad Beckers (koenraad.beckers@heateon.com) or Kevin McCabe (kevin.mccabe@nrel.gov).

2. GEOPHIRES v2.0 Overview

A detailed description of the objectives, capabilities, history, software architecture, and built-in models and correlations of GEOPHIRES v2.0 is provided in an accompanying paper. Below is a short summary:

- GEOPHIRES combines reservoir, wellbore, surface plant, and economic and cost models and correlations to estimate the capital and operation and maintenance costs, instantaneous and lifetime energy production, and overall levelized cost of energy of a geothermal plant.
- The software architecture is illustrated in Figure 1. Green, orange and blue rectangles refer to internal GEOPHIRES components, external user-interface components, and the external reservoir simulator TOUGH2, respectively. Rectangles with solid outline are always executed during a simulation run; rectangles with dashed outline refer to optional or user-provided components.
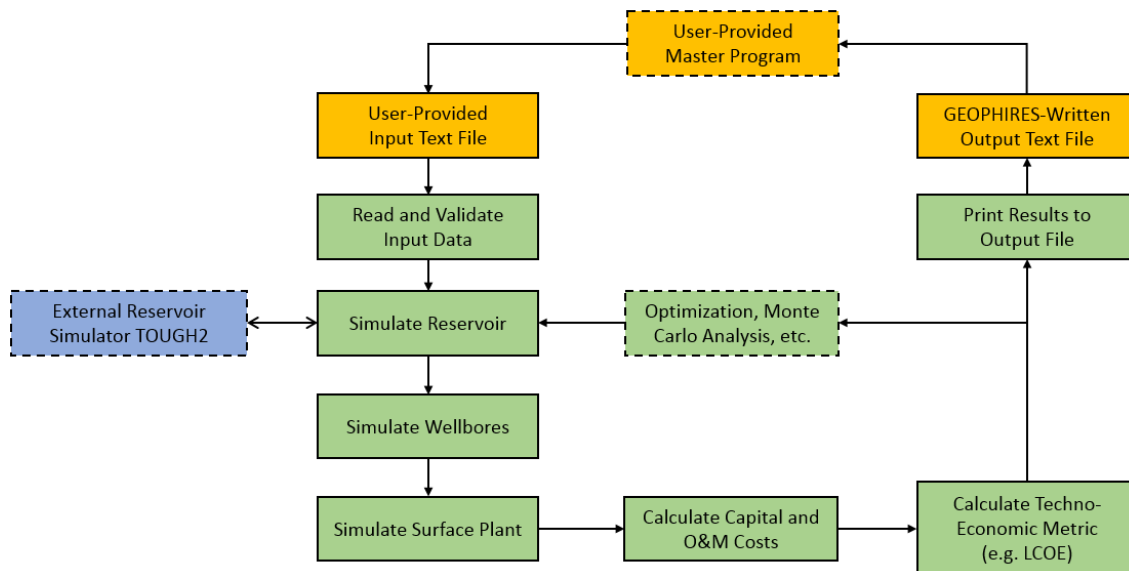

Figure 1. GEOPHIRES v2.0 Software Architecture

- GEOPHIRES v2.0 is open-source under the MIT license (anybody can modify for commercial and non-commercial purposes). Users are encouraged to improve and expand upon the GEOPHIRES code by adding new model features that are not standard built-in (e.g. optimization and Monte Carlo routine), implementing their own models and correlations (e.g. to simulate a specific direct-use heat application), coupling to other simulators (e.g. IPSEpro to simulate the surface plant), etc.
- Unlike its predecessor, GEOPHIRES v.2.0 is written in Python to make it highly readable, easy to modify, and free to compile.

- GEOPHIRES v2.0 has six different built-in reservoir models: (1) multiple parallel fractures model, (2) 1-dimensional linear heat sweep model, (3) *m/a* thermal drawdown parameter model, (4) percentage temperature drawdown model, (5) user-provided reservoir temperature production data, (6) coupling to TOUGH2 external reservoir simulator.

- GEOPHIRES v2.0 can simulate three different end-uses of the geothermal heat: (1) direct-use heat (e.g. for industrial processing heating or residential space heating), (2) electricity (with subcritical ORC, supercritical ORC, single-flash, or double-flash plant), (3) co-generation of heat and electricity. The co-generation option considers bottoming cycle, topping cycle, and parallel cycle.

- GEOPHIRES v2.0 has 3 economic models to calculate the levelized cost of heat or electricity: (1) fixed charge rate (FCR) model, (2) standard discounting levelized cost model, and (3) BICYCLE model.

- The capital and O&M costs for the different geothermal system components (exploration, well drilling, surface plant, etc.) are either provided by the user or calculated with built-in correlations.

3. Quick Start Guide

The following steps guide a new user through the process of running his/her first simulation with GEOPHIRES v2.0:

1. <u>Download and Install Python</u>: If not already installed, the user should download Python and the necessary libraries (math, datetime, numpy, time, os, sys) from www.python.org and install on the computer. If unsure if Python is already installed, typing "python" in a command window will return the Python version if installed. GEOPHIRES v2.0 has successfully been tested on Python 2.7 and 3.5.

2. <u>Download and install advanced text editor or Integrated Development Environment (optional)</u>: while a simple text editor (e.g. notepad for Windows) is sufficient to modify Python code, a more sophisticated text editor (e.g. sublime) or integrated development environment (e.g. Spyder) facilitates writing and modifying Python code by providing functionalities such as automatic code completion, installing missing libraries, debugging, and even compiling.

3. <u>Download GEOPHIRES v2.0 files</u>: the user should download the GEOPHIRES v2.0 files from the GEOPHIRES folder on GitHub. These files include the source code (GEOPHIRESv2.py), three example input files (example1.txt, example2.txt, example3.txt), and an example user-provided reservoir output temperature profile (ReservoirOutput.txt). These files should be located in the same folder.

4. <u>Download TOUGH2 (optional)</u>: if the user would like to make use of the coupling with TOUGH2 (reservoir option 6), a TOUGH2 executable should be provided in the GEOPHIRES folder. Downloading and running a TOUGH reservoir simulator requires purchasing a license from Lawrence Berkeley National Laboratory (LBNL).

5. <u>Run example file</u>: The user should run the included examples (see Section 4) to get familiar with the input format and calculated output results.

4. Example Problems

Six example problems (see Table 1) are included in the GEOPHIRES GitHub folder considering different reservoir types, reservoir models, end-uses, and economic models. These various example problems can help users setting up correctly the GEOPHIRES input text file for their application. Example 6 requires having the TOUGH2-EOS1 executable ("xt2_eos1.exe") located in the same folder as the GEOPHIRES python code ("GEOPHIRESv2.py").

Table 1. Overview of example problems includes in the GEOPHIRES GitHub folder

	Reservoir Type	Reservoir Model	End-Use	Economic Model
Example 1	EGS	Multiple Parallel Fractures	Electricity with Supercritical ORC	Fixed Charge Rate Model
Example 2	EGS	1D Linear Heat Sweep	Industrial Direct-Use Heat	Standard Levelized Cost
Example 3	EGS	m/a Single Fracture Drawdown	CHP: Double Flash Topping Industrial Direct-Use Heat; Electricity as Main Product	BICYCLE
Example 4	Hydrothermal	Percentage Thermal Drawdown	Electricity with Subcritical ORC	BICYCLE
Example 5	EGS	User-Provided Reservoir Output Temperature Data	Industrial Direct-Use Heat	BICYCLE
Example 6	Hydrothermal	TOUGH2 Doublet	Industrial Direct-Use Heat	Standard Levelized Cost

5. Input Parameter Format

In the input text file, each parameter and value are provided by the user on a single line using one of the following two formats:

    Parameter_name, parameter_value

    Parameter_name, parameter_value, any comments

For example, to set the production well flow rate to 50 L/s, the user writes:

    Production Flow Rate per Well, 50

Or when the user wants to include comments, e.g. to explain the units, he/she can write:

    Production Flow Rate per Well, 50, production well flow rate in units of L/s

The user is free to choose any name for the input text file (in .txt format) but has to assign that name to the parameter "fname" at the beginning in the GEOPHIRES Python code.

6. List of GEOPHIRES Input Parameters

This section provides a list of all 92 input parameters with their name, description, parameter type, unit, allowable values or range of values, default value, and when the parameter is required as input. They are grouped into:

- Subsurface technical parameters (47)
- Surface technical parameters (9)
- Financial parameters (13)
- Capital and O&M Cost parameters (21)
- Simulation parameters (2)

6.1 Subsurface Technical Parameters

1. Parameter name: **Reservoir Model**
    o *Description*: Select the reservoir model to be used in GEOPHIRES
    o *Parameter type*: Integer
    o *Units*: N/A
    o *Allowable values*:
        ▪ 1: Multiple parallel fractures model
        ▪ 2: 1D linear heat sweep model
        ▪ 3: m/a single fracture drawdown model
        ▪ 4: Linear thermal drawdown model
        ▪ 5: Generic user-provided temperature profile

- 6: TOUGH2
  - o *When required*: Always
  - o *Default value*: 4
2. Parameter name: **Drawdown Parameter**
  - o *Description*: specify the thermal drawdown for reservoir model 3 and 4
  - o *Parameter type*: Real
  - o *Units*:
    - kg/s/m^2 if reservoir model = 3
    - 1/year if reservoir model = 4
  - o *Allowable value range*:
    - [0,0.2] if reservoir model = 3
    - [0,0.2] if reservoir model = 4
  - o *When required*: if reservoir model = 3 or 4
  - o *Default value*:
    - 0.0001 if reservoir model = 3
    - 0.005 if reservoir model = 3
3. Parameter name: **Reservoir Output File Name**
  - o *Description*: File name of reservoir output in case reservoir model 5 is selected
  - o *Parameter type*: String
  - o *Units*: N/A
  - o *Allowable values*: N/A
  - o *When required*: if reservoir model = 5
  - o *Default value*: ReservoirOutput.txt
4. Parameter name: **TOUGH2 Model/File Name**
  - o *Description*: File name of reservoir output in case reservoir model 5 is selected
  - o *Parameter type*: String
  - o *Units*: N/A
  - o *Allowable values*: N/A
  - o *When required*: if reservoir model = 5
  - o *Default value*: ReservoirOutput.txt
5. Parameter name: **Reservoir Depth**
  - o *Description*: Depth of the reservoir
  - o *Parameter type*: Real
  - o *Units*: km
  - o *Allowable value range*: [0.1,15]
  - o *When required*: Always
  - o *Default value*: 3 km
6. Parameter name: **Number of Segments**
  - o *Description*: Number of rock segments from surface to reservoir depth with specific geothermal gradient
  - o *Parameter type*: Integer
  - o *Units*: N/A
  - o *Allowable values*: [1,2,3,4]
  - o *When required*: Always
  - o *Default value*: 1
7. Parameter name: **Gradient 1**

- o *Description*: Geothermal gradient in rock segment 1
- o *Parameter type*: Real
- o *Units*: °C/km
- o *Allowable value range*: [0,500]
- o *When required*: Always
- o *Default value*: 50

8. Parameter name: **Gradient 2**
- o *Description*: Geothermal gradient in rock segment 2
- o *Parameter type*: Real
- o *Units*: °C/km
- o *Allowable value range*: [0,500]
- o *When required*: If number of segments > 1
- o *Default value*: 50

9. Parameter name: **Thickness 1**
- o *Description*: Thickness of rock segment 1
- o *Parameter type*: Real
- o *Units*: km
- o *Allowable value range*: [0.01,100]
- o *When required*: If number of segments > 1
- o *Default value*: 2

10. Parameter name: **Gradient 3**
- o *Description*: Geothermal gradient in rock segment 3
- o *Parameter type*: Real
- o *Units*: °C/km
- o *Allowable value range*: [0,500]
- o *When required*: If number of segments > 2
- o *Default value*: 50

11. Parameter name: **Thickness 2**
- o *Description*: Thickness of rock segment 2
- o *Parameter type*: Real
- o *Units*: km
- o *Allowable value range*: [0.01,100]
- o *When required*: If number of segments > 2
- o *Default value*: 2

12. Parameter name: **Gradient 4**
- o *Description*: Geothermal gradient in rock segment 4
- o *Parameter type*: Real
- o *Units*: °C/km
- o *Allowable value range*: [0,500]
- o *When required*: If number of segments > 3
- o *Default value*: 50

13. Parameter name: **Thickness 3**
- o *Description*: Thickness of rock segment 3
- o *Parameter type*: Real
- o *Units*: km
- o *Allowable value range*: [0.01,100]

- o *When required*: If number of segments > 3
- o *Default value*: 2

14. Parameter name: **Maximum Temperature**
    - o *Description*: Maximum allowable reservoir temperature (e.g. due to drill bit or logging tools constraints). GEOPHIRES will cap the drilling depth to stay below this maximum temperature.
    - o *Parameter type*: Real
    - o *Units*: °C
    - o *Allowable value range*: [50,1000]
    - o *When required*: Always
    - o *Default value*: 400

15. Parameter name: **Number of Production Wells**
    - o *Description*: Number of (identical) production wells
    - o *Parameter type*: Integer
    - o *Units*: N/A
    - o *Allowable value range*: [1,20]
    - o *When required*: Always
    - o *Default value*: 2

16. Parameter name: **Number of Injection Wells**
    - o *Description*: Number of (identical) injection wells
    - o *Parameter type*: Integer
    - o *Units*: N/A
    - o *Allowable value range*: [1,20]
    - o *When required*: Always
    - o *Default value*: 2

17. Parameter name: **Production Well Diameter**
    - o *Description*: Inner diameter of production wellbore (assumed constant along the wellbore) to calculate frictional pressure drop and wellbore heat transmission with Ramey's model
    - o *Parameter type*: Real
    - o *Units*: Inch
    - o *Allowable value range*: [1,30]
    - o *When required*: Always
    - o *Default value*: 8 inch

18. Parameter name: **Injection Well Diameter**
    - o *Description*: Inner diameter of injection wellbore (assumed constant along the wellbore) to calculate frictional pressure drop
    - o *Parameter type*: Real
    - o *Units*: Inch
    - o *Allowable value range*: [1,30]
    - o *When required*: Always
    - o *Default value*: 8 inch

19. Parameter name: **Ramey Production Wellbore Model**
    - o *Description*: Select whether to use Ramey's model to estimate the geofluid temperature drop in the production wells.
    - o *Parameter type*: Boolean

- o *Units*: N/A
- o *Allowable value range*: 0 (disable) or 1 (enable)
- o *When required*: Always
- o *Default value*: 1

20. Parameter name: **Production Wellbore Temperature Drop**
   - o *Description*: Specify constant production well geofluid temperature drop in case Ramey's model is disabled.
   - o *Parameter type*: Real
   - o *Units*: °C
   - o *Allowable value range*: [-5,50]
   - o *When required*: If Ramey's model is disabled
   - o *Default value*: 5

21. Parameter name: **Injection Wellbore Temperature Gain**
   - o *Description*: Specify constant injection well geofluid temperature gain.
   - o *Parameter type*: Real
   - o *Units*: °C
   - o *Allowable value range*: [-5,50]
   - o *When required*: Always
   - o *Default value*: 0

22. Parameter name: **Production Flow Rate per Well**
   - o *Description*: Geofluid flow rate per production well.
   - o *Parameter type*: Real
   - o *Units*: kg/s
   - o *Allowable value range*: [1,500]
   - o *When required*: Always
   - o *Default value*: 50

23. Parameter name: **Fracture Shape**
   - o *Description*: Specifies the shape of the (identical) fractures in a fracture-based reservoir
   - o *Parameter type*: Integer
   - o *Units*: N/A
   - o *Allowable values*:
     - ▪ 1: Circular fracture with known area
     - ▪ 2: Circular fracture with known diameter
     - ▪ 3: Square fracture
     - ▪ 4: Rectangular fracture
   - o *When required*: If reservoir model = 1 or 2
   - o *Default value*: 1

24. Parameter name: **Fracture Area**
   - o *Description*: Effective heat transfer area per fracture
   - o *Parameter type*: Real
   - o *Units*: m^2
   - o *Allowable value range*: [1,1E8]
   - o *When required*: If reservoir model = 1 or 2 and fracture shape = 1
   - o *Default value*: 250,000 m^2

25. Parameter name: **Fracture Height**

- o *Description*: Diameter (if fracture shape = 2) or height (if fracture shape = 3 or 4) of each fracture
- o *Parameter type*: Real
- o *Units*: m
- o *Allowable value range*: [1,10000]
- o *When required*: If reservoir model = 1 or 2 and fracture shape = 2, 3 or 4
- o *Default value*: 500 m

26. Parameter name: **Fracture Width**
   - o *Description*: Width of each fracture
   - o *Parameter type*: Real
   - o *Units*: m
   - o *Allowable value range*: [1,10000]
   - o *When required*: If reservoir model = 1 or 2 and fracture shape = 4
   - o *Default value*: 500 m

27. Parameter name: **Reservoir Volume Option**
   - o *Description*: Specifies how the reservoir volume, and fracture distribution (for reservoir models 1 and 2) are calculated. The reservoir volume is used by GEOPHIRES to estimate the stored heat in place. The fracture distribution is needed as input for the EGS fracture-based reservoir models 1 and 2.
   - o *Parameter type*: Integer
   - o *Units*: N/A
   - o *Allowable values*:
     - ▪ 1: Specify number of fractures and fracture separation
     - ▪ 2: Specify reservoir volume and fracture separation
     - ▪ 3: Specify reservoir volume and number of fractures
     - ▪ 4: Specify reservoir volume only (sufficient for reservoir models 3, 4, 5 and 6)
   - o *When required*: Always
   - o *Default value*:
     - o 4 if reservoir model = 1 or 2
     - o 3 if reservoir model = 3, 4, 5 or 6

28. Parameter name: **Number of Fractures**
   - o *Description*: Number of identical parallel fractures in EGS fracture-based reservoir model.
   - o *Parameter type*: Integer
   - o *Units*: N/A
   - o *Allowable value range*: [1,20]
   - o *When required*: If reservoir model = 1 or 2 and reservoir volume option = 1 or 3
   - o *Default value*: 10

29. Parameter name: **Fracture Separation**
   - o *Description*: Separation of identical parallel fractures with uniform spatial distribution in EGS fracture-based reservoir.
   - o *Parameter type*: real
   - o *Units*: m
   - o *Allowable value range*: [1,1E4]
   - o *When required*: If reservoir model = 1 or 2 and reservoir volume option = 1 or 2

- *Default value*: 50 m
30. Parameter name: **Reservoir Volume**
    - *Description*: Geothermal reservoir volume
    - *Parameter type*: real
    - *Units*: m^3
    - *Allowable value range*: [10,1E12]
    - *When required*: If reservoir volume option = 3 or 4
    - *Default value*: 500 × 500 × 500 m^3 = 125,000,000 m^3
31. Parameter name: **Water Loss Fraction**
    - *Description*: Fraction of water lost in the reservoir defined as (total geofluid lost)/(total geofluid produced). The total injection flow rate is then calculated as: (injection rate) = (production rate) × (1+ water loss fraction)
    - *Parameter type*: Real
    - *Units*: N/A
    - *Allowable value range*: [0,0.99]
    - *When required*: If reservoir volume option = 3 or 4
    - *Default value*: 0
32. Parameter name: **Reservoir Impedance**
    - *Description*: Reservoir resistance to flow per well-pair. For EGS-type reservoirs when the injection well is in hydraulic communication with the production well, this parameter specifies the overall pressure drop in the reservoir between injection well and production well, calculated as (reservoir impedance) × (reservoir flow rate).
    - *Parameter type*: Real
    - *Units*: GPa·s/m^3
    - *Allowable value range*: [1E-4,1E4]
    - *When required*: Optional; default is specifying productivity and injectivity indices
    - *Default value*: 0.1
33. Parameter name: **Productivity Index**
    - *Description*: Productivity index defined as ratio of production well flow rate over production well inflow pressure drop (hydrostatic reservoir pressure – flowing bottom hole pressure).
    - *Parameter type*: Real
    - *Units*: kg/s/bar
    - *Allowable value range*: [1E-2,1E4]
    - *When required*: Required if not specifying reservoir impedance and no flash power plant considered
    - *Default value*: 10
34. Parameter name: **Injectivity Index**
    - *Description*: Injectivity index defined as ratio of injection well flow rate over injection well outflow pressure drop (flowing bottom hole pressure - hydrostatic reservoir pressure).
    - *Parameter type*: Real
    - *Units*: kg/s/bar
    - *Allowable value range*: [1E-2,1E4]
    - *When required*: Required if not specifying reservoir impedance

o *Default value*: 10

35. Parameter name: **Reservoir Hydrostatic Pressure**
- o *Description*: Reservoir hydrostatic far-field pressure
- o *Parameter type*: Real
- o *Units*: kPa
- o *Allowable value range*: [1E2,1E5]
- o *When required*: Required if specifying productivity/injectivity indices.
- o *Default value*: Built-in modified Xie-Bloomfield-Shook equation (DOE, 2016).

36. Parameter name: **Production Wellhead Pressure**
- o *Description*: Constant production wellhead pressure
- o *Parameter type*: Real
- o *Units*: kPa
- o *Allowable value range*: [0,1E4]
- o *When required*: Required if specifying productivity index
- o *Default value*: Water vapor pressure (at initial production temperature) + 344.7 kPa (50 psi).

37. Parameter name: **Plant Outlet Pressure**
- o *Description*: Constant plant outlet pressure equal to injection well pump(s) suction pressure
- o *Parameter type*: Real
- o *Units*: kPa
- o *Allowable value range*: [0,1E4]
- o *When required*: Required if specifying injectivity index
- o *Default value*:
  - ▪ 100 kPa (1 bar) in case of flash power plant
  - ▪ Production wellhead pressure – 68.95 kPa (10 psi) in all other cases

38. Parameter name: **Injection Temperature**
- o *Description*: Constant geofluid injection temperature at injection wellhead.
- o *Parameter type*: Real
- o *Units*: °C
- o *Allowable value range*: [0,200]
- o *When required*: Always
- o *Default value*: 70°C

39. Parameter name: **Maximum Drawdown**
- o *Description*: Maximum allowable thermal drawdown before redrilling of all wells into new reservoir (most applicable to EGS-type reservoirs with heat farming strategies). E.g. a value of 0.2 means that all wells are redrilled after the production temperature (at the wellhead) has dropped by 20% of its initial temperature.
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: If reservoir model is 1, 2, 3, or 4.
- o *Default value*: 1 (i.e., no redrilling considered)

40. Parameter name: **Reservoir Heat Capacity**
- o *Description*: Constant and uniform reservoir rock heat capacity

- o *Parameter type*: Real
- o *Units*: J/kg/K
- o *Allowable value range*: [100,10000]
- o *When required*: Always
- o *Default value*: 1000 J/kg/K

41. Parameter name: **Reservoir Density**
- o *Description*: Constant and uniform reservoir rock density
- o *Parameter type*: Real
- o *Units*: kg/m^3
- o *Allowable value range*: [100,10000]
- o *When required*: Always
- o *Default value*: 2700 kg/m^3

42. Parameter name: **Reservoir Thermal Conductivity**
- o *Description*: Constant and uniform reservoir rock thermal conductivity
- o *Parameter type*: Real
- o *Units*: W/m/K
- o *Allowable value range*: [0.01,100]
- o *When required*: If use of Ramey model, or reservoir model = 1, 2 or 3, or reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 3 W/m/K

43. Parameter name: **Reservoir Porosity**
- o *Description*: Constant and uniform reservoir porosity
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0.001,0.99]
- o *When required*: If reservoir model = 2, or reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 0.04

44. Parameter name: **Reservoir Permeability**
- o *Description*: Constant and uniform reservoir permeability
- o *Parameter type*: Real
- o *Units*: m^2
- o *Allowable value range*: [1E-20,1E-5]
- o *When required*: If reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 1E-13 m^2

45. Parameter name: **Reservoir Thickness**
- o *Description*: Reservoir thickness for built-in TOUGH2 doublet reservoir model
- o *Parameter type*: Real
- o *Units*: m
- o *Allowable value range*: [10,10000]
- o *When required*: If reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 250 m

46. Parameter name: **Reservoir Width**
- o *Description*: Reservoir width for built-in TOUGH2 doublet reservoir model
- o *Parameter type*: Real
- o *Units*: m

- o *Allowable value range*: [10,10000]
- o *When required*: If reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 500 m

47. Parameter name: **Well Separation**
- o *Description*: Well separation for built-in TOUGH2 doublet reservoir model
- o *Parameter type*: Real
- o *Units*: m
- o *Allowable value range*: [10,10000]
- o *When required*: If reservoir model = 6 and use of built-in TOUGH2 model
- o *Default value*: 1000 m

6.2 Surface Technical Parameters

48. Parameter name: **End-Use Option**
- o *Description*: Select the end-use application of the geofluid heat
- o *Parameter type*: Integer
- o *Units*: N/A
- o *Allowable values*:
  - § 1: Electricity: All the geothermal fluid heat is used to generate electricity (with a certain conversion heat-to-power conversion efficiency. The levelized cost of energy is expressed as levelized cost of electricity (LCOE) in ¢/kWh_e.
  - § 2: Direct-Use Heat: All the geothermal fluid heat is directly used as heat. The levelized cost of energy is expressed as levelized cost of heat (LCOH) in $/MMBTU.
  - § 3X: CHP Topping Cycle: An electricity generation cycle (high temperature) is in series with direct-use heat (low temperature).
    - § 31: The levelized cost of energy is calculated as LCOE (¢/kWh_e) with electricity considered the main product, and the heat sales considered an additional revenue stream subtracted from the annual O&M costs.
    - § 32: The levelized cost of energy is calculated as LCOH ($/MMBTU) with heat considered the main product, and the electricity sales considered an additional revenue stream subtracted from the annual O&M costs.
  - § 4X: CHP Bottoming Cycle: A direct-use heat application (high temperature) is in series with an electricity generation cycle (low temperature).
    - § 41: The levelized cost of energy is calculated as LCOE (¢/kWh_e) with electricity considered the main product, and the heat sales considered an additional revenue stream subtracted from the annual O&M costs.

- 42: The levelized cost of energy is calculated as LCOH ($/MMBTU) with heat considered the main product, and the electricity sales considered an additional revenue stream subtracted from the annual O&M costs.
  - 5X: CHP Parallel Cycle: The geothermal fluid flow splits in two parts two serve an electricity generation cycle in parallel with direct-use heat, both at the same temperature.
    - 51: The levelized cost of energy is calculated as LCOE ($\cent$/kWh$_e$) with electricity considered the main product, and the heat sales considered an additional revenue stream subtracted from the annual O&M costs.
    - 52: The levelized cost of energy is calculated as LCOH ($/MMBTU) with heat considered the main product, and the electricity sales considered an additional revenue stream subtracted from the annual O&M costs.
  - *When required*: Always
  - *Default value*: 1
49. Parameter name: **Power Plant Type**
    - *Description*: Specify the type of power plant in case of electricity generation
    - *Parameter type*: Integer
    - *Units*: N/A
    - *Allowable values*:
      - 1: Subcritical ORC
      - 2: Supercritical ORC
      - 3: Single-flash
      - 4: Double-flash
    - *When required*: If the end-use option is 1, 31, 32, 41, 42, 51, or 52
    - *Default value*: 1
50. Parameter name: **Circulation Pump Efficiency**
    - *Description*: Specify the overall efficiency of the injection and production well pumps
    - *Parameter type*: Real
    - *Units*: N/A
    - *Allowable value range*: [0.1,1]
    - *When required*: Always
    - *Default value*: 0.75
51. Parameter name: **Utilization Factor**
    - *Description*: Ratio of the time the plant is running in normal production in a 1-year time period.
    - *Parameter type*: Real
    - *Units*: N/A
    - *Allowable value range*: [0.1,1]
    - *When required*: Always
    - *Default value*: 0.9

52. Parameter name: **End-Use Efficiency Factor**
- o *Description*: Constant thermal efficiency of the direct-use application
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0.1,1]
- o *When required*: If the end-use option is 2, 31, 32, 41, 42, 51, or 52
- o *Default value*: 0.9

53. Parameter name: **CHP Fraction**
- o *Description*: Fraction of produced geofluid flow rate going to direct-use heat application in CHP parallel cycle
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0.0001, 0.9999]
- o *When required*: If the end-use option is 51 or 52
- o *Default value*: 0.5

54. Parameter name: **CHP Bottoming Entering Temperature**
- o *Description*: Power plant entering geofluid temperature used in CHP bottoming cycle
- o *Parameter type*: Real
- o *Units*: °C
- o *Allowable value range*: [Injection Temperature, Maximum Temperature]
- o *When required*: If the end-use option is 41 or 42
- o *Default value*: 150°C

55. Parameter name: **Surface Temperature**
- o *Description*: Surface temperature used for calculating bottom-hole temperature (with geothermal gradient and reservoir depth)
- o *Parameter type*: Real
- o *Units*: °C
- o *Allowable value range*: [-50,50]
- o *When required*: Always
- o *Default value*: 15°C

56. Parameter name: **Ambient Temperature**
- o *Description*: Ambient (or dead-state) temperature used for calculating power plant utilization efficiency
- o *Parameter type*: Real
- o *Units*: °C
- o *Allowable value range*: [-50,50]
- o *When required*: If the end-use option is 1, 31, 32, 41, 42, 51, or 52
- o *Default value*: 15°C

6.3 Financial Parameters

57. Parameter name: **Plant Lifetime**
- o *Description*: System lifetime
- o *Parameter type*: Integer
- o *Units*: years

- o *Allowable value range*: [1,100]
- o *When required*: Always
- o *Default value*: 30 years

58. Parameter name: **Economic Model**
- o *Description*: Specify the economic model to calculate the levelized cost of energy
- o *Units*: N/A
- o *Allowable values*:
  - o 1: Fixed Charge Rate Model
  - o 2: Standard Levelized Cost Model
  - o 3: BICYCLE Levelized Cost Model
- o *When required*: Always
- o *Default value*: 2

59. Parameter name: **Fixed Charge Rate**
- o *Description*: Fixed charge rate (FCR) used in the Fixed Charge Rate Model
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: If economic model = 1
- o *Default value*: 0.1

60. Parameter name: **Discount Rate**
- o *Description*: Discount rate used in the Standard Levelized Cost Model
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: If economic model = 2
- o *Default value*: 0.07

61. Parameter name: **Fraction of Investment in Bonds**
- o *Description*: Fraction of geothermal project financing through bonds (debt); the remaining will be through equity.
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: If economic model = 3
- o *Default value*: 0.5

62. Parameter name: **Inflated Bond Interest Rate**
- o *Description*: Inflated bond interest rate, defined as: (1+inflated bond interest rate) = (1 + deflated bond interest rate)×(1 + interest rate). This parameter characterizes the cost of debt.
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: If economic model = 3
- o *Default value*: 0.05

63. Parameter name: **Inflated Equity Interest Rate**

- *Description*: Inflated equity interest rate, defined as: (1+inflated equity interest rate) = (1 + deflated equity interest rate)×(1 + interest rate). This parameter characterizes the cost of equity.
- *Parameter type*: Real
- *Units*: N/A
- *Allowable value range*: [0,1]
- *When required*: If economic model = 3
- *Default value*: 0.1

64. Parameter name: **Inflation Rate**
   - *Description*: Inflation rate
   - *Parameter type*: Real
   - *Units*: N/A
   - *Allowable value range*: [-0.1,1]
   - *When required*: If economic model = 3
   - *Default value*: 0.02

65. Parameter name: **Combined Income Tax Rate**
   - *Description*: Combined income tax rate. Income taxes in each year are calculated using (combined income tax rate) × (revenue – deductible expenses) – investment tax credits.
   - *Parameter type*: Real
   - *Units*: N/A
   - *Allowable value range*: [0,1]
   - *When required*: If economic model = 3
   - *Default value*: 0.3

66. Parameter name: **Gross Revenue Tax Rate**
   - *Description*: Gross revenue tax rate. Gross revenue taxes in each year are calculated using (gross revenue tax rate) × (revenue).
   - *Parameter type*: Real
   - *Units*: N/A
   - *Allowable value range*: [0,1]
   - *When required*: If economic model = 3
   - *Default value*: 0

67. Parameter name: **Investment Tax Credit Rate**
   - *Description*: Investment tax credit rate. Investment tax credits are calculated using (investment tax credit rate) × (initial capital investment).
   - *Parameter type*: Real
   - *Units*: N/A
   - *Allowable value range*: [0,1]
   - *When required*: If economic model = 3
   - *Default value*: 0

68. Parameter name: **Property Tax Rate**
   - *Description*: Property tax rate. Property taxes are fixed annual charges and are calculated using (property tax rate) × (initial capital investment).
   - *Parameter type*: Real
   - *Units*: N/A
   - *Allowable value range*: [0,1]

- o *When required*: If economic model = 3
- o *Default value*: 0

69. Parameter name: **Inflation Rate During Construction**
- o *Description*: Initial capital investment can be inflated with this inflation rate during construction before annual revenue kicks in.
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,1]
- o *When required*: Always
- o *Default value*: 0

6.4 Capital and O&M Cost Parameters

70. Parameter name: **Total Capital Cost**
- o *Description*: Total initial capital cost.
- o *Parameter type*: Real
- o *Units*: M$
- o *Allowable value range*: [0,1000]
- o *When required*: Optional
- o *Default value*: If not provided or out of range, GEOPHIRES will calculate total capital cost using built-in capital cost correlations for each plant component.

71. Parameter name: **Well Drilling and Completion Capital Cost**
- o *Description*: Total fixed drilling and completion capital cost per well
- o *Parameter type*: Real
- o *Units*: M$/well
- o *Allowable value range*: [0,200]
- o *When required*: Optional
- o *Default value*: If not provided or out of range, GEOPHIRES will calculate well drilling and completion capital cost using built-in correlation.

72. Parameter name: **Well Drilling and Completion Capital Cost Adjustment Factor**
- o *Description*: Multiplier for built-in well drilling and completion capital cost correlation
- o *Parameter type*: Real
- o *Units*: N/A
- o *Allowable value range*: [0,10]
- o *When required*: If no well drilling and completion capital cost number provided
- o *Default value*: 1 (i.e., use built-in correlation as is)

73. Parameter name: **Well Drilling Cost Correlation**
- o *Description*: Select the built-in well drilling and completion cost correlation
- o *Parameter type*: Integer
- o *Units*: N/A
- o *Allowable value range*:
  - ▪ 1: vertical open-hole, small diameter
  - ▪ 2: deviated liner, small diameter
  - ▪ 3: vertical open-hole, large diameter
  - ▪ 4: deviated liner, large diameter

- o *When required*: If no valid fixed well drilling and completion capital cost is provided
- o *Default value*: 1
74. Parameter name: **Reservoir Stimulation Capital Cost**
    - o *Description*: Total reservoir stimulation capital cost
    - o *Parameter type*: Real
    - o *Units*: M$
    - o *Allowable value range*: [0,100]
    - o *When required*: Optional
    - o *Default value*: If not provided or out of range, GEOPHIRES will calculate reservoir stimulation capital cost using built-in correlation.
75. Parameter name: **Reservoir Stimulation Capital Cost Adjustment Factor**
    - o *Description*: Multiplier for built-in reservoir stimulation capital cost correlation
    - o *Parameter type*: Real
    - o *Units*: N/A
    - o *Allowable value range*: [0,10]
    - o *When required*: If no reservoir stimulation capital cost number provided
    - o *Default value*: 1 (i.e., use built-in correlation as is)
76. Parameter name: **Surface Plant Capital Cost**
    - o *Description*: Total surface plant capital cost
    - o *Parameter type*: Real
    - o *Units*: M$
    - o *Allowable value range*: [0,1000]
    - o *When required*: Optional
    - o *Default value*: If not provided or out of range, GEOPHIRES will calculate surface plant capital cost using built-in correlation.
77. Parameter name: **Surface Plant Capital Cost Adjustment Factor**
    - o *Description*: Multiplier for built-in surface plant capital cost correlation
    - o *Parameter type*: Real
    - o *Units*: N/A
    - o *Allowable value range*: [0,10]
    - o *When required*: If no surface plant capital cost number provided
    - o *Default value*: 1 (i.e., use built-in correlation as is)
78. Parameter name: **Field Gathering System Capital Cost**
    - o *Description*: Total field gathering system capital cost
    - o *Parameter type*: Real
    - o *Units*: M$
    - o *Allowable value range*: [0,100]
    - o *When required*: Optional
    - o *Default value*: If not provided or out of range, GEOPHIRES will calculate field gathering system capital cost using built-in correlation.
79. Parameter name: **Field Gathering System Capital Cost Adjustment Factor**
    - o *Description*: Multiplier for built-in field gathering system capital cost correlation
    - o *Parameter type*: Real
    - o *Units*: N/A
    - o *Allowable value range*: [0,10]

- *When required*: If no field gathering system capital cost number provided
- *Default value*: 1 (i.e., use built-in correlation as is)

80. Parameter name: **Exploration Capital Cost**
- *Description*: Total exploration capital cost
- *Parameter type*: Real
- *Units*: M$
- *Allowable value range*: [0,100]
- *When required*: Optional
- *Default value*: If not provided or out of range, GEOPHIRES will calculate exploration capital cost using built-in correlation.

81. Parameter name: **Exploration Capital Cost Adjustment Factor**
- *Description*: Multiplier for built-in exploration capital cost correlation
- *Parameter type*: Real
- *Units*: N/A
- *Allowable value range*: [0,10]
- *When required*: If no exploration capital cost number provided
- *Default value*: 1 (i.e., use built-in correlation as is)

82. Parameter name: **Total O&M Cost**
- *Description*: Total initial O&M cost.
- *Parameter type*: Real
- *Units*: M$/year
- *Allowable value range*: [0,100]
- *When required*: Optional
- *Default value*: If not provided or out of range, GEOPHIRES will calculate total O&M cost using built-in O&M cost correlations for each plant component.

83. Parameter name: **Wellfield O&M Cost**
- *Description*: Total annual wellfield O&M cost
- *Parameter type*: Real
- *Units*: M$/year
- *Allowable value range*: [0,100]
- *When required*: Optional
- *Default value*: If not provided or out of range, GEOPHIRES will calculate annual wellfield O&M cost using built-in correlation.

84. Parameter name: **Wellfield O&M Cost Adjustment Factor**
- *Description*: Multiplier for built-in wellfield O&M cost correlation
- *Parameter type*: Real
- *Units*: N/A
- *Allowable value range*: [0,10]
- *When required*: If no annual wellfield O&M cost number provided
- *Default value*: 1 (i.e., use built-in correlation as is)

85. Parameter name: **Surface Plant O&M Cost**
- *Description*: Total annual surface plant O&M cost
- *Parameter type*: Real
- *Units*: M$/year
- *Allowable value range*: [0,100]
- *When required*: Optional

o *Default value*: If not provided or out of range, GEOPHIRES will calculate annual surface plant O&M cost using built-in correlation.

86. Parameter name: **Surface Plant O&M Cost Adjustment Factor**
  o *Description*: Multiplier for built-in surface plant O&M cost correlation
  o *Parameter type*: Real
  o *Units*: N/A
  o *Allowable value range*: [0,10]
  o *When required*: If no annual surface plant O&M cost number provided
  o *Default value*: 1 (i.e., use built-in correlation as is)

87. Parameter name: **Water Cost**
  o *Description*: Total annual make-up water cost
  o *Parameter type*: Real
  o *Units*: M$/year
  o *Allowable value range*: [0,100]
  o *When required*: Optional
  o *Default value*: If not provided or out of range, GEOPHIRES will calculate annual make-up water cost using built-in correlation.

88. Parameter name: **Water Cost Adjustment Factor**
  o *Description*: Multiplier for built-in make-up water cost correlation
  o *Parameter type*: Real
  o *Units*: N/A
  o *Allowable value range*: [0,10]
  o *When required*: If no annual make-up water cost number provided
  o *Default value*: 1 (i.e., use built-in correlation as is)

89. Parameter name: **Electricity Rate**
  o *Description*: Price of electricity to calculate pumping costs in direct-use heat only mode or revenue from electricity sales in CHP mode.
  o *Parameter type*: Real
  o *Units*: $/kWh
  o *Range of allowable values*: [0,1]
  o *When required*: In case end-use option = 2, 32, 42, or 52
  o *Default value*: 0.07

90. Parameter name: **Heat Rate**
  o *Description*: Price of heat to calculate revenue from heat sales in CHP mode.
  o *Parameter type*: Real
  o *Units*: $/kWh
  o *Range of allowable values*: [0,1]
  o *When required*: In case end-use option = 31, 41, or 51
  o *Default value*: 0.02

6.5 Simulation Parameters

91. Parameter name: **Print Output to Console**
  o *Description*: Select whether to print simulation results to the console screen
  o *Parameter type*: Boolean
  o *Units*: N/A

- *Allowable values*: 0 (no) or 1 (yes)
- *When required*: Always
- *Default value*: 1

92. Parameter name: **Time steps per year**
- *Description*: Number of internal simulation time steps per year
- *Parameter type*: Integer
- *Units*: N/A
- *Range of allowable values*: [1,100]
- *When required*: Always
- *Default value*: 4